High School Anatomy & Physiology

First edition **10 units** **45 lessons** **One credit with lab** **A video for every lesson**

Clinical-skills labs **Quick reference: Anatomy & physiology · Nursing entrance exams**

Where this leads

Fields of study: Nursing, Medicine, EMT and paramedic, Physical therapy, Radiologic technology, Athletic training, Respiratory therapy, Kinesiology and exercise science, Pharmacy, Dental hygiene.

Jobs and careers (trades, licenses and degree paths):

- **DEGREE** Registered nurse
- **DEGREE** Physician or physician assistant
- **DEGREE** Physical or occupational therapist
- **DEGREE** Athletic trainer
- **2-YR / CERT** Radiologic (X-ray) technologist
- **2-YR / CERT** Respiratory therapist
- **2-YR / CERT** Licensed practical nurse
- **2-YR / CERT** Dental hygienist
- **LICENSE** EMT or paramedic
- **CERT** Certified nursing assistant (CNA)
- **CERT** Phlebotomist or medical assistant

Key topics and where they're used:

- **Anatomical language and vital signs**: charting, triage, every clinical job
- **Heart, blood pressure and breathing**: nursing, EMS, respiratory therapy
- **Bones, joints and muscles**: physical therapy, athletic training, radiology
- **Hormones, kidneys and acid–base**: nursing, pharmacy, the TEAS and HESI entrance exams

Paths are examples, not promises. Most careers need further training, an apprenticeship, a license or a degree.

FIRST EDITION

Course guide

This is a full-year, college-preparatory course in human anatomy and physiology with lab for students in grades 11–12, worth one credit of laboratory science. It covers the whole introductory core in ten units and 45 lessons: the body as a whole

and its language, cells and tissues, skin and bones, joints and muscles, the nervous system, the endocrine system, blood, heart and defense, respiration, digestion, metabolism and the kidneys, and life, growth and care. Every lesson has key terms, the story of a discovery, labeled schematic figures, worked examples, a practice set with answers, a home lab, a review game and a scripture. Each unit ends with a 100-point test, and there is a midterm after Unit 5 and a final at the end.

The body is taught as a designed whole: “I will praise thee; for I am fearfully and wonderfully made” (Psalm 139:14). Each system is studied first as a working mechanism (a sensor, a control center, an effector, a loop that holds the body steady), and then a disease is explained as that mechanism broken, the way doctors and nurses reason. The history follows the people who looked closely: Vesalius, Harvey, Laennec, Cajal, Loewi, Landsteiner, Einthoven, Cannon, Banting and Best. The labs use the student’s own body and kitchen materials: pulse, temperature and blood pressure, reflexes and a neuro check, chicken bones in vinegar and in the oven, a chicken drumstick, a bell-jar lung and a coffee-filter kidney.

The prerequisites are High School Biology and High School Chemistry, which supply the cells, molecules, gases, solutions and pH this course builds on. Anatomy & Physiology is the gateway course for nursing, EMT and paramedic, physical therapy, radiologic technology, athletic training and pre-med study. The practice sets and unit tests include the item types of the nursing entrance exams (TEAS and HESI A2): multiple choice, select-all-that-apply, ordering and labeling questions, and the capstone lesson 10.4 is a TEAS-style review that pairs well with the site’s Nursing Entrance Exam Review.

> Each lesson has a main video and a backup, chosen from trusted teaching channels: CrashCourse’s Anatomy & Physiology series (the main video for most lessons), the Amoeba Sisters, Dr Matt & Dr Mike, Khan Academy Medicine, Cognito, TED-Ed, RegisteredNurseRN, Kenhub, Launchpad Learning, Miss Angler, Nucleus Medical Media, Alila Medical Media, Professor Dave Explains, Nurse Cheung and a few other medical and science teachers. Each video was matched to its lesson by topic and length and confirmed to play embedded; a few longer backups have a note saying which part to watch. Crash Course videos are lively and sometimes joke; preview them if you prefer a quieter style.

Start with Lesson 1.1 →

Who it is for

Written for students in grades 11–12 who have completed High School Biology and High School Chemistry (or are finishing Chemistry alongside this course). Comfort with metric units, percents and simple formulas is needed; there is no algebra beyond rearranging a formula. Students work fairly independently, reading each lesson and checking their own practice, with a parent or partner for the vital-signs and clinical-skills labs and an adult for anything involving the oven, a knife, raw chicken or hot water.

How to use this course

1. **The weekly rhythm.** Most lessons take four sessions of about 45 minutes: (1) warm-up, video and core ideas; (2) worked examples and the first practice questions; (3) the lab and lab notebook; (4) the rest of the practice set, checked and corrected. Lessons whose labs are short take three sessions, and Lesson 5.5 adds a fifth session for the clinical-skills neuro check. Each unit ends with a review day and a test day, and the midterm and final each have a review day. At five sessions a week the course fills about 39 weeks.
2. **Mechanism, then breakdown, then care.** Read the core ideas in order. Learn how the healthy part works first; the "When it goes wrong" notes then explain a disease as a broken step in that mechanism. A student who can name the broken step can usually predict the symptoms.
3. **Practice.** Questions are marked easy, medium and hard, with groups for concept checks, diagram questions, disorders and test prep. Mark your work against the answers the same day and correct every miss. Say the full anatomical term aloud and spell it; most mistakes on entrance exams are vocabulary.
4. **The figures.** Every figure is a schematic line drawing, not a photograph. Labeling figures have letters or numbers in place of names: cover the caption, name each part, then check.
5. **The lab notebook.** Use a bound notebook for the whole year. For every lab write the date, question, prediction with a reason, procedure, measurements in a data table with units, a graph where it fits, and a conclusion with sources of error. Vital signs taken on family members stay in the notebook and are never shared.

6. **Tests and exams.** Each unit test is worth 100 points and mixes labeling and ordering items, short calculations, application questions and a short essay that explains a disorder as a broken mechanism. The midterm covers Units 1–5 and the final covers the whole course.
7. **Lesson 10.3 is parent-led.** It treats the testes and ovaries only as endocrine glands, links them to meiosis, and traces development before birth alongside Psalm 139. A parent should read it first and go through it with the student.
8. **Safety.** Read the safety note before every lab. The labs never break the skin, draw blood or use real blood. A parent handles the oven, knives, raw chicken and hot water. Stop any exercise lab at dizziness or pain. Home measurements are for learning only: a worrying reading (a very high blood pressure, a fever, a low oxygen reading) goes to a parent and a doctor, not to self-diagnosis.

Scope and Sequence

UNIT 1 · WEEKS 1–4

The Body as a Whole

Levels of organization from atom to person, the language of position, planes, cavities and regions, homeostasis and feedback loops with a vital-signs lab, and seeing inside with X-ray, CT, MRI and ultrasound.

1.1 Levels of Organization: “Fearfully and Wonderfully Made”

1.2 Anatomical Language: Position, Planes, Cavities and Regions

1.3 Homeostasis and Feedback Loops

1.4 Seeing Inside: X-ray, CT, MRI and Ultrasound

UNIT 2 · WEEKS 4–7

Cells and Tissues

The cell reviewed for A&P, membrane transport and IV fluids, Bichat’s tissues (epithelial and connective), muscle and nervous tissue, and how tissues heal or scar.

2.1 The Cell Reviewed for Anatomy and Physiology

2.2 Membrane Transport in the Body

2.3 Epithelial and Connective Tissue

2.4 Muscle and Nervous Tissue; How Tissues Heal

UNIT 3 · WEEKS 7–11

Skin and Bones

The skin's layers and accessory structures, burns, wounds and the rule of nines, bone as living tissue with growth and fracture repair, and the axial and appendicular skeletons.

3.1 Skin: Layers and Accessory Structures

3.2 Burns, Wounds and Healing

3.3 Bone Tissue, Growth and Fracture Repair

3.4 The Axial Skeleton

3.5 The Appendicular Skeleton

UNIT 4 · WEEKS 11–16

Joints and Muscles

Joints and body movements, the sliding-filament contraction of a muscle fiber, levers and muscle names, the major muscle groups, and exercise, energy systems and training.

4.1 Joints and Body Movements: Hunter's Cartilage (1743) and Charnley's Hip (1962)

4.2 How a Muscle Fiber Contracts: From Nerve Signal to Sliding Filaments

4.3 Levers and Naming Muscles: Borelli's Muscle Machines (1680)

4.4 The Major Muscle Groups: Duchenne's Electrical Map (1860s)

4.5 Exercise and Muscle: A. V. Hill, Energy Systems and Training

UNIT 5 · WEEKS 16–20

The Nervous System

Neurons and the action potential, Loewi's synapse, the brain and spinal cord with reflex arcs, the senses, and the autonomic nervous system with a clinical-skills neuro check.

5.1 Neurons and the Action Potential: Cajal (1888) and Hodgkin and Huxley (1952)

5.2 The Synapse: Loewi's Dream Experiment (1921)

5.3 The Brain and Spinal Cord: Broca (1861) and Penfield's Maps

5.4 The Senses: Helmholtz's Ophthalmoscope (1851)

5.5 The Autonomic Nervous System and the Neuro Check: Cannon's "Fight or Flight" (1915)

UNIT 6 · WEEKS 21–24

The Endocrine System

Hormones and receptors from Bayliss and Starling's secretin, the hypothalamus and pituitary, the thyroid, parathyroids and adrenals, and insulin, diabetes and Banting and Best.

6.1 Hormones and Receptors: Bayliss and Starling's Secretin (1902)

6.2 The Hypothalamus and Pituitary: Cushing, Harris and the Master Control

6.3 Thyroid, Parathyroids and Adrenals: Iodine, Goiter and Kendall's Hormones

6.4 Insulin and Diabetes: Banting and Best (1921)

UNIT 7 · WEEKS 24–28

Blood, Heart and Defense

Blood and Landsteiner's blood groups, the heart's electrical system and the ECG, vessels and blood pressure with a measuring lab, lymph and innate defense, and adaptive immunity and vaccines.

7.1 Blood and Blood Typing: Landsteiner's Three Groups (1901)

7.2 The Heart and Its Electrical System: Laennec's Stethoscope (1816) and Einthoven's ECG (1903)

7.3 Vessels and Blood Pressure: Hales's Glass Tube (1733) and Korotkov's Sounds (1905)

7.4 The Lymphatic System and Innate Defense: Metchnikoff's Starfish (1882)

7.5 Adaptive Immunity and Vaccines: Von Behring's Antitoxin (1890)

UNIT 8 · WEEKS 28–31

Respiration

The airway and lungs, how breathing works by Boyle's law and the spirometer, gas exchange and oxygen transport, and the control of breathing at altitude and under smoke.

8.1 The Airway and Lungs: Laennec Listens to the Chest (1819)

8.2 How Breathing Works: Boyle's Law (1662) and Hutchinson's Spirometer (1846)

8.3 Gas Exchange and Transport: Dalton's Partial Pressures and Bohr's Shift (1904)

8.4 Control of Breathing, Altitude and Smoking: Haldane's Carbon Dioxide (1905) and Paul Bert's Mountains

UNIT 9 · WEEKS 31–36

Digestion, Metabolism and the Kidneys

The digestive tract, the liver, pancreas and absorption, metabolism and energy needs, the kidney and nephron, and fluids, electrolytes and acid–base balance.

9.1 The Digestive Tract: Cannon's X-Ray Pictures of a Working Stomach (1897)

9.2 Liver, Pancreas and Absorption: Bayliss and Starling Find the First Hormone (1902)

9.3 Metabolism and Nutrition: From Lavoisier's Guinea Pig to the Harris–Benedict Equation (1918–1919)

9.4 The Kidney and the Nephron: From Bowman's Capsule to Kolff's Artificial Kidney

9.5 Fluids, Electrolytes and Acid–Base Balance: Henderson and Hasselbalch's Equation (1908–1916)

UNIT 10 · WEEKS 36–39

Life, Growth and Care

Inheritance in the body from Garrod to sickle cell, growth and aging across the lifespan, a parent-led lesson on the gonads as glands and development before birth (Psalm 139), and a body-systems capstone with TEAS-style review.

10.1 Inheritance in the Body: Garrod's Inborn Errors (1902) and Pauling's Molecular Disease (1949)

10.2 Growth and Aging Across the Lifespan: Montbeillard's Growth Chart (1759–1777)

10.3 Reproduction and Development: The Gonads as Glands and Psalm 139

10.4 Capstone: A Body-Systems Case Study and TEAS-Style Review

Weekly pacing calendar

WEEK	PLAN
1	• Day 1: Lesson 1.1 Levels of Organization: "Fearfully and Wonderfully Made": warm-up, video and core ideas • Day 2: Lesson 1.1: worked examples, first practice problems and the lab • Day 3: Lesson 1.1: lab notebook, rest of the practice set and corrections • Day 4: Lesson 1.2 Anatomical Language: Position, Planes, Cavities and Regions: warm-up, video and core ideas • Day 5: Lesson 1.2: worked examples and first practice problems *Five sessions a week of about 45 minutes. Lessons with short labs take three sessions, so the weeks do not always line up with lessons. Families on a four-day week can combine the practice day of one lesson with the first day of the next.*
2	• Day 1: Lesson 1.2: lab and lab notebook • Day 2: Lesson 1.2: rest of the practice set and corrections • Day 3: Lesson 1.3 Homeostasis and Feedback Loops: warm-up, video and core ideas

WEEK	PLAN
	• Day 4: Lesson 1.3: worked examples and first practice problems • Day 5: Lesson 1.3: lab and lab notebook
3	• Day 1: Lesson 1.3: rest of the practice set and corrections • Day 2: Lesson 1.4 Seeing Inside: X-ray, CT, MRI and Ultrasound: warm-up, video and core ideas • Day 3: Lesson 1.4: worked examples, first practice problems and the lab • Day 4: Lesson 1.4: lab notebook, rest of the practice set and corrections • Day 5: Unit 1 review: mastery checklist, key terms and missed practice problems
4	• Day 1: Unit 1 test • Day 2: Lesson 2.1 The Cell Reviewed for Anatomy and Physiology: warm-up, video and core ideas • Day 3: Lesson 2.1: worked examples, first practice problems and the lab • Day 4: Lesson 2.1: lab notebook, rest of the practice set and corrections • Day 5: Lesson 2.2 Membrane Transport in the Body: warm-up, video and core ideas
5	• Day 1: Lesson 2.2: worked examples and first practice problems • Day 2: Lesson 2.2: lab and lab notebook • Day 3: Lesson 2.2: rest of the practice set and corrections • Day 4: Lesson 2.3 Epithelial and Connective Tissue: warm-up, video and core ideas • Day 5: Lesson 2.3: worked examples and first practice problems
6	• Day 1: Lesson 2.3: lab and lab notebook • Day 2: Lesson 2.3: rest of the practice set and corrections • Day 3: Lesson 2.4 Muscle and Nervous Tissue; How Tissues Heal: warm-up, video and core ideas • Day 4: Lesson 2.4: worked examples and first practice problems • Day 5: Lesson 2.4: lab and lab notebook
7	• Day 1: Lesson 2.4: rest of the practice set and corrections • Day 2: Unit 2 review: mastery checklist, key terms and missed practice problems • Day 3: Unit 2 test • Day 4: Lesson 3.1 Skin: Layers and Accessory Structures: warm-up, video and core ideas • Day 5: Lesson 3.1: worked examples and first practice problems
8	• Day 1: Lesson 3.1: lab and lab notebook • Day 2: Lesson 3.1: rest of the practice set and corrections

WEEK	PLAN
	• Day 3: Lesson 3.2 Burns, Wounds and Healing: warm-up, video and core ideas • Day 4: Lesson 3.2: worked examples and first practice problems • Day 5: Lesson 3.2: lab and lab notebook
9	• Day 1: Lesson 3.2: rest of the practice set and corrections • Day 2: Lesson 3.3 Bone Tissue, Growth and Fracture Repair: warm-up, video and core ideas • Day 3: Lesson 3.3: worked examples and first practice problems • Day 4: Lesson 3.3: lab and lab notebook • Day 5: Lesson 3.3: rest of the practice set and corrections
10	• Day 1: Lesson 3.4 The Axial Skeleton: warm-up, video and core ideas • Day 2: Lesson 3.4: worked examples and first practice problems • Day 3: Lesson 3.4: lab and lab notebook • Day 4: Lesson 3.4: rest of the practice set and corrections • Day 5: Lesson 3.5 The Appendicular Skeleton: warm-up, video and core ideas
11	• Day 1: Lesson 3.5: worked examples, first practice problems and the lab • Day 2: Lesson 3.5: lab notebook, rest of the practice set and corrections • Day 3: Unit 3 review: mastery checklist, key terms and missed practice problems • Day 4: Unit 3 test • Day 5: Lesson 4.1 Joints and Body Movements: Hunter's Cartilage (1743) and Charnley's Hip (1962): warm-up, video and core ideas
12	• Day 1: Lesson 4.1: worked examples and first practice problems • Day 2: Lesson 4.1: lab and lab notebook • Day 3: Lesson 4.1: rest of the practice set and corrections • Day 4: Lesson 4.2 How a Muscle Fiber Contracts: From Nerve Signal to Sliding Filaments: warm-up, video and core ideas • Day 5: Lesson 4.2: worked examples and first practice problems
13	• Day 1: Lesson 4.2: lab and lab notebook • Day 2: Lesson 4.2: rest of the practice set and corrections • Day 3: Lesson 4.3 Levers and Naming Muscles: Borelli's Muscle Machines (1680): warm-up, video and core ideas • Day 4: Lesson 4.3: worked examples and first practice problems • Day 5: Lesson 4.3: lab and lab notebook

WEEK	PLAN
14	• Day 1: Lesson 4.3: rest of the practice set and corrections • Day 2: Lesson 4.4 The Major Muscle Groups: Duchenne's Electrical Map (1860s): warm-up, video and core ideas • Day 3: Lesson 4.4: worked examples and first practice problems • Day 4: Lesson 4.4: lab and lab notebook • Day 5: Lesson 4.4: rest of the practice set and corrections
15	• Day 1: Lesson 4.5 Exercise and Muscle: A. V. Hill, Energy Systems and Training: warm-up, video and core ideas • Day 2: Lesson 4.5: worked examples and first practice problems • Day 3: Lesson 4.5: lab and lab notebook • Day 4: Lesson 4.5: rest of the practice set and corrections • Day 5: Unit 4 review: mastery checklist, key terms and missed practice problems
16	• Day 1: Unit 4 test • Day 2: Lesson 5.1 Neurons and the Action Potential: Cajal (1888) and Hodgkin and Huxley (1952): warm-up, video and core ideas • Day 3: Lesson 5.1: worked examples and first practice problems • Day 4: Lesson 5.1: lab and lab notebook • Day 5: Lesson 5.1: rest of the practice set and corrections
17	• Day 1: Lesson 5.2 The Synapse: Loewi's Dream Experiment (1921): warm-up, video and core ideas • Day 2: Lesson 5.2: worked examples and first practice problems • Day 3: Lesson 5.2: lab and lab notebook • Day 4: Lesson 5.2: rest of the practice set and corrections • Day 5: Lesson 5.3 The Brain and Spinal Cord: Broca (1861) and Penfield's Maps: warm-up, video and core ideas
18	• Day 1: Lesson 5.3: worked examples and first practice problems • Day 2: Lesson 5.3: lab and lab notebook • Day 3: Lesson 5.3: rest of the practice set and corrections • Day 4: Lesson 5.4 The Senses: Helmholtz's Ophthalmoscope (1851): warm-up, video and core ideas • Day 5: Lesson 5.4: worked examples and first practice problems
19	• Day 1: Lesson 5.4: lab and lab notebook • Day 2: Lesson 5.4: rest of the practice set and corrections

WEEK	PLAN
	• Day 3: Lesson 5.5 The Autonomic Nervous System and the Neuro Check: Cannon's "Fight or Flight" (1915): warm-up, video and core ideas • Day 4: Lesson 5.5: worked examples and first practice problems • Day 5: Lesson 5.5: clinical-skills lab, part 1: practice each step of the neuro check
20	• Day 1: Lesson 5.5: clinical-skills lab, part 2: the full neuro check on a partner, recorded in the lab notebook • Day 2: Lesson 5.5: rest of the practice set and corrections • Day 3: Unit 5 review: mastery checklist, key terms and missed practice problems • Day 4: Unit 5 test • Day 5: Midterm review: missed unit-test problems from Units 1–5 and the five-part feedback loop
21	• Day 1: Midterm exam • Day 2: Lesson 6.1 Hormones and Receptors: Bayliss and Starling's Secretin (1902): warm-up, video and core ideas • Day 3: Lesson 6.1: worked examples and first practice problems • Day 4: Lesson 6.1: lab and lab notebook • Day 5: Lesson 6.1: rest of the practice set and corrections
22	• Day 1: Lesson 6.2 The Hypothalamus and Pituitary: Cushing, Harris and the Master Control: warm-up, video and core ideas • Day 2: Lesson 6.2: worked examples and first practice problems • Day 3: Lesson 6.2: lab and lab notebook • Day 4: Lesson 6.2: rest of the practice set and corrections • Day 5: Lesson 6.3 Thyroid, Parathyroids and Adrenals: Iodine, Goiter and Kendall's Hormones: warm-up, video and core ideas
23	• Day 1: Lesson 6.3: worked examples and first practice problems • Day 2: Lesson 6.3: lab and lab notebook • Day 3: Lesson 6.3: rest of the practice set and corrections • Day 4: Lesson 6.4 Insulin and Diabetes: Banting and Best (1921): warm-up, video and core ideas • Day 5: Lesson 6.4: worked examples and first practice problems
24	• Day 1: Lesson 6.4: lab and lab notebook • Day 2: Lesson 6.4: rest of the practice set and corrections • Day 3: Unit 6 review: mastery checklist, key terms and missed practice problems

WEEK	PLAN
	• Day 4: Unit 6 test • Day 5: Lesson 7.1 Blood and Blood Typing: Landsteiner's Three Groups (1901): warm-up, video and core ideas
25	• Day 1: Lesson 7.1: worked examples and first practice problems • Day 2: Lesson 7.1: lab and lab notebook • Day 3: Lesson 7.1: rest of the practice set and corrections • Day 4: Lesson 7.2 The Heart and Its Electrical System: Laennec's Stethoscope (1816) and Einthoven's ECG (1903): warm-up, video and core ideas • Day 5: Lesson 7.2: worked examples and first practice problems
26	• Day 1: Lesson 7.2: lab and lab notebook • Day 2: Lesson 7.2: rest of the practice set and corrections • Day 3: Lesson 7.3 Vessels and Blood Pressure: Hales's Glass Tube (1733) and Korotkov's Sounds (1905): warm-up, video and core ideas • Day 4: Lesson 7.3: worked examples and first practice problems • Day 5: Lesson 7.3: lab and lab notebook
27	• Day 1: Lesson 7.3: rest of the practice set and corrections • Day 2: Lesson 7.4 The Lymphatic System and Innate Defense: Metchnikoff's Starfish (1882): warm-up, video and core ideas • Day 3: Lesson 7.4: worked examples, first practice problems and the lab • Day 4: Lesson 7.4: lab notebook, rest of the practice set and corrections • Day 5: Lesson 7.5 Adaptive Immunity and Vaccines: Von Behring's Antitoxin (1890): warm-up, video and core ideas
28	• Day 1: Lesson 7.5: worked examples, first practice problems and the lab • Day 2: Lesson 7.5: lab notebook, rest of the practice set and corrections • Day 3: Unit 7 review: mastery checklist, key terms and missed practice problems • Day 4: Unit 7 test • Day 5: Lesson 8.1 The Airway and Lungs: Laennec Listens to the Chest (1819): warm-up, video and core ideas
29	• Day 1: Lesson 8.1: worked examples, first practice problems and the lab • Day 2: Lesson 8.1: lab notebook, rest of the practice set and corrections • Day 3: Lesson 8.2 How Breathing Works: Boyle's Law (1662) and Hutchinson's Spirometer (1846): warm-up, video and core ideas • Day 4: Lesson 8.2: worked examples and first practice problems

WEEK	PLAN
	• Day 5: Lesson 8.2: lab and lab notebook
30	• Day 1: Lesson 8.2: rest of the practice set and corrections • Day 2: Lesson 8.3 Gas Exchange and Transport: Dalton's Partial Pressures and Bohr's Shift (1904): warm-up, video and core ideas • Day 3: Lesson 8.3: worked examples, first practice problems and the lab • Day 4: Lesson 8.3: lab notebook, rest of the practice set and corrections • Day 5: Lesson 8.4 Control of Breathing, Altitude and Smoking: Haldane's Carbon Dioxide (1905) and Paul Bert's Mountains: warm-up, video and core ideas
31	• Day 1: Lesson 8.4: worked examples, first practice problems and the lab • Day 2: Lesson 8.4: lab notebook, rest of the practice set and corrections • Day 3: Unit 8 review: mastery checklist, key terms and missed practice problems • Day 4: Unit 8 test • Day 5: Lesson 9.1 The Digestive Tract: Cannon's X-Ray Pictures of a Working Stomach (1897): warm-up, video and core ideas
32	• Day 1: Lesson 9.1: worked examples and first practice problems • Day 2: Lesson 9.1: lab and lab notebook • Day 3: Lesson 9.1: rest of the practice set and corrections • Day 4: Lesson 9.2 Liver, Pancreas and Absorption: Bayliss and Starling Find the First Hormone (1902): warm-up, video and core ideas • Day 5: Lesson 9.2: worked examples and first practice problems
33	• Day 1: Lesson 9.2: lab and lab notebook • Day 2: Lesson 9.2: rest of the practice set and corrections • Day 3: Lesson 9.3 Metabolism and Nutrition: From Lavoisier's Guinea Pig to the Harris–Benedict Equation (1918–1919): warm-up, video and core ideas • Day 4: Lesson 9.3: worked examples and first practice problems • Day 5: Lesson 9.3: lab and lab notebook
34	• Day 1: Lesson 9.3: rest of the practice set and corrections • Day 2: Lesson 9.4 The Kidney and the Nephron: From Bowman's Capsule to Kolff's Artificial Kidney: warm-up, video and core ideas • Day 3: Lesson 9.4: worked examples and first practice problems • Day 4: Lesson 9.4: lab and lab notebook • Day 5: Lesson 9.4: rest of the practice set and corrections

WEEK	PLAN
35	• Day 1: Lesson 9.5 Fluids, Electrolytes and Acid–Base Balance: Henderson and Hasselbalch's Equation (1908–1916): warm-up, video and core ideas • Day 2: Lesson 9.5: worked examples and first practice problems • Day 3: Lesson 9.5: lab and lab notebook • Day 4: Lesson 9.5: rest of the practice set and corrections • Day 5: Unit 9 review: mastery checklist, key terms and missed practice problems
36	• Day 1: Unit 9 test • Day 2: Lesson 10.1 Inheritance in the Body: Garrod's Inborn Errors (1902) and Pauling's Molecular Disease (1949): warm-up, video and core ideas • Day 3: Lesson 10.1: worked examples and first practice problems • Day 4: Lesson 10.1: lab and lab notebook • Day 5: Lesson 10.1: rest of the practice set and corrections
37	• Day 1: Lesson 10.2 Growth and Aging Across the Lifespan: Montbeillard's Growth Chart (1759–1777): warm-up, video and core ideas • Day 2: Lesson 10.2: worked examples and first practice problems • Day 3: Lesson 10.2: lab and lab notebook • Day 4: Lesson 10.2: rest of the practice set and corrections • Day 5: Lesson 10.3 Reproduction and Development: The Gonads as Glands and Psalm 139: warm-up, video and core ideas
38	• Day 1: Lesson 10.3: worked examples, first practice problems and the lab • Day 2: Lesson 10.3: lab notebook, rest of the practice set and corrections • Day 3: Lesson 10.4 Capstone: A Body-Systems Case Study and TEAS-Style Review: warm-up, video and core ideas • Day 4: Lesson 10.4: worked examples and first practice problems • Day 5: Lesson 10.4: lab and lab notebook
39	• Day 1: Lesson 10.4: rest of the practice set and corrections • Day 2: Unit 10 review: mastery checklist, key terms and missed practice problems • Day 3: Unit 10 test • Day 4: Final review: missed unit-test problems, key terms and the broken-mechanism essays • Day 5: Final exam

Materials

Blood-pressure monitor

An upper-arm automatic monitor, about $25–40 (Lessons 6.3, 7.3, 10.4). A manual aneroid cuff with a stethoscope, about $25–35, lets the student hear Korotkov's sounds.

Stethoscope and pulse oximeter

A basic stethoscope, about $10 (a paper-towel tube works for the heart-sounds lab), and a fingertip pulse oximeter, about $20–30 (optional; Lesson 8.3 gives a data table to use instead).

Clinical-skills kit

A digital thermometer, a watch or phone timer with seconds, a penlight or phone flashlight, a cotton ball and a rubber reflex hammer (optional, about $5; the side of the hand works).

Microscope

For the cheek-cell lab (Lesson 2.1): the Biology course's microscope or a phone clip-on lens, slides, cover slips and iodine or methylene blue. Good micrographs from the library or the Biology course can stand in.

Kitchen and grocery supplies

Three cooked chicken leg bones and a jar of white vinegar, a raw chicken drumstick, gummy bears, table salt, baking soda, crackers, milk, cooking oil, dish soap, food coloring, modeling clay, balloons, coffee filters, dried beans and a quarter of a red cabbage; about $25.

Science-supplier items

Urine glucose test strips with a color chart (about $10, pharmacy), bromothymol blue indicator (about $10) and, if you prefer it to the milk-and-vinegar version, a simulated blood-typing kit (about $20–30). Lactase drops or tablets, about $8 (optional).

Measuring tools

A kitchen scale reading to 0.1 g (about $15), a tape measure, a 30 cm ruler, a meter stick, a clear protractor, a bathroom scale, measuring cups and spoons, a stopwatch and graph paper.

Lab safety

Nitrile gloves for handling raw chicken (shared with Biology and Chemistry), paper towels and a cutting board kept for lab use.

Bound lab notebook, pencil, ruler, colored pencils

For every lab, data table, sketch and corrected practice set.

Budget

The core lab total is about $60–80 with a borrowed or Biology-course microscope and the do-it-yourself blood-typing lab, and about $150–180 with a blood-pressure monitor, stethoscope, pulse oximeter and a typing kit. Most items are household goods, and the clinical tools stay useful for a family.

Grading

Grades come from the practice sets, the labs, the lab notebook, the unit tests, the midterm and the final. A lab earns full credit for honest measurements carefully recorded and explained, even when the result is not what was expected.

PART	%
Practice sets (completed and corrected)	**15**
Labs and clinical-skills labs	**20**
Lab notebook (data, sketches, honesty)	**10**
Unit tests	**30**
Midterm exam	**10**
Final exam	**15**

Scale: A 90–100, B 80–89, C 70–79, D 60–69, F below 60.

- Practice is graded for completion and correction: a question done, checked and correctly reworked earns full credit.
- The broken-mechanism essays are graded on whether the normal mechanism is stated correctly, the failed step is named, and the symptoms follow from it in a clear chain.

- The clinical-skills labs (Lessons 1.3, 5.5, 7.3 and 10.4) are graded on correct technique and careful recording, not on the readings themselves.
- For a high-school transcript this course is one full credit of laboratory science (Anatomy & Physiology).

A NOTE TO PARENTS

You do not need to know anatomy to supervise this course well. Your jobs are to keep the rhythm, check the practice against the answers, ask the student to explain one mechanism aloud each week, look over the lab notebook, act as the partner or volunteer for the vital-signs labs, and handle the oven, knife and raw chicken.

Lesson 10.3 is a parent-led lesson. It treats the testes and ovaries only as endocrine glands, explains the hormone feedback loop and its link to meiosis, and traces the child's development before birth week by week alongside Psalm 139:13–16. It contains no external anatomy and no discussion of sexual activity, contraception or abortion. Please read it before your student and go through it together; nursing entrance exams do test these hormones.

All figures are schematic line drawings: organs, cells and loops drawn as simple labeled shapes, and any whole-body outline shown as a plain, neutral silhouette. There are no photographs of bodies anywhere in the course. Videos come from medical and science teachers; a parent preview is wise, and Crash Course in particular is fast and jokey.

The body is taught as designed, and human beings as made in God's image, male and female (Genesis 1:27), with worth at every stage of life. Diseases are explained as mechanisms that have failed, and care for the sick is presented as a calling. Home measurements are for learning; they are not a diagnosis, and any worrying reading should go to a doctor.

Series verse: "I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well." (Psalm 139:14)

UNIT 1

The Body as a Whole

The body is one person made of many parts that work together. This unit climbs the ladder from atoms to the whole person, learns the shared language of positions, planes, cavities and regions that every nurse, medic and surgeon uses, traces the feedback loops that hold temperature and blood sugar steady, and looks inside the living body with X-rays, CT, MRI and ultrasound.

The home labs are a life-size organ map, cutting clay figures along the three planes, a vital-signs lab and a mystery-box imaging model. Like the Biology course, this course studies the body as designed: “I am fearfully and wonderfully made” (Psalm 139:14).

PREREQUISITES

- High School Biology Units 2–3 (biological molecules and cells), or equivalent
- Comfort with metric units, percents and simple formulas

MASTERY CHECKLIST

- ☐ I can name the levels of organization and the eleven organ systems with a job for each.
- ☐ I can describe anatomical position and use directional terms, planes, cavities and quadrants correctly.
- ☐ I can trace a negative feedback loop through its five parts and tell negative from positive feedback.
- ☐ I can explain how X-ray, CT, MRI and ultrasound form images and choose a suitable test for a problem.

LESSONS IN THIS UNIT

1.1 Levels of Organization: “Fearfully and Wonderfully Made”

3 sessions of 45 minutes

1.2 Anatomical Language: Position, Planes, Cavities and Regions

4 sessions of 45 minutes

1.3 Homeostasis and Feedback Loops — 4 sessions of 45 minutes

Unit 1 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. Use complete anatomical terms. The test is worth 100 points.

1. **8 pts** **Lesson 1.1**
   Put in order from smallest to largest and give one example of each: organ system, cell, chemical, organism, tissue, organ.

2. **8 pts** **Lesson 1.1**
   Name the organ system for each: (a) skin and nails, (b) thyroid and pancreas islets, (c) kidneys and bladder, (d) spleen and lymph nodes.

3. **8 pts** **Lesson 1.2**
   Fill in: (a) The elbow is ___ to the wrist. (b) The nose is ___ to the ears. (c) The heart is ___ to the spine. (d) Muscle is ___ to skin.

4. **8 pts** **Lesson 1.2**
   Name the plane that divides the body into (a) front and back, (b) right and left, (c) upper and lower. Which is the usual plane of a CT slice?

5. **8 pts** **Lesson 1.2**
   Name the body cavity that holds (a) the brain, (b) the lungs and heart, (c) the stomach and intestines. What muscle separates (b) from (c)?

6. **8 pts** **Lesson 1.3**
   When blood pressure drops, stretch receptors in the large arteries signal the brainstem, which speeds the heart and narrows blood vessels, and pressure rises. Label the stimulus, receptor, control center, effectors and response, and name the type of feedback.

7. **8 pts** **Lesson 1.3**

   Explain the difference between negative and positive feedback and give one example of each.

8. **8 pts** **Lesson 1.3**

   Convert 38.5 °C to °F and say whether it is a fever.

9. **8 pts** **Lesson 1.4**

   Choose the best imaging test and give a reason: (a) a swallowed coin, (b) gallstones, (c) a torn rotator-cuff tendon, (d) bleeding in the brain after a fall.

10. **8 pts** **Lesson 1.4**

    An ultrasound echo returns 52 µs after the pulse. Sound travels at 1540 m/s in soft tissue. How deep is the boundary?

LAB AND DATA

11. **8 pts** **Lesson 1.3**

    Resting pulse: 68 beats/min. After 2 minutes of stair stepping: 128. At the end of minutes 1 to 4: 110, 94, 82, 74. (a) By how many beats per minute did the pulse rise? (b) After how many minutes was it within 10 percent of resting? (c) Which part of the feedback loop does the heart play?

SHORT ESSAY

12. **12 pts**

    Claude Bernard called the steady internal environment “the condition for a free and independent life.” Explain what homeostasis is, describe one negative feedback loop in detail, and show how one disease can be understood as a broken loop.

ANSWER KEY

1. Chemical (water, protein), cell (neuron), tissue (epithelium), organ (stomach), organ system (digestive), organism (a person).
2. (a) Integumentary, (b) endocrine, (c) urinary, (d) lymphatic and immune.
3. (a) proximal, (b) medial, (c) anterior (ventral), (d) deep.
4. (a) Frontal (coronal), (b) sagittal, (c) transverse. CT slices are usually transverse.
5. (a) Cranial (dorsal) cavity, (b) thoracic cavity, (c) abdominopelvic cavity. The diaphragm.
6. Stimulus: falling pressure. Receptors: stretch receptors in the arteries. Control center: brainstem. Effectors: heart and vessel muscle. Response: pressure rises back toward normal. Negative feedback.
7. Negative feedback reverses a change (temperature control, blood sugar, blood pressure); positive feedback strengthens a change until an event ends it (blood clotting, childbirth contractions).
8. 101.3 °F; a fever

   $9/5 \times 38.5 + 32 = 101.3$
9. (a) X-ray (metal blocks X-rays; quick), (b) ultrasound (shows stones; no radiation), (c) MRI (soft tissue detail), (d) CT (fast; shows fresh bleeding).
10. About 4.0 cm

    $1540 \times 52 \times 10^{-6} \div 2 = 0.040$ m
11. (a) 60 beats/min. (b) 4 minutes (within 10% means 74.8 or below; 74 at minute 4). (c) The effector.
12. Look for: a definition (internal conditions kept within a narrow range); Bernard and Cannon; a full loop with all five parts (temperature or blood sugar); a disease explained by which part fails (type 1 diabetes: no insulin signal; fever: raised set point; heat stroke: cooling overwhelmed), with clear cause-and-effect.

1.1 Levels of Organization: "Fearfully and Wonderfully Made"

Mark up this lesson

OBJECTIVES

- Tell anatomy from physiology and explain why structure and function always go together.
- Name the levels of organization from chemicals to the whole organism and give an example of each.
- Name the eleven organ systems and one main job of each, and show how systems work together.

> **Warm-up.** Put your hand flat on your chest and take one slow, deep breath. List every body part you think had to work to make that single breath happen. Keep the list: at the end of the lesson you will sort it by organ system.

WATCH

Introduction to Anatomy & Physiology: Crash Course Anatomy & Physiology #1

CrashCourse · 11:20

https://www.youtube.com/watch?v=uBGl2BujkPQ

> **WHEN TO WATCH**
> After the first two core ideas.

BACKUP VIDEO

Human Body Systems Overview (Updated 2024)

Amoeba Sisters · 9:47

https://www.youtube.com/watch?v=0JDCViWGn-0

With the organ-systems core idea.

KEY TERMS

anatomy

The study of the body's structure: what the parts are, where they are and how they are built (Greek *ana* + *tomē*, "cutting up").

physiology

The study of how the body's parts work and keep it alive (Greek *physis*, "nature").

complementarity of structure and function

The rule that a part's shape fits its job: thin walls where gases must cross, one-way valves where blood must not flow back.

tissue

A group of similar cells and the material around them working together on one job.

organ

A structure made of two or more tissue types that does a particular job, such as the stomach or heart.

organ system

A group of organs that work together for a broad purpose, such as digestion or circulation.

organism

The whole living individual: in this course, the human person.

CORE IDEAS

Why study the body. Every nurse, medic, coach, physical therapist and parent uses anatomy and physiology, and every one of us lives in a body for a lifetime. *Anatomy* asks what a part is and where it is; *physiology* asks how it works. The two cannot be pulled apart, because in the body shape fits job. The air sacs of the lungs have walls thinner than a soap bubble because oxygen must cross them quickly; the bones of the thigh are hollow tubes because a tube resists bending with less weight than a solid rod; heart valves are flaps that open one way only. Learning to ask "why is it shaped like that?" is the habit that makes anatomy stick.

The ladder of organization. The body is built in levels, each made of the one below. At the *chemical* level, atoms form molecules such as water, proteins and DNA. Molecules build *cells*, the smallest units that are alive. Similar cells with the material

between them form *tissues*. Two or more tissues form an *organ*: the stomach has a lining of epithelial cells, walls of smooth muscle, connective tissue holding it together and nerves controlling it. Organs that work together form an *organ system*, and the systems together make the *organism*. Each level can do things the level below cannot: a single heart-muscle cell twitches, but only a whole heart pumps blood.

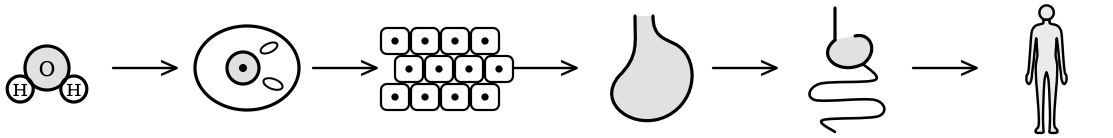
Eleven organ systems. The *integumentary* system (skin, hair, nails) protects; the *skeletal* system supports and makes blood cells; the *muscular* system moves us and makes heat; the *nervous* system senses and commands in milliseconds; the *endocrine* system sends slower hormone messages; the *cardiovascular* system carries blood; the *lymphatic and immune* system returns fluid and defends; the *respiratory* system exchanges oxygen and carbon dioxide; the *digestive* system breaks down food; the *urinary* system filters blood and balances water and salts; and the *reproductive* system makes the next generation. This course takes them one or two at a time.

What it takes to stay alive. Living bodies stay organized, carry out metabolism (building up and breaking down molecules), respond to change, move, grow and replace cells. To do this the body needs a steady supply of oxygen, nutrients and water, a body temperature near 37 °C and the right pressure of air to breathe. Water makes up roughly 55 to 60 percent of an adult's mass, and recent estimates put the number of human cells in an adult at roughly 30 to 37 trillion, most of them red blood cells.

Systems never work alone. Climb a flight of stairs and nearly every system joins in. Muscles pull on bones; the nervous system times every step; the lungs and heart speed up to deliver oxygen; the skin sweats to shed heat; hormones release stored sugar for fuel; the kidneys adjust water. Paul used the body to picture this kind of teamwork: "the eye cannot say unto the hand, I have no need of thee" (1 Corinthians 12:21). Disease in one system soon shows up in others, which is why clinicians always ask about the whole patient.

Fearfully and wonderfully made. About three thousand years ago David wrote, "I will praise thee; for I am fearfully and wonderfully made" (Psalm 139:14). He knew nothing of cells or DNA, yet every discovery since has made the words fit better. This course studies the body as a designed whole: carefully, honestly and with the humility of people examining something they did not make.

Try it. In the lab you will trace a life-size outline of your body and place paper organs where they really sit, color-coded by system.



Chemical (atoms, molecules) · **Cell** · **Tissue** · **Organ** (stomach) · **Organ system** (digestive) · **Organism**

The levels of organization. Each level is built from the one before it, and each can do something the level below cannot.

LAB

Life-Size Organ-System Map

You will build a full-size map of your own organs and sort them by system.

You will need

- A sheet of butcher or wrapping paper a little longer than you are tall, markers, colored paper, scissors, tape
- A reference: the lesson videos, a library anatomy atlas or the course reference guide

Steps

1. Wearing ordinary clothes, lie on the paper in anatomical position (arms at your sides, palms forward) while a parent traces your outline.
2. Cut paper organs at life size: the heart about the size of your fist, the liver under the right ribs, the stomach under the left ribs, the lungs filling the chest, two kidneys at the back just above the waist, the brain, the bladder, the intestines.
3. Tape each organ where it belongs. Color-code by system with a key in the corner.
4. Next to each organ write one job it does.
5. Sort your warm-up list of “breathing parts” into systems.

Check your work

- ☐ Which organs belong to more than one system? (Try the pancreas and the bones.)
- ☐ Which system did you find hardest to place on the map, and why?

LAB NOTEBOOK

1. The ladder of organization with one example at every level, from a water molecule to you.
2. A table of the eleven organ systems: main organs and one job each.

From history. Galen of Pergamon (about AD 129–216) began his career as physician to the gladiators of his home city, where deep wounds gave him what he called windows into the body. He went on to serve emperors in Rome and wrote *On the Usefulness of the Parts*, seventeen books arguing that every part of the body is fitted to its use; he called the work a hymn of praise to its Maker. Many of his details came from apes and pigs and were later corrected by Vesalius (Biology 10.1), but his question "what is this part for?" still drives anatomy.

Practice habit. Whenever you meet a new body part, ask two questions out loud: what is it made of (one level down), and what is it part of (one level up)?

Review first. This course builds on Biology Unit 3 (cells) and Unit 2 (biological molecules). The Anatomy & Physiology reference guide is a handy companion all year.

WORKED EXAMPLES

Example 1. Name the level of organization: (a) the stomach, (b) a single neuron, (c) a molecule of hemoglobin, (d) the sheet of cells lining the small intestine, (e) the digestive tract from mouth to colon.

Show solution

1. Ask what each thing is made of and what it is part of.
2. (a) The stomach is made of several tissues: organ.
3. (b) One neuron: cell.
4. (c) Hemoglobin is a protein molecule: chemical.
5. (d) Many similar cells doing one job: tissue.
6. (e) Many organs working together: organ system.

Answer: (a) organ, (b) cell, (c) chemical, (d) tissue, (e) organ system

Example 2. A typical body cell is about 10 µm across. How many such cells laid end to end would span the height of a student 1.70 m tall?

Show solution

1. 10 µm = 10×10^{-6} m = 1.0×10^{-5} m
2. 1.70 m ÷ (1.0×10^{-5} m) = 170,000

Answer: About 170,000 cells

Example 3. An adult has about 5 liters of blood, and each microliter holds about 5 million red blood cells. About how many red blood cells is that?

Show solution

1. 1 L = 1,000,000 µL, so 5 L = 5,000,000 µL
2. 5,000,000 µL × 5,000,000 cells/µL = 2.5×10^{13} cells
3. Compare with 30–37 trillion total cells: red cells are more than two-thirds of the count.

Answer: About 25 trillion red blood cells

PRACTICE

CONCEPT CHECKS

1. Easy Define anatomy and physiology, and write one question each field would ask about the heart.

   Show answer

   Anatomy studies structure (Where is the heart, and what are its chambers?); physiology studies function (How does the heart pump, and what sets its rate?).

2. Easy Put these in order from smallest to largest: organ, cell, organism, chemical, organ system, tissue.

   Show answer

   Chemical, cell, tissue, organ, organ system, organism.

3. **Medium** Which organ system (a) makes blood cells, (b) filters the blood and makes urine, (c) returns leaked fluid to the blood and fights infection, (d) sends hormone messages?

Show answer

(a) Skeletal (red bone marrow); (b) urinary; (c) lymphatic and immune; (d) endocrine.

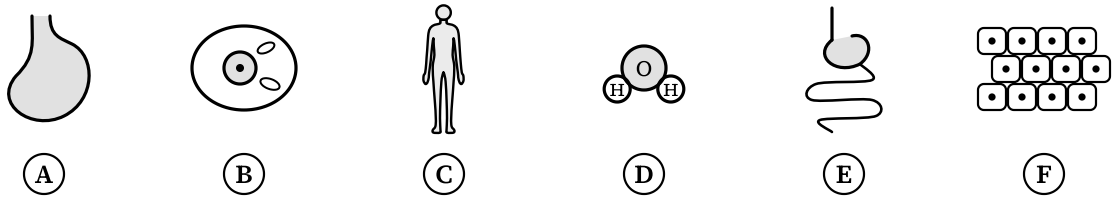
4. **Medium** Explain the complementarity of structure and function using either the air sacs of the lungs or the valves of the heart.

Show answer

Air sacs: walls one cell thin so oxygen and carbon dioxide diffuse across a very short distance. Valves: flaps that open one way so blood moves forward and cannot flow back.

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the level of organization shown in each drawing A–F, then list the letters in order from smallest to largest.



Show answer

A organ (stomach), B cell, C organism, D chemical (water molecule), E organ system (digestive tract), F tissue. Order: D, B, F, A, E, C.

6. **Medium** A red blood cell is about 7.5 µm across. About how many red cells lined up edge to edge would span 1 cm?

Show answer

About 1,300 cells

1 cm = 10,000 µm; 10,000 ÷ 7.5 ≈ 1,333

7. Medium About 60 percent of a 60 kg student's mass is water. About how many kilograms (and liters) of water is that?

Show answer

36 kg, about 36 liters

0.60 × 60 kg = 36 kg; 1 L of water has a mass of about 1 kg

DISORDER AS A BROKEN MECHANISM

8. Hard Cystic fibrosis begins with a single faulty protein: a chloride channel in the membranes of epithelial cells. Trace how this chemical-level fault shows up at the cell, tissue, organ, system and organism levels.

Show answer

Chemical: the CFTR channel protein is misshapen or missing. Cell: chloride, and the water that follows it, cannot leave the cell normally. Tissue: the mucus on airway and duct linings becomes thick and sticky. Organ: the lungs clog and stay infected; pancreatic ducts block, so digestive enzymes do not reach the intestine. System: respiratory and digestive systems both fail to do their jobs. Organism: chronic cough, lung infections and poor growth unless treated.

TEST PREP

9. Medium Which list runs from smallest to largest?

A. cell, tissue, molecule, organ

B. molecule, cell, tissue, organ

C. tissue, cell, organ, organ system

D. organ, tissue, cell, molecule

Show answer

B. molecule, cell, tissue, organ

10. Hard You run up three flights of stairs. Name five organ systems that join in and the job each one does.

Show answer

Any five, for example: muscular (pulls on bones), skeletal (levers and support), nervous (coordinates every step), respiratory (more oxygen in, more carbon dioxide out), cardiovascular (faster heart delivers blood), integumentary (sweat sheds heat), endocrine (hormones release stored fuel).

COMMON MISTAKES

- Skipping the chemical level and calling the cell the smallest level of organization; cells are the smallest *living* level.
- Calling a tissue an organ: a tissue is one kind of cell, an organ combines several tissues.
- Thinking each organ belongs to only one system; the pancreas is both digestive and endocrine.
- Mixing up anatomy (structure) and physiology (function).

Make it a game · Level Ladder. Stand at the bottom of a staircase. The parent names something in the body (hemoglobin, the liver, a neuron, the skin's outer layer, the nervous system, bone tissue, you). Name its level to climb one step; a wrong answer sends you down one. Reach the top in under three minutes to win, then swap roles.

Scripture. "I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well." (Psalm 139:14, KJV)

David praised God for a body he could see only from the outside. This year we look inside, and the more closely we look, the more the words fit.

1.2 Anatomical Language: Position, Planes, Cavities and Regions

Mark up this lesson

OBJECTIVES

- Describe anatomical position and use the paired directional terms correctly.
- Name the three body planes and the cut each one makes.
- Name the dorsal and ventral body cavities, the serous membranes, and the four abdominal quadrants and nine regions.

> **Warm-up.** Without pointing, tell a partner exactly where an imaginary mosquito bite is on your left forearm, so precisely that they could put a sticker on it with their eyes shut until you finish. What words did you wish you had?

WATCH

Regional Terms, Directional Terms, and Planes & Sections

Dr Matt & Dr Mike · 14:23

https://www.youtube.com/watch?v=1ugYf9ezKv4

> **WHEN TO WATCH**
> After the directional terms core idea.

BACKUP VIDEO

Body Cavities and Membranes (Dorsal, Ventral)- Anatomy and Physiology

RegisteredNurseRN · 9:06

https://www.youtube.com/watch?v=4GLMjSj4k9U

With the body cavities.

KEY TERMS

anatomical position

Standing upright, facing forward, feet flat and pointing forward, arms at the sides with palms facing forward. Every directional term refers to it.

superior / inferior

Toward the head / toward the feet.

anterior (ventral) / posterior (dorsal)

Toward the front of the body / toward the back.

medial / lateral

Toward the midline / away from the midline.

proximal / distal

Closer to / farther from where a limb attaches to the trunk.

superficial / deep

Toward the body surface / away from it.

sagittal, frontal (coronal) and transverse planes

Cuts that divide the body into right and left, front and back, and upper and lower parts.

serous membrane

A thin double membrane lining a closed cavity and covering its organs, with a film of fluid between the layers: pleura, pericardium, peritoneum.

CORE IDEAS

Why a special language. "The cut is above the knee" means nothing if the patient is lying on her side, and "on the left" changes depending on whether you face the patient or stand behind her. Medicine needs words that do not change when the patient moves or the speaker turns. Precise words prevent real harm: hospitals mark surgical sites and repeat them aloud precisely because confusing right and left has led to operations on the wrong limb. Most of the words come from Latin and Greek, so students of the site's Latin and Greek courses will recognize many of them.

Anatomical position. All descriptions assume the body is standing upright, facing forward, feet flat and pointing forward, arms at the sides with palms forward and thumbs pointing away from the body. Right and left always mean the *patient's* right and left, so in a front-view picture the patient's right is on your left. A person lying face up is *supine*; face down is *prone*. Whatever the real position, we describe parts as if the body were in anatomical position.

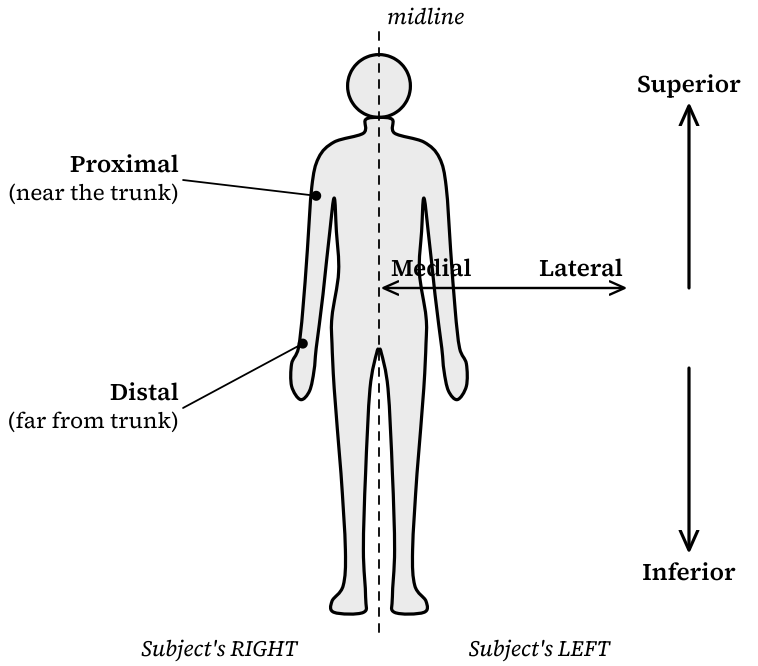
Directions come in pairs. Superior and inferior (head and feet); anterior and posterior, also called ventral and dorsal in humans (front and back); medial and lateral (toward and away from the midline); proximal and distal (nearer and farther from the trunk along a limb); superficial and deep (toward and away from the surface). So the sternum is medial to the arms, the knee is proximal to the ankle, the skin is superficial to the muscles, and the spine is posterior to the sternum. The thumb is lateral to the little finger, which is why palms-forward matters.

Planes and sections. A *sagittal* plane runs vertically from front to back and divides the body into right and left; the *midsagittal* (median) plane makes equal halves. A *frontal* or *coronal* plane runs vertically from side to side and divides front from back. A *transverse* (horizontal) plane divides upper from lower and gives a cross-section. CT and MRI scans (lesson 1.4) are stacks of such slices, usually transverse.

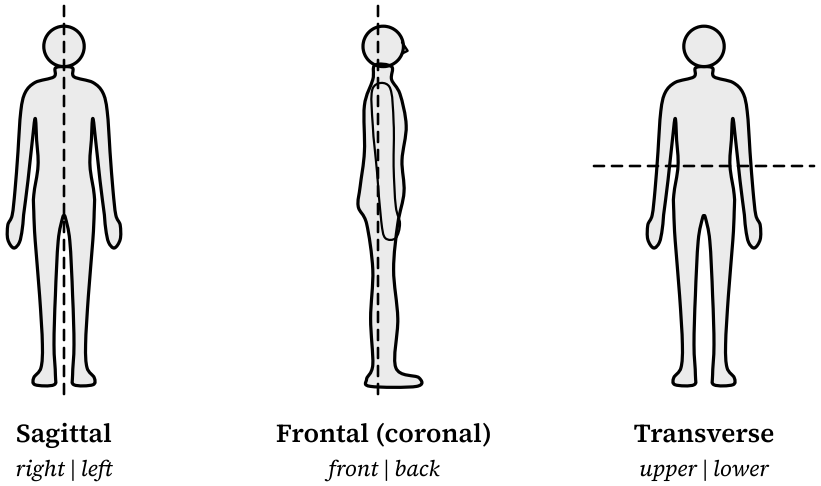
Body cavities. The *dorsal* cavity holds the nervous system: the cranial cavity around the brain and the vertebral canal around the spinal cord. The *ventral* cavity holds most organs. The dome-shaped diaphragm divides it into the *thoracic* cavity above (two pleural cavities around the lungs and the pericardial cavity around the heart, with the mediastinum between them) and the *abdominopelvic* cavity below. Ventral organs are wrapped in *serous membranes*: the parietal layer lines the wall, the visceral layer covers the organ, and a thin film of serous fluid between them lets a beating heart and breathing lungs glide without friction, like a fist pushed into a half-filled balloon.

Regions and quadrants. To report where abdominal pain is, clinicians divide the abdomen into four *quadrants* with lines through the navel: right upper (most of the liver and the gallbladder), left upper (stomach and spleen), right lower (appendix) and left lower (the last turn of the colon). Anatomists use nine finer regions in a tic-tac-toe grid: right and left hypochondriac, epigastric, right and left lumbar, umbilical, right and left iliac, and hypogastric. Regional names cover the rest of the body: cephalic (head), cervical (neck), brachial (arm), antebrachial (forearm), femoral (thigh), patellar (front of knee), popliteal (back of knee), plantar (sole).

Try it. In the lab you will cut clay figures along the three planes and play a direction relay in which a partner must find a hidden sticker from your words alone.



Anatomical position with the main direction pairs. The patient's right is on the viewer's left.



The three planes and the halves each one makes.

> **Safety first.** Cut the clay with a plastic or butter knife on a board, moving the blade away from your hand.

LAB

Cutting the Planes and the Direction Relay

You will make each plane with your own hands and practice giving directions a stranger could follow.

You will need

- Modeling clay (or three large potatoes with faces drawn on the front), a plastic knife, a cutting board
- Small sticky notes or stickers, a stuffed animal or doll, a timer

Steps

1. Shape three simple clay people about 15 cm tall in anatomical position. Press a pea of different-colored clay into each where the heart sits (left of center, behind the breastbone) and a flattened bean where the liver sits (right side, under the ribs).
2. Cut figure 1 on the midsagittal plane, figure 2 on a frontal plane through the shoulders and figure 3 on a transverse plane at chest level.
3. Sketch each cut surface. Which cuts show the heart? Which show both right and left lungs?
4. Direction relay: one partner secretly puts a sticker on the stuffed animal and describes the spot using only anatomical terms (for example “anterior, left, distal forearm, lateral side”). The other places a second sticker from the words alone. Measure how far apart the stickers are. Take five turns each and try to shrink the gap.

Check your work

- ☐ Which plane gave equal right and left halves?
- ☐ Which words in the relay caused the biggest misses?

LAB NOTEBOOK

1. A body outline in anatomical position with the six direction pairs drawn as arrows.
2. The three planes, each with its cut surface sketched.
3. A cavity map with the diaphragm, the serous membranes and the four quadrants.

From history. Until the 1890s the same body part could have a dozen names, and anatomists in different countries often could not understand each other's books. In 1895 the German Anatomical Society, meeting at Basel, published the *Basle Nomina Anatomica*, which replaced tens of thousands of competing names with a single list of a few thousand Latin terms. Its successor, *Terminologia Anatomica* (first published in 1998), is still the international standard, which is why a doctor in Tokyo and a nurse in Ohio use the same words.

Practice habit. Before you label right or left on any diagram, turn your body to face the same way as the figure and say "the patient's right" out loud.

Career connection. An emergency medical technician (EMT) radios the hospital: "Adult male, conscious and alert, laceration to the anterior left forearm about four centimeters proximal to the wrist, bleeding controlled." The emergency room knows exactly what is coming before the ambulance arrives. EMT training is a course of one semester or less, followed by the National Registry (NREMT) exam and a state license, and many paramedics, nurses and physician assistants started as EMTs.

WORKED EXAMPLES

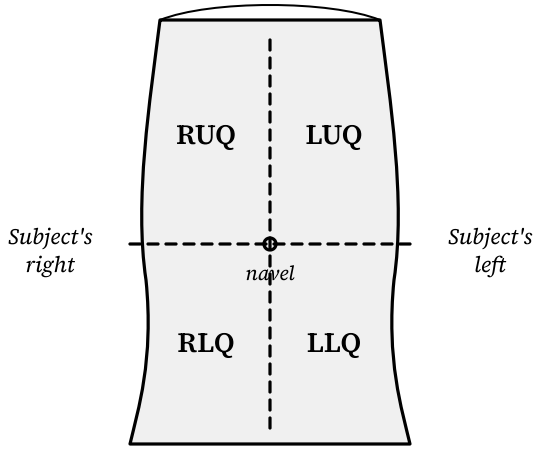
Example 1. Fill in the directional term: The heart is ___ to the lungs. The wrist is ___ to the elbow. The skin is ___ to the muscles. The spine is ___ to the sternum. The ears are ___ to the nose.

Show solution

1. Picture anatomical position and the midline.
2. The heart lies near the midline, the lungs to either side: medial.
3. The wrist is farther from the shoulder than the elbow: distal.
4. The skin is nearer the surface: superficial.
5. The spine is behind the breastbone: posterior (dorsal).
6. The ears are farther from the midline than the nose: lateral.

Answer: medial, distal, superficial, posterior, lateral

Example 2. A patient lying on a stretcher points to sharp pain low on the right side of her abdomen, halfway between the navel and the top of the hip bone. Which quadrant is this, and which organ is the classic suspect?



Show solution

1. Use the patient's right, which is on the viewer's left in the drawing.
2. The pain is below the horizontal line through the navel: a lower quadrant.
3. Right lower quadrant (RLQ). The appendix hangs from the large intestine here, so appendicitis is the first worry.

Answer: Right lower quadrant; the appendix

Example 3. Translate into everyday English: "superficial laceration, posterior right antebrachial region, distal third."

Show solution

1. Superficial: shallow, near the surface.
2. Laceration: a cut.
3. Posterior right antebrachial: the back of the right forearm (in anatomical position the palm faces forward, so posterior is the back of the forearm).
4. Distal third: the third nearest the wrist.

Answer: A shallow cut on the back of the right forearm, near the wrist

PRACTICE

CONCEPT CHECKS

1. Easy Describe anatomical position in four parts.

   Show answer

   Standing upright; facing forward; feet flat and pointing forward; arms at the sides with palms facing forward.

2. Easy Give the opposite of each: superior, anterior, medial, proximal, superficial.

   Show answer

   Inferior, posterior, lateral, distal, deep.

3. Medium Fill in the blank: (a) The knee is ___ to the hip. (b) In anatomical position the thumb is ___ to the little finger. (c) The lungs are ___ to the heart. (d) The brain is ___ to the spinal cord.

   Show answer

   (a) distal, (b) lateral, (c) lateral, (d) superior.

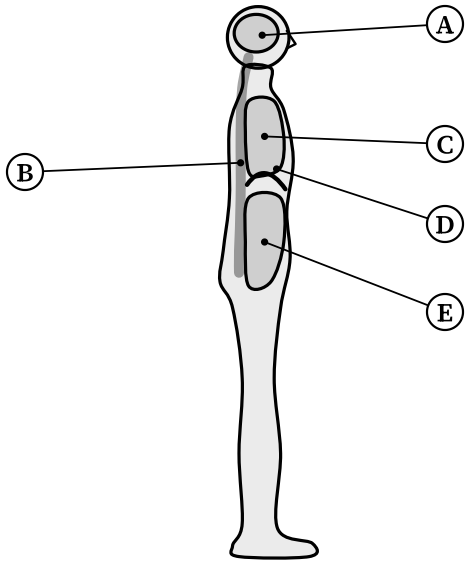
4. Medium Which plane (a) divides the body into front and back, (b) produces the cross-section shown on most CT images of the abdomen, (c) passes between the eyes and splits the nose into equal halves?

   Show answer

   (a) Frontal (coronal), (b) transverse, (c) midsagittal.

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name each space or structure A–E in this side view. Which two are part of the dorsal cavity?



Show answer

A cranial cavity, B vertebral canal, C thoracic cavity, D diaphragm, E abdominopelvic cavity. A and B are dorsal.

6. **Medium** In which quadrant would you feel (a) most of the liver and the gallbladder, (b) the stomach and spleen, (c) the appendix, (d) the S-shaped last turn of the colon?

Show answer

(a) Right upper, (b) left upper, (c) right lower, (d) left lower.

7. **Medium** Name the serous membrane around (a) the lungs, (b) the heart, (c) the abdominal organs. Which layer, parietal or visceral, touches the organ itself?

Show answer

(a) Pleura, (b) pericardium, (c) peritoneum. The visceral layer covers the organ; the parietal layer lines the cavity wall.

DISORDER AS A BROKEN MECHANISM

8. Hard Normally a film of serous fluid lets the visceral and parietal pleura slide smoothly. In pleurisy the layers become inflamed and rough. Predict the main symptom and explain why it is worse on a deep breath.

Show answer

Sharp chest pain with breathing. The rough layers rub instead of gliding, and a deep breath stretches and slides them the farthest, so the friction and pain are greatest then. A doctor may hear the rubbing through a stethoscope.

TEST PREP

9. Easy A patient lying face down on an exam table is

A. supine

B. prone

C. in anatomical position

D. lateral

Show answer

B. prone

10. Medium Translate the regional terms: cephalic, cervical, brachial, femoral, plantar.

Show answer

Head, neck, arm, thigh, sole of the foot.

11. Hard A patient is lying flat on a stretcher. A wound and her knee are at the same height above the floor, yet the chart says the wound is superior to the knee. Is the chart wrong? Explain.

Show answer

No. Directional terms always refer to anatomical position, not to the body's actual position. Standing in anatomical position, the wound would be closer to the head than the knee is, so it is superior.

COMMON MISTAKES

- Using your own right and left instead of the patient's; in a front-view drawing the patient's right is on your left.
- Confusing superior (toward the head) with superficial (toward the surface).

- Using proximal and distal for trunk structures; they describe positions along a limb (or along a tube such as the gut).
- Forgetting that the palms face forward in anatomical position, which makes the thumb lateral and the radius the lateral forearm bone.

Make it a game · Direction Dash. The parent hides a sticker somewhere on a stuffed animal or doll and gives clues using only anatomical terms ("posterior… right… proximal to the knee…"). The student must find it within 30 seconds. Swap roles; the clue-giver loses a point for any everyday word like "top" or "back of".

Scripture. "But now hath God set the members every one of them in the body, as it hath pleased him." (1 Corinthians 12:18, KJV)

Every member has a set place in the body. The language of anatomy is simply a careful way of naming those places.

1.3 Homeostasis and Feedback Loops

Mark up this lesson

OBJECTIVES

- Define homeostasis and explain why the body keeps conditions within a normal range.
- Trace a negative feedback loop through stimulus, receptor, control center, effector and response.
- Contrast negative and positive feedback and explain how disease can be a broken loop.

> **Warm-up.** Count your pulse at the wrist for 15 seconds and multiply by 4. Now do 30 jumping jacks and count again. Write down why you think it changed, and predict what your pulse will do over the next three minutes. You will test the prediction in the lab.

WATCH

Homeostasis and Negative/Positive Feedback

Amoeba Sisters · 6:24

https://www.youtube.com/watch?v=Iz0Q9nTZCw4

> **WHEN TO WATCH**
> After the parts of a feedback loop.

BACKUP VIDEO

Homeostasis and Negative/Positive Feedback

MooMooMath and Science · 2:37

https://www.youtube.com/watch?v=k6rVcGp5Jkk

As a quick review before the practice.

KEY TERMS

homeostasis

Keeping the body's internal conditions (temperature, blood sugar, pH, water) within a narrow normal range while the outside world changes.

receptor (sensor)

A structure that detects a change and reports it to the control center.

effector

A muscle or gland that carries out the command.

positive feedback

A loop in which the response strengthens the original change until some event ends it.

set point

The target value a control center works toward, such as about 37 °C for core temperature; the body allows a small normal range around it.

control center

Usually a part of the brain or an endocrine gland; it compares the input with the set point and sends commands.

negative feedback

A loop in which the response reverses the original change, bringing the value back toward the set point.

CORE IDEAS

The story. In the 1850s and 1860s the French physiologist Claude Bernard noticed that the blood and tissue fluid of an animal stay remarkably steady whatever the weather or diet. He called this fluid the *milieu intérieur*, the internal environment, and wrote that its constancy is the condition for a free and independent life. In 1926 the American physiologist Walter Cannon gave the idea its name, *homeostasis* (Greek, "staying similar"), and in 1932 he described it in a book called *The Wisdom of the Body*.

Why a narrow range. Enzymes, membranes and nerves work only within tight limits. Core temperature stays near 37 °C (about 36.5–37.5 °C through the day); blood pH stays between 7.35 and 7.45; fasting blood glucose stays roughly 70–99 mg/dL; blood sodium stays near 135–145 mmol/L. Homeostasis is not a frozen number but

a steady wobble around a set point, like a driver making small corrections to stay in a lane.

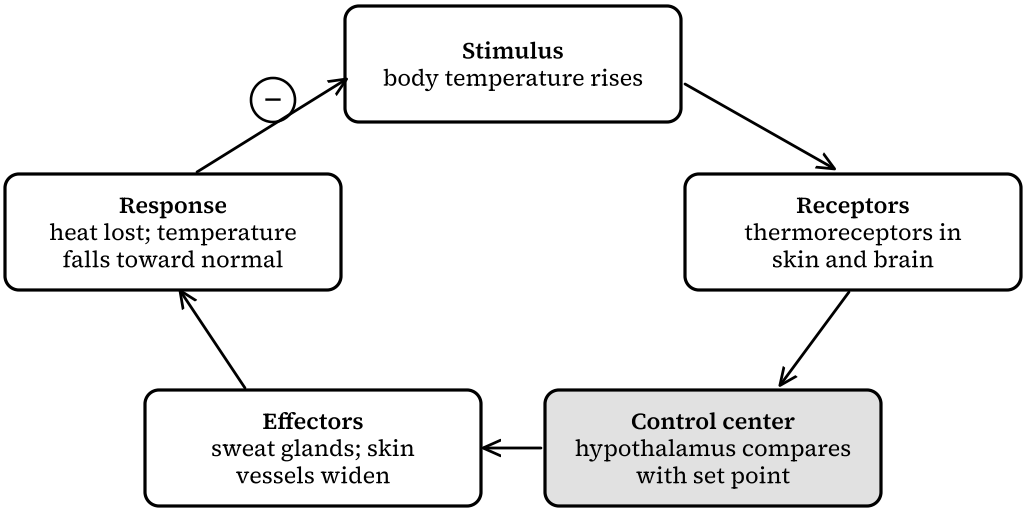
The parts of a loop. A change (the *stimulus*) is detected by a *receptor*, which sends information to a *control center*. The control center compares it with the set point and sends commands to an *effector*, a muscle or gland, whose action is the *response*. Nerves carry fast messages; hormones in the blood carry slower ones. Learn the five boxes now, because you will draw them for nearly every system this year.

Negative feedback: the body's thermostat. In *negative* feedback the response reverses the change. When you overheat, thermoreceptors report to the hypothalamus, which signals sweat glands to secrete and skin blood vessels to widen; heat leaves and temperature falls, so the signal stops. When you are cold, the same center makes skin vessels narrow, raises goose bumps and starts shivering, since muscle work releases heat. After a meal, rising blood sugar triggers insulin, which helps cells take up glucose; when sugar falls too low, glucagon releases stored glucose. Almost all of homeostasis runs on negative feedback.

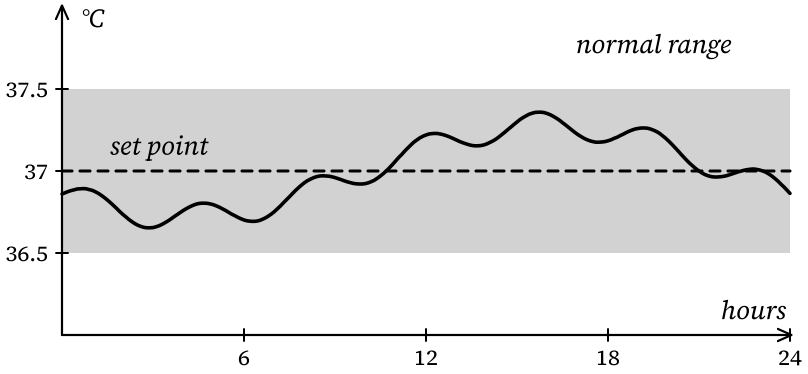
Positive feedback: pushing to a finish. In *positive* feedback the response strengthens the change. At a cut, platelets that stick to the wound release chemicals that call more platelets, which release more chemicals, until a plug and clot seal the vessel. During childbirth, pressure on the cervix triggers the hormone oxytocin, which strengthens contractions, which increase the pressure, until the baby is born and the loop ends. Positive feedback is rare and always has a built-in stopping point.

When it goes wrong. Many diseases are broken loops. In type 1 diabetes the insulin-making cells are destroyed, so blood sugar after a meal stays high. In a fever, chemicals from infection raise the hypothalamus's set point, so the body shivers and feels cold while its temperature climbs. In heat stroke the cooling loop is overwhelmed: when sweating fails, the rising temperature speeds up metabolism, which makes more heat, which turns a healthy negative loop into a dangerous runaway. The PE course treats this in PE 9, lesson 2.2.

Try it. In the lab you will measure your own vital signs at rest, after exercise and during recovery, and graph a negative feedback loop at work.



Negative feedback for body temperature. The response cancels the stimulus, so the loop switches itself off.



Homeostasis is a steady wobble inside a normal range, not a frozen number.

> **Safety first.** Skip the exercise part, or ask your doctor first, if you have a heart or breathing condition. Stop at once if you feel dizzy, faint or short of breath. Clean the thermometer with soap and water or rubbing alcohol between users.

LAB

Clinical Skills Lab 1: Vital Signs and Recovery

Nurses call pulse, breathing rate and temperature vital signs. You will measure yours and watch a feedback loop bring them home.

You will need

- A watch or phone timer with seconds, a digital thermometer, a partner, graph paper

Steps

1. Sit quietly for 5 minutes. Count your radial pulse (thumb side of the wrist, two fingers, not your thumb) for 30 seconds and double it. Repeat once and average.
2. Have your partner count your breaths for 30 seconds without telling you when they start (people breathe differently when they know they are watched). Double it.
3. Take your oral temperature.
4. Do 2 minutes of jumping jacks or stair stepping.
5. Measure pulse and breathing immediately and then at the end of every minute for 5 minutes. Take your temperature again at the end.
6. Graph pulse and breathing rate against time. Mark your resting values with a dashed line.

Check your work

- ☐ How many minutes did your pulse take to come back within 10 percent of resting?
- ☐ Name the receptors, control center and effectors that brought it down.
- ☐ Did your temperature change much? Which effectors kept it steady?

LAB NOTEBOOK

1. Your vital-signs data table and recovery graph.
2. Feedback-loop diagrams for overheating, getting cold and blood sugar after a meal.

KEY FORMULAS

$$^\circ\mathrm{F} = \tfrac{9}{5}\,(^\circ\mathrm{C}) + 32 \qquad ^\circ\mathrm{C} = \tfrac{5}{9}\,(^\circ\mathrm{F} - 32)$$

From history. In 1868 the German physician Carl Wunderlich published the results of temperature readings on about 25,000 patients, taken with a foot-long thermometer held in the armpit for many minutes. He set 37 °C (98.6 °F) as the healthy average and called temperatures above about 38 °C a fever. Studies with modern thermometers find averages a little lower, around 36.6 °C, which is why "normal" is now taught as a range rather than a single number.

Practice habit. For every body process you learn this year, draw it as five boxes: stimulus, receptor, control center, effector, response.

Review first. The kidneys' water sensor in PE 9, lesson 2.1 is another negative feedback loop worth tracing with the five boxes.

WORKED EXAMPLES

Example 1. You step outside on a 2 °C winter morning without a coat. Trace the negative feedback loop that protects your core temperature.

Show solution

1. Stimulus: skin and blood begin to cool.
2. Receptors: cold receptors in the skin and temperature-sensing neurons in the hypothalamus.
3. Control center: the hypothalamus compares the input with its set point of about 37 °C.
4. Effectors: skin arterioles narrow (less warm blood near the surface), arrector pili muscles raise goose bumps, and skeletal muscles shiver to release heat.
5. Response: heat is kept and made, core temperature rises back toward 37 °C, and the stimulus fades, so shivering stops.

Answer: Stimulus → receptors → hypothalamus → vessels, hair muscles and shivering → temperature restored (negative feedback)

Example 2. A thermometer reads 102.2 °F. Convert to °C and decide whether it is a fever.

Show solution

1. °C = 5/9 × (102.2 − 32)
2. = 5/9 × 70.2 = 39.0 °C
3. Above about 38 °C counts as a fever.

Answer: 39.0 °C: a fever

Example 3. Classify each loop as negative or positive feedback: (a) insulin lowers blood sugar after a meal; (b) platelets at a cut release chemicals that attract more platelets; (c) you sweat during a run.

Show solution

1. Ask: does the response reverse the change or strengthen it?
2. (a) Sugar rose; insulin brings it down: reverses.
3. (b) Platelets bring more platelets: strengthens, until the clot ends it.
4. (c) Heat rose; sweating removes heat: reverses.

Answer: (a) negative, (b) positive, (c) negative

PRACTICE

CONCEPT CHECKS

1. Easy Define homeostasis. Why do we speak of a normal range rather than a single exact value?

   Show answer

   Keeping internal conditions within narrow limits despite outside change. The value constantly drifts and is corrected, so it wobbles within a range around the set point.

2. Easy List the five parts of a feedback loop in order.

   Show answer

   Stimulus, receptor, control center, effector, response.

3. **Medium** Negative or positive feedback? (a) Shivering when cold. (b) Oxytocin strengthening contractions during childbirth. (c) Glucagon released when blood sugar falls. (d) Thirst and drinking when you are dehydrated.

   Show answer

   (a) negative, (b) positive, (c) negative, (d) negative.

4. **Medium** Convert 36.2 °C to °F. Is it within the normal daily range?

   Show answer

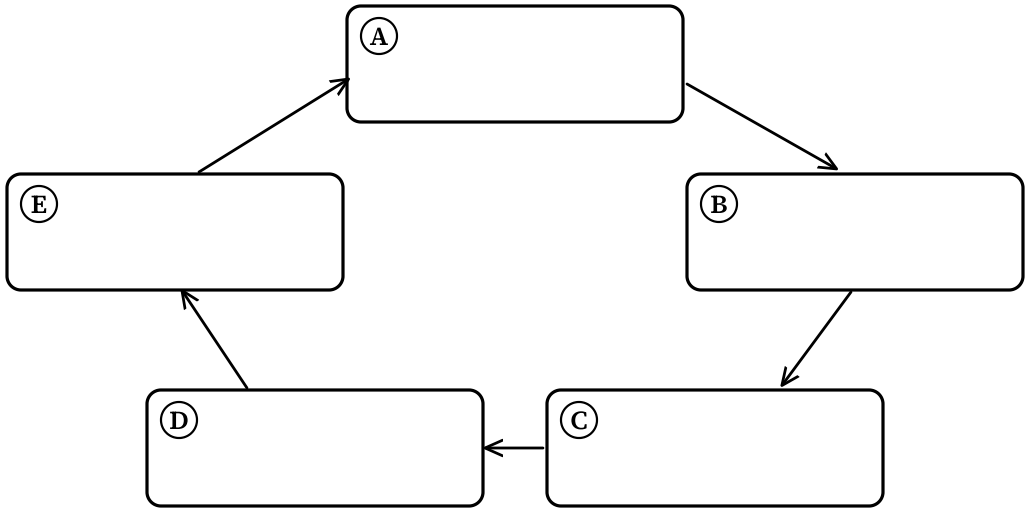
   97.2 °F

   9/5 × 36.2 + 32 = 97.16

   Slightly below 36.5 °C; it can be normal for some people, especially early in the morning, but a nurse would recheck it.

DIAGRAM AND DATA QUESTIONS

5. **Medium** This cycle shows how blood sugar is brought down after a meal. Place each statement in its box A–E: blood glucose falls back toward normal; liver, muscle and fat cells take up glucose; blood glucose rises after a meal; beta cells of the pancreas release insulin into the blood; beta cells of the pancreas sense the rise.



Show answer

A: blood glucose rises after a meal (stimulus). B: beta cells sense the rise (receptor). C: beta cells release insulin (control center). D: liver, muscle and fat cells take up glucose (effectors). E: blood glucose falls back toward normal (response). In the pancreas the same cells act as both receptor and control center.

6. **Medium** A student's resting pulse is 72 beats per minute. Right after exercise it is 132, then at the end of minutes 1 to 5 it is 118, 104, 92, 84 and 78. (a) By what percent did the pulse rise? (b) After how many minutes was it within 10 percent of resting?

Show answer

(a) 83% higher

$(132 - 72)/72 \times 100 = 83.3\%$

(b) 5 minutes (within 10% means 79 or below; 78 at minute 5).

7. Easy You count 19 pulse beats in 15 seconds and 7 breaths in 30 seconds. Find the pulse and breathing rate per minute. Are they in the usual resting range (pulse 60–100, breathing 12–20)?

Show answer

Pulse 76 beats/min (19 × 4); breathing 14 breaths/min (7 × 2). Both are normal.

DISORDER AS A BROKEN MECHANISM

8. Hard In type 1 diabetes the immune system destroys the insulin-making beta cells. Using the parts of a feedback loop, explain what is broken and predict what happens to blood glucose after a meal without treatment.

Show answer

The stimulus (rising glucose) still happens, but the cells that act as receptor and control center are gone, so no insulin is sent and the effectors (liver, muscle, fat) never get the command to take up glucose. Blood glucose stays high; glucose spills into the urine, taking water with it, and cells starve in the midst of plenty. Treatment supplies the missing signal by injecting insulin (Unit 6).

TEST PREP

9. Medium Which is an example of positive feedback?

A. sweating on a hot day

B. shivering on a cold day

C. platelets gathering at a cut

D. insulin release after a meal

Show answer

C. platelets gathering at a cut

10. Hard At the start of a fever the hypothalamus raises its set point to 39 °C while body temperature is still 37 °C. Explain why the person shivers and feels cold, and what happens when the fever "breaks" and the set point returns to 37 °C.

Show answer

At 37 °C the body is now below the new set point, so the control center runs the warming effectors: shivering, narrowed skin vessels, chills. When the set point drops back to 37 °C the body, now near 39 °C, is above it, so the cooling effectors run: heavy sweating and flushed skin.

COMMON MISTAKES

- Thinking "positive" feedback means good and "negative" means bad; the words describe whether the response strengthens or reverses the change.
- Treating the set point as an exact number that never moves.
- Mixing up receptors (which detect) and effectors (which act).
- Saying positive feedback is common; it is rare and always has a stopping point.

Make it a game · Loop Relay. The parent names a change: blood sugar rises, you jump into a cold lake, you get a paper cut, you drink a liter of water, you run a mile on a hot day. Within 30 seconds the student names the receptor, control center, effector and response and says positive or negative. One point per correct box; bonus point for the right feedback type.

Scripture. "And he is before all things, and by him all things consist." (Colossians 1:17, KJV)

"Consist" here means hold together. A body held steady moment by moment through day and night is a small picture of a world held together by its Maker.

1.4 Seeing Inside: X-ray, CT, MRI and Ultrasound

Mark up this lesson

OBJECTIVES

- Explain how X-ray, CT, MRI and ultrasound each form an image and which tissues each shows best.
- Tell which methods use ionizing radiation and explain why doses are kept low.
- Read a sectional image using the body planes and the patient's right and left.

> **Warm-up.** In a dark room, hold a small flashlight against the back of your fingers and look at the palm side (do not look into the light itself). Which parts glow and which stay dark? What does that tell you about how light passes through different tissues?

WATCH

How X-rays see through your skin - Ge Wang

TED-Ed · 4:42

https://www.youtube.com/watch?v=gsV7SJDDCY4

> **WHEN TO WATCH**
> After the Röntgen story.

BACKUP VIDEO

Diagnostic Imaging Explained (X-Ray / CT Scan / Ultrasound / MRI)

Physio Explain · 3:10

https://www.youtube.com/watch?v=0d_P5kXkAvE

As a review of all four methods.

KEY TERMS

radiograph

An X-ray image. Dense materials that block X-rays (bone, metal) look white; air looks black; soft tissue looks gray.

ionizing radiation

Radiation with enough energy to knock electrons off atoms and damage DNA, such as X-rays. Doses are kept as low as reasonably achievable.

computed tomography (CT)

An X-ray tube and detectors rotate around the body while a computer builds cross-sectional slices (Greek *tomos*, "slice").

magnetic resonance imaging (MRI)

Imaging with a strong magnet and radio pulses that read signals from hydrogen nuclei in water and fat; no X-rays.

ultrasound (sonography)

Imaging with high-frequency sound; echoes from tissue boundaries are timed to find their depth.

contrast agent

A substance swallowed or injected (barium, iodine, gadolinium) to make vessels or organs stand out.

CORE IDEAS

The story. On 8 November 1895, in Würzburg, Germany, the physicist Wilhelm Röntgen was running current through a glass tube wrapped in black cardboard when a chemically coated screen across the room began to glow. Some unknown ray was passing through the cardboard; he called it "X." Within weeks he had made an image of the bones in his wife Anna Bertha's hand, wedding ring and all. Surgeons were using X-rays to find bullets and set fractures within months. Röntgen received the first Nobel Prize in Physics in 1901 and refused to patent his discovery, so that everyone could use it.

X-rays: shadows of density. X-rays pass easily through soft tissue but are absorbed by dense, heavy atoms such as the calcium in bone. On a radiograph, bone and metal look white, air in the lungs looks black and soft tissues look gray. X-rays are quick and cheap and are the first test for broken bones, pneumonia and dental decay. Because X-rays are ionizing, doses are kept low: a chest X-ray gives about 0.1 millisievert, about as much as we each receive in twelve days from natural background radiation.

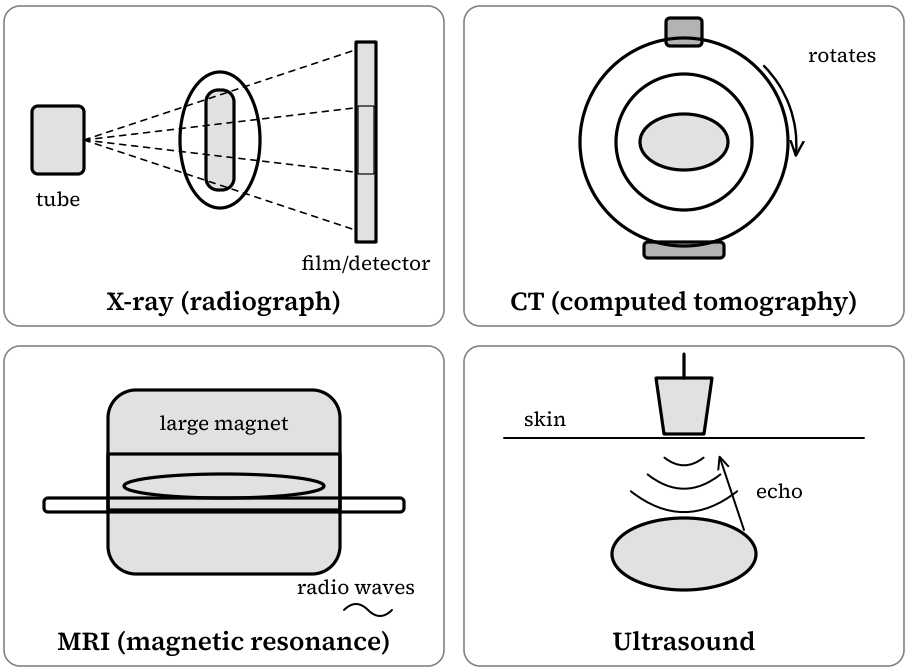
CT: X-ray slices. In 1971 the engineer Godfrey Hounsfield scanned the first patient with his computed tomography machine. A CT scanner spins an X-ray tube and a ring of detectors around the patient, and a computer turns thousands of readings into transverse slices, which can be stacked into 3-D views. CT shows soft tissue far better than a plain radiograph and is fast, so it is used after head injuries and car crashes to look for bleeding. It gives a larger dose than a plain X-ray, so it is ordered only when the answer matters.

MRI: listening to hydrogen. MRI uses no X-rays. The patient lies in a magnet of 1.5 to 3 tesla, tens of thousands of times stronger than the earth's field. The hydrogen nuclei in water and fat line up; radio pulses tip them over, and as they relax they give off faint radio signals. Different tissues relax at different rates, so MRI shows brain, spinal cord, ligaments and cartilage in exquisite detail. Scans are slow and loud, and any iron-containing object can become a dangerous projectile, so every patient is screened for metal, pacemakers and implants.

Ultrasound: echoes. A hand-held probe sends pulses of sound far above human hearing into the body and listens for echoes from the boundaries between tissues. Sound travels through soft tissue at about 1540 meters per second, so the time an echo takes to return gives the depth of the boundary. Ultrasound is cheap, portable, shows motion in real time and uses no ionizing radiation, so it is used for the beating heart, the gallbladder and babies before birth (first done by Ian Donald in Glasgow in the 1950s). Air and bone reflect nearly all the sound, so it cannot see through lungs or skull.

Reading the slices. Transverse CT and MRI images are displayed as if you stood at the patient's feet looking toward the head: the patient's right is on your left, and the front of the body is at the top. Knowing the planes from lesson 1.2 lets you find the liver on the left of the screen and know that it is normal.

Choosing a test. Doctors weigh what must be seen, how fast, how much it costs and how much radiation is acceptable. A suspected broken wrist gets an X-ray, a head injury with possible bleeding gets a CT, a torn knee ligament gets an MRI and a pregnancy check gets an ultrasound.



Four ways to see inside. X-ray and CT use ionizing radiation; MRI and ultrasound do not.

> **Safety first.** Never look into the flashlight beam. Skewers are sharp: push them straight down, and keep your other hand off the lid.

LAB

Mystery-Box Imaging

Doctors cannot open the body to look, so they sample it from outside. You will image a hidden object the same way.

You will need

- A shoebox with a lid, modeling clay, a long wooden skewer marked every 0.5 cm, a ruler, graph paper
- A flashlight and a bedsheet for the shadow test

Steps

1. A partner hides a clay shape stuck to the floor of the box and closes the lid without letting you see it.
2. Draw a 2-cm grid on the lid and poke a small hole at every grid point.
3. At each hole, lower the skewer straight down until it touches clay or the floor. Record the depth on a matching grid on paper.
4. Shade your paper grid: shallow readings dark, deep readings light. Sketch what you think the shape is, then open the box.
5. Repeat with a 1-cm grid on a new shape and compare how sharp your picture is.
6. Shadow test: shine the flashlight through a hanging sheet onto two objects, first from the front and then from the side. Note what one view hides that two views reveal.

Check your work

- ☐ How is the skewer like an ultrasound echo? How is the two-view shadow test like CT?
- ☐ Why did the finer grid give a better picture, and what did it cost you?

LAB NOTEBOOK

1. The four imaging setups with one strength and one limit of each.
2. Your mystery-box depth map beside a sketch of the real shape.

KEY FORMULAS

$$\text{depth} = \frac{v\,t}{2} \qquad v \approx 1540 \text{ m/s in soft tissue}$$

From history. Godfrey Hounsfield, the engineer who built the first CT scanner while working for the British electronics firm EMI, never earned a university degree. The first patient scan, at Atkinson Morley's Hospital in London in 1971, showed a tumor in a woman's brain. Hounsfield shared the 1979 Nobel Prize in Physiology or Medicine with Allan Cormack, a physicist who had worked out the mathematics of rebuilding a slice from many X-ray readings years earlier.

Practice habit. Whenever you look at a medical image, first find the patient's right and the plane of the slice, and only then look for the organs.

Career connection. Radiologic technologists position patients and run X-ray and CT machines; sonographers run ultrasound; MRI technologists run the magnets. Most radiographers train in a two-year associate-degree program, pass the ARRT certification exam and hold a state license. Radiologists, the physicians who read the images, train for many more years. All of them use this unit's planes and directional terms every day.

WORKED EXAMPLES

Example 1. An ultrasound echo from the back wall of the gallbladder returns 65 μs after the pulse is sent. Sound travels at 1540 m/s in soft tissue. How deep is the wall?

Show solution

1. The pulse goes down and back, so divide the trip by 2.
2. depth = 1540 m/s × 65 × 10^{-6} s ÷ 2
3. = 0.050 m

Answer: About 5.0 cm

Example 2. Choose the best first imaging test and give a reason: (a) a suspected broken wrist after a fall; (b) a sudden severe headache after a car crash; (c) checking a baby's growth before birth; (d) a suspected torn ligament in the knee.

Show solution

1. (a) Bone shows clearly on a quick, cheap radiograph.
2. (b) CT is fast and shows bleeding in the brain.
3. (c) Ultrasound uses no ionizing radiation and shows the baby in real time.
4. (d) MRI shows ligaments and cartilage best.

Answer: (a) X-ray, (b) CT, (c) ultrasound, (d) MRI

Example 3. On a transverse CT slice of the upper abdomen, the liver appears on the left side of the screen. Is that the patient's right or left side, and is it normal?

Show solution

1. Transverse images are viewed from the feet: the patient's right is on the viewer's left.
2. The liver lies mostly in the right upper quadrant.

Answer: The patient's right side; normal

PRACTICE

CONCEPT CHECKS

1. Easy Why do bones look white on a radiograph and the lungs look dark?

   Show answer

   Calcium-rich bone absorbs most of the X-rays, so little reaches the detector; air in the lungs absorbs almost none, so the detector there is fully exposed and looks dark.

2. Easy Which two of the four methods use ionizing radiation?

   Show answer

   X-ray (radiography) and CT.

3. **Medium** An ultrasound echo returns after 39 µs. How deep is the reflecting boundary?

Show answer

About 3.0 cm

$1540 \times 39 \times 10^{-6} \div 2 = 0.030$ m

4. **Medium** A kidney boundary lies 8.0 cm below the skin. How long after the pulse will its echo return?

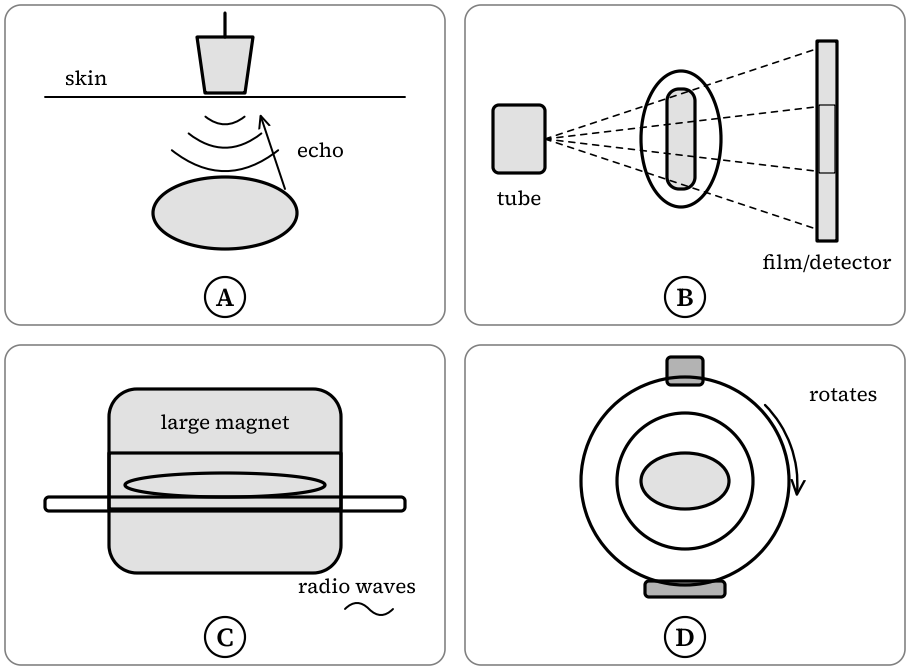
Show answer

About 104 µs

$t = 2d/v = 2 \times 0.080 \div 1540 = 1.04 \times 10^{-4}$ s

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the imaging method drawn in each panel A–D, and say which two use ionizing radiation.



Show answer

A ultrasound, B X-ray, C MRI, D CT. B and D use ionizing radiation.

6. Medium A chest X-ray gives about 0.1 mSv. Natural background radiation gives about 3 mSv per year. How many days of background radiation equal one chest X-ray?

Show answer

About 12 days

$0.1 \div 3 \times 365 = 12.2$

7. Medium Rank from whitest to darkest on a radiograph: air in the lungs, fat, muscle, bone, a metal filling.

Show answer

Metal filling, bone, muscle, fat, air.

DISORDER AS A BROKEN MECHANISM

8. Hard In osteoporosis the bone loses mineral because bone-dissolving cells outpace bone-building cells. Predict how an osteoporotic hip looks on an X-ray compared with a healthy hip, and explain why in terms of absorption.

Show answer

It looks grayer and thinner, with a thin outer shell and a faint, sparse inner lattice. With less calcium in the path, fewer X-rays are absorbed, so more reach the detector. (A special two-energy X-ray scan, DEXA, measures the density directly.)

TEST PREP

9. Easy Which test best shows the spinal cord in detail without ionizing radiation?

A. a plain X-ray

B. CT

C. MRI

D. a chest radiograph

Show answer

C. MRI

10. Medium An MRI magnet is 3.0 tesla. The earth's magnetic field is about 50 microtesla. How many times stronger is the magnet?

Show answer

About 60,000 times

$3.0 \div (50 \times 10^{-6}) = 60{,}000$

11. Hard Why can ultrasound not see well through the lungs or the skull, and why does the sonographer spread gel on the skin first?

Show answer

Air and bone reflect nearly all of the sound at their boundaries, so little passes beyond them. A thin layer of air between probe and skin would do the same, so gel fills the gap and lets the sound enter.

COMMON MISTAKES

- Thinking MRI uses X-rays; it uses a magnet and radio waves.
- Reading white on a radiograph as "empty"; white means dense material that blocked the rays.
- Forgetting that an echo travels down and back, so the time must be halved.
- Reading a transverse slice as if facing the patient's back; the patient's right is on the viewer's left.

Make it a game · Which Scan?. Write ten case cards (a twisted ankle, a kidney stone, a concussion, a heart-valve check, a swallowed coin, a torn knee cartilage…). The parent reads a card; the student names X-ray, CT, MRI or ultrasound and gives one reason in ten seconds. Two points for a good reason, one for the right method alone. Swap after five cards.

Scripture. "My substance was not hid from thee, when I was made in secret, and curiously wrought in the lowest parts of the earth." (Psalm 139:15, KJV)

Imaging lets us glimpse what is hidden from our eyes; nothing about us was ever hidden from God's.

UNIT 1

The Body as a Whole

The body is one person made of many parts that work together. This unit climbs the ladder from atoms to the whole person, learns the shared language of positions, planes, cavities and regions that every nurse, medic and surgeon uses, traces the feedback loops that hold temperature and blood sugar steady, and looks inside the living body with X-rays, CT, MRI and ultrasound.

The home labs are a life-size organ map, cutting clay figures along the three planes, a vital-signs lab and a mystery-box imaging model. Like the Biology course, this course studies the body as designed: “I am fearfully and wonderfully made” (Psalm 139:14).

PREREQUISITES

- High School Biology Units 2–3 (biological molecules and cells), or equivalent
- Comfort with metric units, percents and simple formulas

MASTERY CHECKLIST

- ☐ I can name the levels of organization and the eleven organ systems with a job for each.
- ☐ I can describe anatomical position and use directional terms, planes, cavities and quadrants correctly.
- ☐ I can trace a negative feedback loop through its five parts and tell negative from positive feedback.
- ☐ I can explain how X-ray, CT, MRI and ultrasound form images and choose a suitable test for a problem.

LESSONS IN THIS UNIT

1.1 Levels of Organization: “Fearfully and Wonderfully Made”

3 sessions of 45 minutes

1.2 Anatomical Language: Position, Planes, Cavities and Regions

4 sessions of 45 minutes

1.3 Homeostasis and Feedback Loops — 4 sessions of 45 minutes

Unit 1 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. Use complete anatomical terms. The test is worth 100 points.

1. **8 pts** **Lesson 1.1**

   Put in order from smallest to largest and give one example of each: organ system, cell, chemical, organism, tissue, organ.

2. **8 pts** **Lesson 1.1**

   Name the organ system for each: (a) skin and nails, (b) thyroid and pancreas islets, (c) kidneys and bladder, (d) spleen and lymph nodes.

3. **8 pts** **Lesson 1.2**

   Fill in: (a) The elbow is ___ to the wrist. (b) The nose is ___ to the ears. (c) The heart is ___ to the spine. (d) Muscle is ___ to skin.

4. **8 pts** **Lesson 1.2**

   Name the plane that divides the body into (a) front and back, (b) right and left, (c) upper and lower. Which is the usual plane of a CT slice?

5. **8 pts** **Lesson 1.2**

   Name the body cavity that holds (a) the brain, (b) the lungs and heart, (c) the stomach and intestines. What muscle separates (b) from (c)?

6. **8 pts** **Lesson 1.3**

   When blood pressure drops, stretch receptors in the large arteries signal the brainstem, which speeds the heart and narrows blood vessels, and pressure rises. Label the stimulus, receptor, control center, effectors and response, and name the type of feedback.

7. **8 pts** **Lesson 1.3**

   Explain the difference between negative and positive feedback and give one example of each.

8. **8 pts** **Lesson 1.3**

   Convert 38.5 °C to °F and say whether it is a fever.

9. **8 pts** **Lesson 1.4**

   Choose the best imaging test and give a reason: (a) a swallowed coin, (b) gallstones, (c) a torn rotator-cuff tendon, (d) bleeding in the brain after a fall.

10. **8 pts** **Lesson 1.4**

    An ultrasound echo returns 52 µs after the pulse. Sound travels at 1540 m/s in soft tissue. How deep is the boundary?

LAB AND DATA

11. **8 pts** **Lesson 1.3**

    Resting pulse: 68 beats/min. After 2 minutes of stair stepping: 128. At the end of minutes 1 to 4: 110, 94, 82, 74. (a) By how many beats per minute did the pulse rise? (b) After how many minutes was it within 10 percent of resting? (c) Which part of the feedback loop does the heart play?

SHORT ESSAY

12. **12 pts**

    Claude Bernard called the steady internal environment “the condition for a free and independent life.” Explain what homeostasis is, describe one negative feedback loop in detail, and show how one disease can be understood as a broken loop.

ANSWER KEY

1. Chemical (water, protein), cell (neuron), tissue (epithelium), organ (stomach), organ system (digestive), organism (a person).
2. (a) Integumentary, (b) endocrine, (c) urinary, (d) lymphatic and immune.
3. (a) proximal, (b) medial, (c) anterior (ventral), (d) deep.
4. (a) Frontal (coronal), (b) sagittal, (c) transverse. CT slices are usually transverse.
5. (a) Cranial (dorsal) cavity, (b) thoracic cavity, (c) abdominopelvic cavity. The diaphragm.
6. Stimulus: falling pressure. Receptors: stretch receptors in the arteries. Control center: brainstem. Effectors: heart and vessel muscle. Response: pressure rises back toward normal. Negative feedback.
7. Negative feedback reverses a change (temperature control, blood sugar, blood pressure); positive feedback strengthens a change until an event ends it (blood clotting, childbirth contractions).
8. 101.3 °F; a fever

   $9/5 \times 38.5 + 32 = 101.3$
9. (a) X-ray (metal blocks X-rays; quick), (b) ultrasound (shows stones; no radiation), (c) MRI (soft tissue detail), (d) CT (fast; shows fresh bleeding).
10. About 4.0 cm

    $1540 \times 52 \times 10^{-6} \div 2 = 0.040$ m
11. (a) 60 beats/min. (b) 4 minutes (within 10% means 74.8 or below; 74 at minute 4). (c) The effector.
12. Look for: a definition (internal conditions kept within a narrow range); Bernard and Cannon; a full loop with all five parts (temperature or blood sugar); a disease explained by which part fails (type 1 diabetes: no insulin signal; fever: raised set point; heat stroke: cooling overwhelmed), with clear cause-and-effect.

UNIT 2

Cells and Tissues

Every organ is built from a few kinds of tissue, and every tissue from cells. This unit reviews the cell with a clinician's eye, follows water, ions and nutrients across membranes in the body's fluid compartments, and sorts the body's cells into the four tissue families: epithelial, connective, muscle and nervous. It ends with how tissues heal and why some heal without a trace while others scar.

Labs: cheek cells under the microscope, gummy-bear osmosis and IV fluids, a tissue tour of a chicken drumstick, and a reaction-time and muscle-fatigue lab.

PREREQUISITES

- Unit 1 (levels of organization, homeostasis)
- Biology 3.1–3.4 (cells and membranes) and 6.3 (protein synthesis), or equivalent

MASTERY CHECKLIST

- ☐ I can name the main organelles and explain how a cell's structure fits its job.
- ☐ I can explain diffusion, osmosis and active transport and choose an isotonic IV fluid.
- ☐ I can classify epithelium and connective tissue and say where each is found.
- ☐ I can compare the three muscle tissues, describe a neuron and predict whether an injured tissue will regenerate or scar.

LESSONS IN THIS UNIT

2.1	**The Cell Reviewed for Anatomy and Physiology**	3 sessions of 45 minutes
2.2	**Membrane Transport in the Body**	4 sessions of 45 minutes
2.3	**Epithelial and Connective Tissue**	4 sessions of 45 minutes
2.4	**Muscle and Nervous Tissue; How Tissues Heal**	4 sessions of 45 minutes

Unit 2 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. 8 pts **Lesson 2.1**

   Match each organelle to its job: mitochondrion, rough ER, Golgi apparatus, lysosome. Jobs: packages proteins; makes ATP; digests worn-out parts; makes proteins for export.

2. 8 pts **Lesson 2.1**

   Explain how the structure of a red blood cell and of an intestinal lining cell each fit their jobs.

3. 8 pts **Lesson 2.2**

   Distinguish simple diffusion, facilitated diffusion and active transport, with one example of a substance moved by each.

4. 8 pts **Lesson 2.2**

   A nurse is about to hang a liter of sterile water as an IV. Explain what would happen to the patient’s red blood cells and name a safe fluid instead.

5. 8 pts **Lesson 2.2**

   Find the osmolarity of a 0.45 percent NaCl solution (4.5 g per liter; molar mass 58.44 g/mol). Is it isotonic, hypotonic or hypertonic to plasma (about 290 mOsm/L)?

6. 8 pts **Lesson 2.3**

   Name the epithelium and explain how its structure fits its job: (a) the air sacs of the lungs, (b) the skin surface.

7. 8 pts **Lesson 2.3**

   Name the kind of connective tissue: (a) tendon, (b) the matrix is liquid plasma, (c) stores fat under the skin, (d) glassy and smooth on bone ends, with no blood vessels.

8. **8 pts** **Lesson 2.4**

Which muscle tissue: (a) branched cells with intercalated discs, (b) spindle cells in the wall of the intestine, (c) long multinucleate striated fibers attached to bones?

9. **8 pts** **Lesson 2.4**

A ruler falls 18.0 cm before a student catches it. Find the reaction time ($g = 9.8\ m/s^2$).

10. **8 pts** **Lesson 2.4**

Explain why a cut in the epidermis heals without a trace while damage to heart muscle leaves a scar.

LAB AND DATA

11. **8 pts** **Lesson 2.2**

Gummy bears were soaked for 24 hours. Mass before and after: plain water 2.50 g → 5.75 g; 0.9% salt 2.48 g → 4.22 g; 10% salt 2.52 g → 2.27 g. (a) Find the percent change for each. (b) Which solution made the bear lose mass, and why?

SHORT ESSAY

12. **12 pts**

Virchow said that every disease is a disease of cells. Choose one disease from this unit (sickle-cell disease, Tay-Sachs, cholera, scurvy or multiple sclerosis) and explain it as a broken mechanism, tracing the fault from molecule or cell to tissue and to the whole person.

ANSWER KEY

1. Mitochondrion: makes ATP. Rough ER: makes proteins for export. Golgi: packages proteins. Lysosome: digests worn-out parts.
2. Red cell: no nucleus or mitochondria, leaving room for hemoglobin and not using the oxygen it carries; small flexible disc for passing through capillaries. Intestinal cell: microvilli multiply the surface area for absorption.
3. Simple diffusion: through the lipid bilayer, downhill (oxygen, CO_2). Facilitated: downhill through a channel or carrier (Na^+ through a channel, glucose on a carrier). Active: uphill using ATP (Na^+ out and K^+ in by the pump).
4. Sterile water is hypotonic, so water would rush into red cells by osmosis and many would swell and burst (hemolysis). Use an isotonic fluid such as 0.9% saline or lactated Ringer's.
5. About 154 mOsm/L: hypotonic

   $4.5 \div 58.44 = 0.0770$ mol/L $\times 2 = 0.154$ osmol/L
6. (a) Simple squamous: one thin layer for fast diffusion of gases. (b) Keratinized stratified squamous: many layers, tough surface cells that resist rubbing and water loss and are replaced from below.
7. (a) Dense regular, (b) blood, (c) adipose, (d) hyaline cartilage.
8. (a) Cardiac, (b) smooth, (c) skeletal.
9. About 0.19 s

   $\sqrt{(2 \times 0.180 \div 9.8)} = 0.192$
10. Epidermal cells divide readily and regenerate the same tissue. Cardiac muscle cells barely divide, so fibroblasts fill the gap with collagen scar tissue.
11. (a) Plain water +130%; 0.9% salt +70.2%; 10% salt −9.9%. (b) The 10% salt water: it was hypertonic to the bear, so water moved out.
12. Look for: the normal mechanism stated correctly; the exact fault (changed hemoglobin, missing lysosomal enzyme, channels locked open, unstable collagen, stripped myelin); a clear chain from cell to tissue to organ and symptoms; and, where fitting, how treatment restores or bypasses the broken step.

2.1 The Cell Reviewed for Anatomy and Physiology

Mark up this lesson

OBJECTIVES

- Name the main organelles and the job of each.
- Explain how a cell's structure fits its job, using red blood cells, muscle, liver, gland and intestinal cells.
- Summarize how a cell makes and ships a protein and how quickly different tissues replace their cells.

> **Warm-up.** A mature red blood cell has no nucleus at all. A single skeletal-muscle fiber has hundreds of nuclei. Before you read, write a guess for why each cell is built the way it is.

WATCH

Biology: Cell Structure I Nucleus Medical Media

Nucleus Medical Media · 7:22

https://www.youtube.com/watch?v=URUJD5NEXC8

> **WHEN TO WATCH**
> After the organelle tour.

BACKUP VIDEO

Cell Organelles and Structures Review

Amoeba Sisters · 8:16

https://www.youtube.com/watch?v=6mgkoqcm6Sg

As review if Biology 3.2 is far behind you.

KEY TERMS

plasma membrane

The phospholipid bilayer with proteins that encloses the cell and controls what enters and leaves.

nucleus

The organelle that holds the cell's DNA and directs its work; the nucleolus inside it builds ribosome parts.

ribosome

A small particle of RNA and protein that links amino acids into proteins; free in the cytoplasm or on rough ER.

endoplasmic reticulum (ER)

A network of membrane sacs and tubes: rough ER (with ribosomes) makes proteins for export; smooth ER makes lipids and breaks down drugs.

Golgi apparatus

Stacked sacs that modify, sort and package proteins into vesicles for shipping.

lysosome

A sac of digestive enzymes that breaks down worn-out parts and engulfed bacteria.

mitochondrion

The organelle that releases energy from food molecules and stores it as ATP (cellular respiration).

CORE IDEAS

Why review the cell. In 1858 the German physician Rudolf Virchow argued in *Cellular Pathology* that every disease is, at bottom, a disease of cells. He was largely right: an infection, a burn, a heart attack and a cancer all begin as something happening to cells. The medicines a nurse gives act on cell membranes, enzymes and receptors. This lesson reviews Biology 3.2 with a clinician's eye: not just what the parts are, but which cells have more of which part, and why.

A tour of the workshop. The *plasma membrane* is the gatekeeper. The *nucleus* is the library, holding about two meters of DNA folded into a sphere a few micrometers across. *Ribosomes* assemble proteins. *Rough ER*, studded with ribosomes, makes proteins that will leave the cell or sit in its membrane; *smooth ER* makes lipids and, in the liver, breaks down drugs and alcohol. The *Golgi apparatus* finishes, sorts and packages. *Lysosomes* recycle and digest. *Mitochondria* turn the energy of food into ATP. The *cytoskeleton* gives shape and moves things; centrioles organize cell division; cilia and microvilli decorate the surface of some cells.

Built for the job. All the body's cells carry the same DNA, yet they look and work very differently, because each turns on different genes and builds different parts. A red blood cell throws out its nucleus and mitochondria as it matures, leaving room for about 270 million hemoglobin molecules and keeping it from burning the oxygen

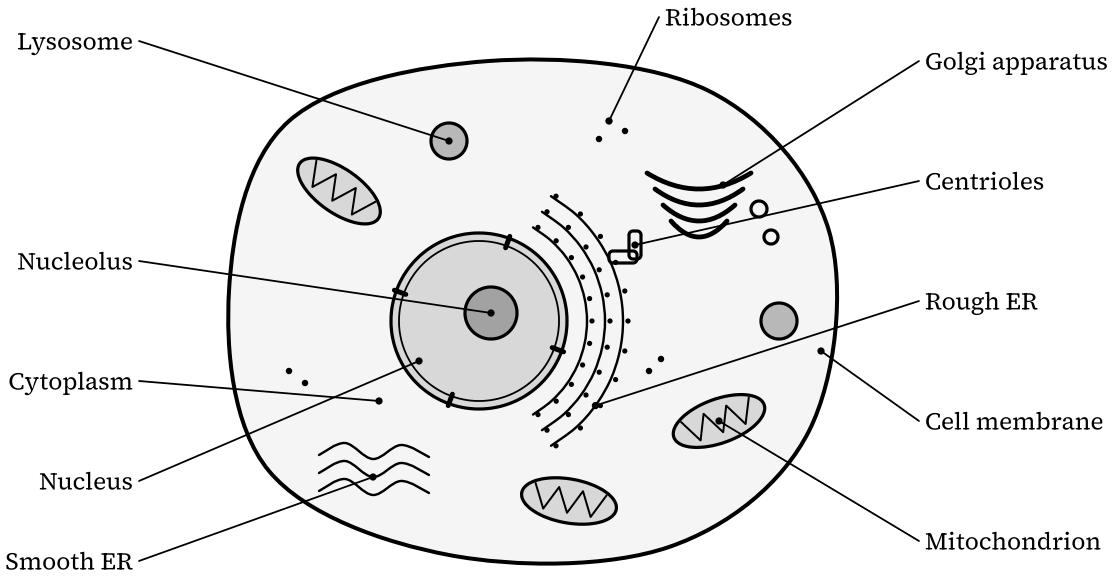
it carries. A skeletal-muscle fiber, formed by many cells fusing, has hundreds of nuclei and is packed with mitochondria and protein filaments. A liver cell is full of smooth ER for detoxifying. A pancreatic cell that ships digestive enzymes, or a plasma cell that pours out antibodies, is crowded with rough ER and Golgi. An intestinal lining cell wears thousands of microvilli that multiply its surface for absorption, and airway cells beat cilia that sweep mucus upward.

Making and shipping a protein. Take insulin. In a beta cell of the pancreas the insulin gene is copied into messenger RNA in the nucleus (transcription). The mRNA travels to ribosomes on the rough ER, which read it and build the protein (translation). The new protein is folded in the ER, trimmed and packaged in the Golgi, and stored in vesicles until rising blood sugar triggers their release at the membrane (exocytosis). Biology 6.3 tells this story in detail.

Renewal at different speeds. Tissues replace cells by mitosis at very different rates. The lining of the small intestine is renewed every few days; the outer skin in about a month; red blood cells live about 120 days, so the marrow makes roughly two million new ones every second. Most neurons and heart-muscle cells, by contrast, last a lifetime and are seldom replaced. Small populations of stem cells in many tissues supply the new cells. When division escapes its controls, the result is a tumor (Biology 3.4).

When it goes wrong. Many diseases can be traced to one organelle. In sickle-cell disease a single changed amino acid in hemoglobin makes the molecules stick together when oxygen is low, bending red cells into rigid sickles that jam capillaries and break apart early. In lysosomal storage diseases one missing enzyme lets material pile up inside lysosomes until the cell fails. Knowing the normal part is the first step to understanding the broken one.

Try it. In the lab you will look at your own cheek cells under the microscope, estimate their size, and build a “cell as a hospital” analogy chart.



A generalized animal cell. Real cells have more of some organelles and fewer of others, depending on their job.

> **Safety first.** Use a clean toothpick once and throw it away; never share. Iodine stains skin and clothes. Wash hands after the lab.

LAB

Cheek Cells and the Cell as a Hospital

You will see real human cells, measure them, and explain each organelle by comparing it with a department of a hospital.

You will need

- A microscope (40× to 400×), slides and cover slips, flat toothpicks, iodine or methylene blue, paper towels
- If you have no microscope: a set of good micrographs from the library or the Biology course
- Poster paper and markers

Steps

1. Gently scrape the inside of your cheek with the flat end of a toothpick. Smear it on a slide, add one drop of stain and lower a cover slip at an angle.
2. Find cells at 100×, then switch to 400×. Draw three cells and label the membrane, cytoplasm and nucleus.
3. Estimate size: at 400× the field of view is about 0.45 mm (450 µm) across on many school microscopes. Count how many cells would fit across it and divide.
4. Make a two-column chart: organelle and hospital department (for example, nucleus: records office; Golgi: shipping and mail room; lysosome: cleaning and recycling). Add one sentence defending each match.

Check your work

- ☐ Which organelles from the lesson could you not see, and why not?
- ☐ Where does your analogy break down?

LAB NOTEBOOK

1. Three cheek cells drawn at 400× with labels and a scale bar.
2. Your hospital analogy chart.

From history. In the 1950s George Palade, a Romanian-born scientist at the Rockefeller Institute in New York, used the new electron microscope to find the tiny particles we now call ribosomes. With radioactive tags he then followed newly made proteins in pancreas cells from the rough ER to the Golgi and out of the cell. He shared the 1974 Nobel Prize in Physiology or Medicine with Albert Claude, who had learned to separate cell parts by spinning them, and Christian de Duve, who discovered the lysosome.

Practice habit. Each time you learn a new cell type, name the one organelle it has most of and say why its job needs it.

Review first. If cells feel rusty, reread Biology 3.1 (cell theory), 3.2 (organelles), 3.3 (membranes) and 6.3 (protein synthesis) before this lesson.

WORKED EXAMPLES

Example 1. At 400× a microscope's field of view is 450 µm across. About 7 cheek cells laid side by side would fill it. Estimate the width of one cheek cell.

Show solution

1. width ≈ field ÷ number of cells
2. = 450 µm ÷ 7 ≈ 64 µm

Answer: About 60 µm

Example 2. An adult has about 25 trillion red blood cells, each living about 120 days. About how many must the marrow replace every second to keep the number steady?

Show solution

1. 120 days × 86,400 s/day = 1.04×10^7 s
2. 2.5×10^{13} cells ÷ 1.04×10^7 s ≈ 2.4×10^6 cells per second

Answer: About 2.4 million red cells per second

Example 3. Which organelle would you expect to find in large amounts in (a) a liver cell that breaks down medicines, (b) a pancreas cell that ships digestive enzymes, (c) a heart-muscle cell, (d) a white blood cell that digests bacteria?

Show solution

1. Match the job to the organelle that does it.
2. (a) Detoxifying lipid-soluble drugs: smooth ER.
3. (b) Making and exporting protein: rough ER and Golgi.
4. (c) Constant work needing ATP: mitochondria.
5. (d) Digesting what it engulfs: lysosomes.

Answer: (a) smooth ER, (b) rough ER and Golgi, (c) mitochondria, (d) lysosomes

PRACTICE

CONCEPT CHECKS

1. Easy Give the job of each: nucleus, ribosome, mitochondrion, Golgi apparatus, lysosome.

   Show answer

   Nucleus: holds DNA and directs the cell. Ribosome: builds proteins. Mitochondrion: makes ATP. Golgi: modifies, sorts and packages proteins. Lysosome: digests and recycles.

2. Easy Why is it an advantage for a mature red blood cell to have no nucleus or mitochondria?

   Show answer

   There is more room for hemoglobin, and without mitochondria the cell does not use up the oxygen it is carrying.

3. Medium A cell is packed with rough ER and Golgi. What is it probably doing? Give two examples of such cells.

   Show answer

   Making and exporting protein. Examples: pancreatic cells that secrete digestive enzymes or insulin, plasma cells that make antibodies, salivary gland cells.

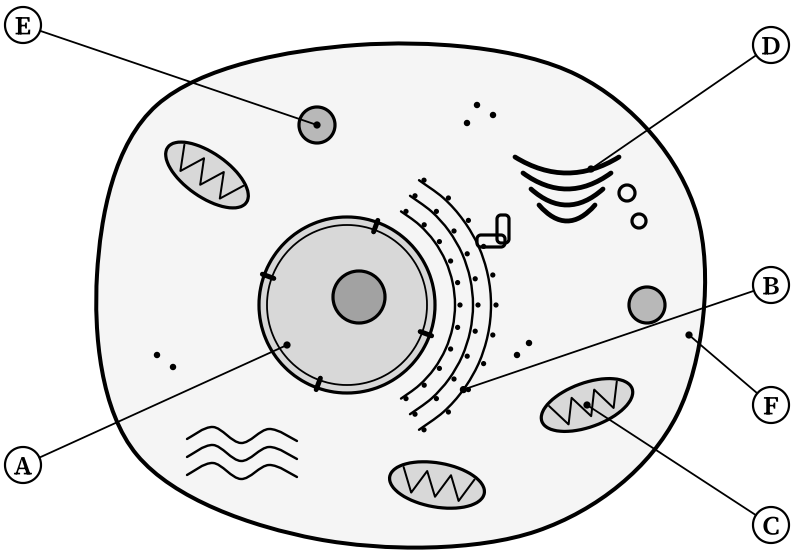
4. Hard In sickle-cell disease one amino acid in the hemoglobin protein is changed. Explain how this one change shows up at the cell, tissue and organism levels.

Show answer

Molecule: the changed hemoglobin sticks together into long fibers when oxygen is low. Cell: red cells bend into stiff sickles. Tissue: sickled cells jam small vessels so tissue downstream is starved of oxygen (pain crises). Organism: sickled cells break early, causing anemia and fatigue; organs such as the spleen are damaged.

DIAGRAM AND DATA QUESTIONS

5. Easy Name the parts lettered A–F.



Show answer

A nucleus, B rough endoplasmic reticulum, C mitochondrion, D Golgi apparatus, E lysosome, F plasma (cell) membrane.

6. Medium At 400× the field of view is 450 µm across, and about 60 red blood cells would span it. Estimate the diameter of a red cell.

Show answer

About 7.5 µm

450 ÷ 60 = 7.5

7. Medium Each body cell holds about 2 m of DNA. If an adult has about 30 trillion cells, about how long is all of that DNA laid end to end? How many times the earth–sun distance (1.5×10^{11} m) is that?

Show answer

About 6×10^{13} m, roughly 400 times the earth–sun distance

$2\text{ m} \times 3 \times 10^{13} = 6 \times 10^{13}$ m; $6 \times 10^{13} \div 1.5 \times 10^{11} = 400$

DISORDER AS A BROKEN MECHANISM

8. Hard In Tay-Sachs disease one lysosomal enzyme is missing, so a fatty substance it should break down builds up, especially in nerve cells. Using what lysosomes do, explain why the nerve cells fail and why the disease worsens with time.

Show answer

Lysosomes digest worn-out molecules. Without the enzyme the fatty material cannot be broken down, so it collects inside lysosomes that swell and crowd the neuron until it stops working and dies. Because neurons are seldom replaced and the material keeps arriving, the damage accumulates, and nervous function declines steadily.

TEST PREP

9. Easy Which organelle releases energy from food and stores it as ATP?

A. ribosome

B. Golgi apparatus

C. mitochondrion

D. lysosome

Show answer

C. mitochondrion

10. Medium The lining of the small intestine is renewed about every 4 days. About how many times is it replaced in a year? Why would a cancer drug that attacks dividing cells often cause stomach upset?

Show answer

About 91 times (365 ÷ 4). The gut lining divides so often that drugs aimed at fast-dividing cancer cells also damage it.

COMMON MISTAKES

- Confusing ribosomes (build proteins) with lysosomes (digest).
- Saying mitochondria "make energy"; they convert the energy in food into ATP.
- Thinking every cell has every organelle in the same amounts; cells are specialized.
- Assuming all cells divide at the same pace; most neurons and heart-muscle cells rarely divide.

> **Make it a game · Which Organelle Am I?.** The parent reads a clue in the first person ("I package and ship", "I hold two meters of instructions", "I have hundreds of me in a muscle fiber", "I dissolve old parts"). The student answers within five seconds. After ten clues, swap and let the student write the clues.

> **Scripture.** "Thine eyes did see my substance, yet being unperfect; and in thy book all my members were written, which in continuance were fashioned, when as yet there was none of them." (Psalm 139:16, KJV)
>
> "In thy book all my members were written." Every cell carries a written set of instructions for building the body, read out a little at a time as we grow.

2.2 Membrane Transport in the Body

Mark up this lesson

OBJECTIVES

- Distinguish simple diffusion, facilitated diffusion, osmosis, active transport and bulk transport.
- Predict the effect of isotonic, hypotonic and hypertonic fluids on red blood cells and choose a safe IV fluid.
- Describe the body's fluid compartments and the job of the sodium-potassium pump.

> **Warm-up.** Hospitals hang bags of "normal saline," which is 0.9 percent salt water, and run them straight into a vein. Why not use pure water, which is cheaper? Write a prediction about what pure water would do to blood cells.

WATCH

Cell Transport

Amoeba Sisters · 7:50

https://www.youtube.com/watch?v=Ptmlvtei8hw

> **WHEN TO WATCH**
> After the passive and active transport core ideas.

BACKUP VIDEO

Sodium Potassium Pump

Amoeba Sisters · 7:01

https://www.youtube.com/watch?v=7NY6XdPBhxo

With the sodium-potassium pump.

KEY TERMS

diffusion

Net movement of particles from higher to lower concentration, without using the cell's energy.

facilitated diffusion

Diffusion through a membrane protein: a channel (for ions or water) or a carrier (for glucose).

osmosis

Diffusion of water across a selectively permeable membrane toward the side with more dissolved particles.

tonicity

How a solution changes a cell's volume: isotonic (no change), hypotonic (cell swells), hypertonic (cell shrinks).

active transport

Moving a substance against its concentration gradient using energy, usually from ATP.

sodium-potassium pump

A membrane protein that uses one ATP to push three Na^+ ions out and bring two K^+ ions in.

intracellular and extracellular fluid

Fluid inside cells (about two-thirds of body water) and outside them, in tissue spaces and blood plasma (about one-third).

osmolarity

The total concentration of dissolved particles; body fluids are about 285–295 milliosmoles per liter.

CORE IDEAS

Why it matters. Every cell lives in a small private sea. About two-thirds of the body's water is inside cells (intracellular fluid); the remaining third is outside them (extracellular fluid), most of it bathing the tissues and about a fifth to a quarter of it as blood plasma. Oxygen, nutrients, wastes and salts must cross cell membranes and capillary walls constantly. Dehydration, swelling (edema), IV therapy and kidney failure all come down to how these exchanges work.

Passive transport: downhill. In *diffusion* particles spread from where they are crowded to where they are scarce, with no energy from the cell. Diffusion is faster when the gradient is steep, the temperature warm, the particles small and the distance short, which is why lung and capillary walls are one cell thin. Small or fat-soluble molecules such as oxygen, carbon dioxide and steroid hormones slip right through the lipid bilayer. Ions and sugars cannot; they need *facilitated diffusion* through proteins: *channels* that open a pore for particular ions or for water (aquaporins), and *carriers* that change shape to carry glucose across.

Osmosis and IV fluids. Water moves by osmosis toward the side with more dissolved particles. Red blood cells show it best. In an *isotonic* fluid such as 0.9 percent saline, which matches the roughly 300 milliosmoles per liter of plasma, they keep their shape. In a *hypotonic* fluid such as pure water they swell and can burst (hemolysis).

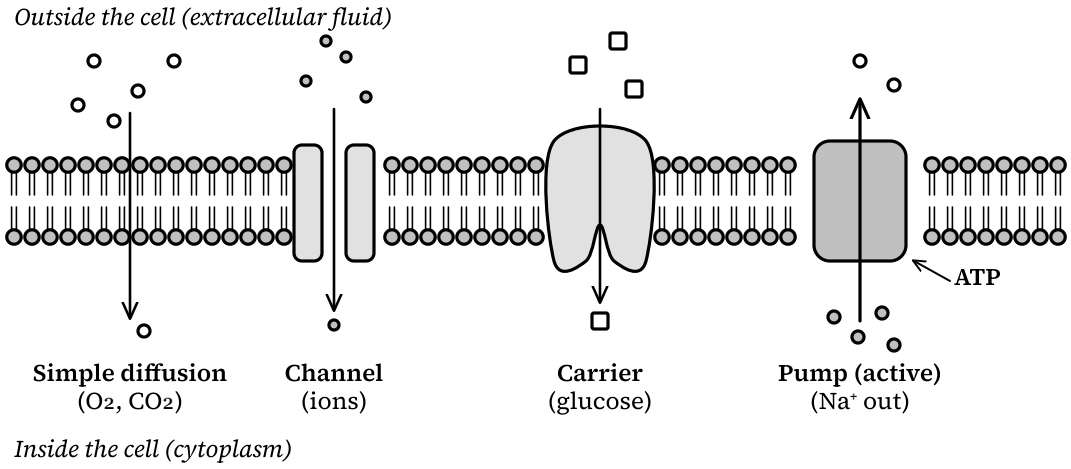
In a *hypertonic* fluid they shrivel into spiky shapes (crenation). That is why IV fluids are almost always isotonic, and why a bag of sterile water is never run straight into a vein.

Active transport: uphill. The *sodium-potassium pump* uses one ATP to push three sodium ions out of the cell and pull two potassium ions in, keeping sodium high outside and potassium high inside. This gradient controls cell volume, gives the membrane its electrical charge (the basis of every nerve impulse in Unit 5) and powers other transport. A large share of the body's resting energy, more in nerve tissue, goes to running these pumps. In the intestine and kidney, sodium rushing back into cells drags glucose with it through a shared carrier. Oral rehydration solution, a simple mix of salt and sugar in water, uses this carrier to pull water out of the gut and is credited with saving millions of lives from diarrheal diseases such as cholera.

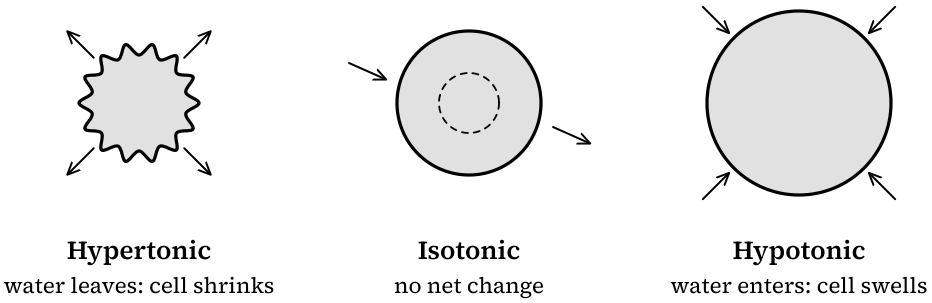
Bulk transport. Large particles move in membrane bubbles. White blood cells swallow bacteria by *phagocytosis*, a kind of endocytosis. Gland and nerve cells release insulin, enzymes and neurotransmitters by *exocytosis*, fusing vesicles with the membrane.

When it goes wrong. The cholera bacterium makes a toxin that jams chloride channels open in the cells lining the gut. Chloride floods out into the intestine, sodium follows it, and water follows the salt by osmosis, so a patient can lose many liters of watery stool a day. The transport machinery is not destroyed, only misused, which is why replacing salt and water, by mouth or by IV, cures most patients.

Try it. In the lab gummy bears play the part of cells in plain water, "normal saline" and strong salt water.



Four ways across the membrane. Only the pump uses ATP and moves a substance uphill.



Red blood cells in three kinds of fluid. IV fluids are chosen to be isotonic.

> **Safety first.** Do not eat the gummy bears or drink any of the solutions. Label every cup.

LAB

Gummy-Bear Osmosis and the IV Bag

Gelatin gummies take up and lose water much as cells do. You will measure the change and relate it to IV fluids.

You will need

- Six gummy bears of one color, four clear cups, a kitchen scale reading to 0.1 g or better, a ruler, paper towels
- Tap water, table salt, a measuring cup and teaspoon

Steps

1. Make “normal saline” (9 g, about 1½ level teaspoons, of salt in 1 liter of water) and strong salt water (100 g, about ⅓ cup, of salt in 1 liter).
2. Weigh and measure the length of each bear. Put one dry in an empty cup (control), and the others in plain water, normal saline and strong salt water.
3. After 24 hours blot each bear gently and weigh and measure it again.
4. Calculate percent change in mass: (final − initial) ÷ initial × 100. Graph mass change against salt concentration.

Check your work

- ☐ Which solution came closest to “isotonic” for a gummy bear? Is it the same as for a red blood cell?
- ☐ A gummy bear has no membrane and no pumps. In what ways is it a poor model of a cell?

LAB NOTEBOOK

1. Your data table and graph of percent mass change.
2. Sketches of a red blood cell in hypotonic, isotonic and hypertonic fluid, with arrows for water.

KEY FORMULAS

$$\%\ \text{change} = \frac{\text{final} - \text{initial}}{\text{initial}} \times 100$$

$$\text{osmolarity} \approx \text{molarity} \times \text{particles per formula unit} \quad (\text{NaCl} \rightarrow 2)$$

From history. In 1882 the London physician Sydney Ringer kept a frog's heart beating for hours in a salt solution, then found that it soon stopped when he repeated the work with distilled water. His first solution had been made with London tap water, which carried calcium. Ringer had discovered that the heart needs calcium to contract, and versions of his fluid, such as lactated Ringer's solution, still hang beside hospital beds.

Practice habit. Before predicting water movement, write the solute concentration on each side of the membrane and draw the arrow toward the higher number.

Review first. Biology 3.3 covers diffusion, osmosis and the potato-core lab; this lesson applies the same ideas to blood, IV fluids and the gut.

WORKED EXAMPLES

Example 1. Normal saline is 0.9 percent NaCl: 9 g of salt per liter. The molar mass of NaCl is 58.44 g/mol. Find its osmolarity and compare it with plasma (about 285–295 mOsm/L).

Show solution

1. moles per liter = 9 ÷ 58.44 = 0.154 mol/L
2. Each NaCl separates into Na^+ and Cl^-: 2 particles.
3. 0.154 × 2 = 0.308 osmol/L ≈ 308 mOsm/L
4. This is close to plasma, so the fluid is treated as isotonic.

Answer: About 308 mOsm/L: isotonic

Example 2. Predict what 3 percent saline (30 g NaCl per liter) does to red blood cells.

Show solution

1. 30 ÷ 58.44 = 0.513 mol/L; × 2 = about 1027 mOsm/L
2. That is more than three times plasma: strongly hypertonic.
3. Water leaves the cells by osmosis.

Answer: The cells shrink (crenate). Doctors use small amounts of such fluid only for special purposes, such as drawing water out of a swollen brain.

Example 3. A gummy bear weighed 2.40 g before and 6.12 g after a day in plain water. Find the percent change.

Show solution

1. (6.12 − 2.40) ÷ 2.40 × 100
2. = 3.72 ÷ 2.40 × 100 = 155%

Answer: +155%: it took up water

PRACTICE

CONCEPT CHECKS

1. Easy What is the difference between passive and active transport?

   Show answer

   Passive transport moves substances down their gradient without the cell's energy; active transport moves them against the gradient using energy (ATP).

2. Easy Which of these cross the lipid bilayer directly, without a protein: oxygen, glucose, Na^+, carbon dioxide?

   Show answer

   Oxygen and carbon dioxide.

3. Medium Predict what happens to red blood cells placed in (a) distilled water, (b) 0.9 percent saline, (c) 5 percent saline.

   Show answer

   (a) They swell and burst (hypotonic). (b) No change (isotonic). (c) They shrink and crenate (hypertonic).

4. Medium A bag of 5 percent dextrose holds 50 g of glucose (molar mass 180.16 g/mol) per liter. Find its osmolarity. Glucose does not split into ions.

   Show answer

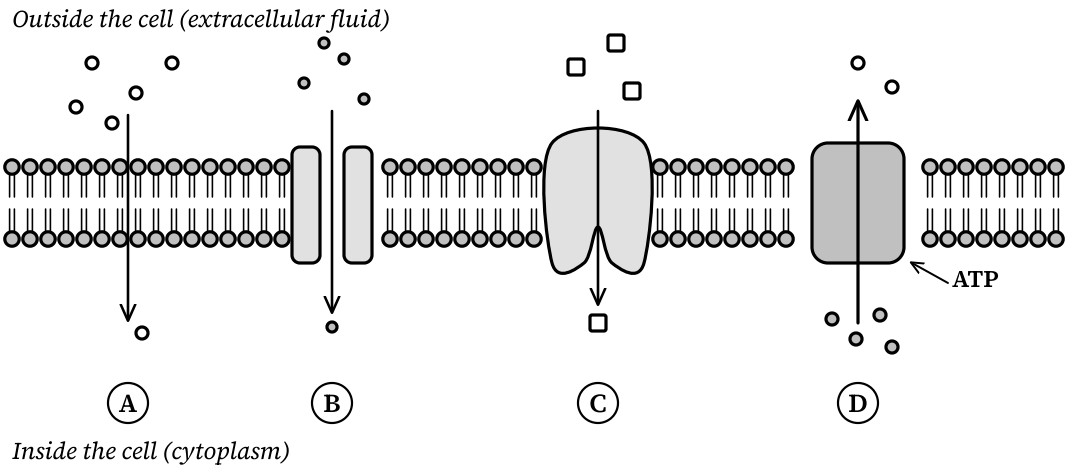
   About 278 mOsm/L, close to isotonic in the bag

   50 ÷ 180.16 = 0.278 mol/L × 1 particle

   (Once infused, cells use up the glucose, leaving free water, so it behaves like a hypotonic fluid in the body.)

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the four ways across the membrane lettered A–D. Which one needs ATP?



Show answer

A simple diffusion, B channel (facilitated diffusion), C carrier (facilitated diffusion), D pump (active transport). Only D needs ATP.

6. **Medium** A sodium-potassium pump completes 300 cycles. How many Na^+ ions are moved out, how many K^+ ions in, and how many ATP used?

Show answer

900 Na^+ out, 600 K^+ in, 300 ATP used.

7. **Medium** A 70 kg man is about 60 percent water. Estimate his total body water, intracellular fluid, extracellular fluid and plasma (take plasma as one-quarter of the extracellular fluid).

Show answer

Total 42 L; intracellular 28 L; extracellular 14 L; plasma about 3.5 L

$0.60 \times 70 = 42$; $\frac{2}{3} \times 42 = 28$; $\frac{1}{3} \times 42 = 14$; $\frac{1}{4} \times 14 = 3.5$

DISORDER AS A BROKEN MECHANISM

8. Hard Cholera toxin locks chloride channels open in the cells lining the small intestine. Explain step by step why this causes severe watery diarrhea and dehydration.

Show answer

Chloride pours out of the lining cells into the gut. Sodium follows to balance the charge. The salt makes the gut contents hypertonic, so water follows by osmosis, liters of it. The colon cannot absorb it all, so it leaves as watery stool, and the body loses water and salts faster than it can drink them.

TEST PREP

9. Easy Which IV fluid would make red blood cells burst?

A. 0.9% sodium chloride

B. lactated Ringer's solution

C. sterile water

D. 5% dextrose in the bag

Show answer

C. sterile water

10. Medium A gummy bear weighed 2.50 g before and 2.10 g after a day in strong salt water. Find the percent change.

Show answer

−16%

$(2.10 - 2.50) \div 2.50 \times 100 = -16$

11. Hard Why does oral rehydration solution contain both salt and sugar instead of plain water?

Show answer

The intestinal lining absorbs sodium and glucose together through a shared carrier. Taking them up raises the solute concentration inside the lining cells, so water follows by osmosis into the body. The carrier still works even during cholera, so salt plus sugar pulls water back in.

COMMON MISTAKES

- Saying salt or sugar moves in osmosis; osmosis is the movement of water.

- Mixing up hypotonic and hypertonic: “hyper” means more solute outside, so water leaves the cell.
- Forgetting that NaCl gives two particles when calculating osmolarity.
- Calling any transport through a protein “active”; channels and carriers are passive unless energy is used.

> **Make it a game · Gatekeeper.** The parent names a substance (oxygen, glucose, a sodium ion, water, insulin, a bacterium, carbon dioxide, potassium going in). Within five seconds the student names how it crosses: simple diffusion, channel, carrier, pump, endocytosis or exocytosis. Three in a row earns a bonus question on tonicity.

> **Scripture.** “As the hart panteth after the water brooks, so panteth my soul after thee, O God.” (Psalm 42:1, KJV)
>
> Thirst is the body’s alarm that its fluids are running low. The psalmist borrows it to describe a deeper thirst.

2.3 Epithelial and Connective Tissue

Mark up this lesson

OBJECTIVES

- Name the four tissue types and the main job of each.
- Classify epithelium by its layers and the shape of its surface cells, and match each kind to where it is found.
- Describe connective tissue (cells, fibers and ground substance), its main kinds and the body's membranes.

> **Warm-up.** Run your tongue along the inside of your cheek, press the tip of your nose and pinch the skin on the back of your hand. All three are made of tissues. How do they feel different, and what does each need to be good at?

WATCH

Tissues, Part 2 - Epithelial Tissue: Crash Course Anatomy & Physiology #3

CrashCourse · 10:16

https://www.youtube.com/watch?v=lUe_RI_m-Vg

> **WHEN TO WATCH**
> After the epithelium core ideas.

BACKUP VIDEO

Tissues, Part 3 - Connective Tissues: Crash Course Anatomy & Physiology #4

CrashCourse · 10:29

https://www.youtube.com/watch?v=D-SzmURNBH0

With the connective tissue core idea.

KEY TERMS

histology
The study of tissues, usually in thin stained slices under a microscope.

epithelium
Tissue of tightly packed cells that covers surfaces, lines cavities and tubes and forms glands.

basement membrane

A thin sheet of fibers on which an epithelium rests, joining it to the connective tissue below.

simple / stratified

One layer of cells / several layers. Epithelium is named by layers plus the shape of its surface cells: squamous (flat), cuboidal or columnar (tall).

connective tissue

Tissue of scattered cells in an extracellular matrix of fibers and ground substance; it supports, binds, protects, stores and transports.

collagen

The tough, rope-like protein fiber of connective tissue and the most abundant protein in the body.

gland

Epithelial tissue that secretes: exocrine glands use ducts (sweat, saliva); endocrine glands release hormones into the blood.

CORE IDEAS

The story. Around 1800, in a Paris hospital, the young physician Xavier Bichat sorted the materials of the body into 21 kinds by drying, boiling, soaking and examining them, without using a microscope. He called them *tissus,* French for woven fabrics, and argued that organs are built of tissues, so diseases should be studied tissue by tissue. With the microscope, histologists later reduced his list to four basic families: *epithelial* tissue covers and lines; *connective* tissue supports and binds; *muscle* tissue moves; *nervous* tissue senses and controls. Almost every organ uses all four.

Epithelium: the body's linings. Epithelial cells are packed edge to edge with little between them, joined by tight seals, so they make barriers. One surface faces the outside or a cavity; the other rests on a *basement membrane*. Epithelium has no blood vessels of its own and is fed by diffusion from the connective tissue beneath, but it replaces its cells quickly. Its jobs are to protect, absorb, filter, secrete and sense.

Naming epithelium. Give the number of layers, then the shape of the cells at the surface. *Simple squamous* (one layer of flat cells) lines the lung's air sacs and the inside of blood vessels, where substances must cross quickly. *Simple cuboidal* lines kidney tubules and small gland ducts. *Simple columnar*, often with microvilli and

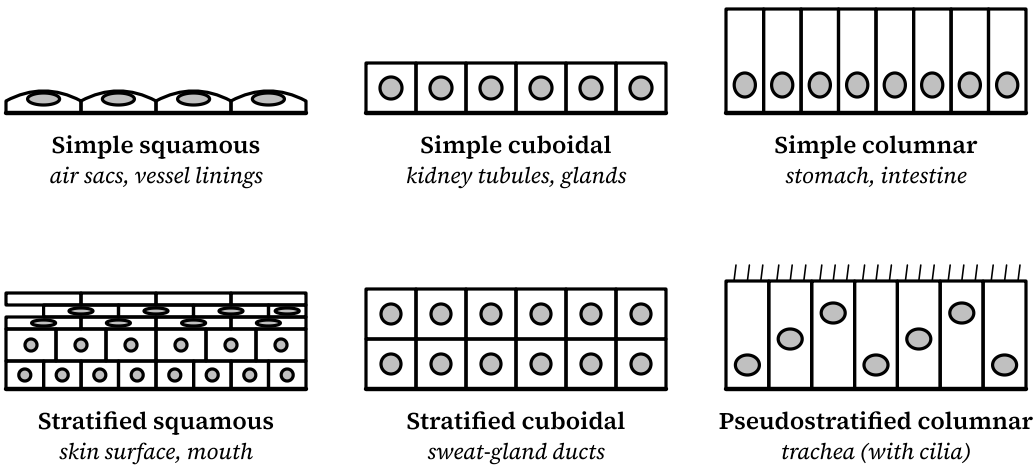
mucus-making goblet cells, lines the stomach and intestine. *Stratified squamous*, many layers flattening toward the surface, stands up to rubbing in the skin, mouth and esophagus. *Pseudostratified columnar* looks layered because its nuclei sit at different heights, but every cell touches the basement membrane; with cilia it sweeps mucus up the trachea. *Transitional* epithelium stretches as the bladder fills.

Glands. Glands are epithelium specialized to secrete. *Exocrine* glands deliver through ducts to a surface: sweat, oil, saliva, digestive juices. *Endocrine* glands have no ducts and release hormones into the blood: the thyroid, adrenals and pituitary. The pancreas is both.

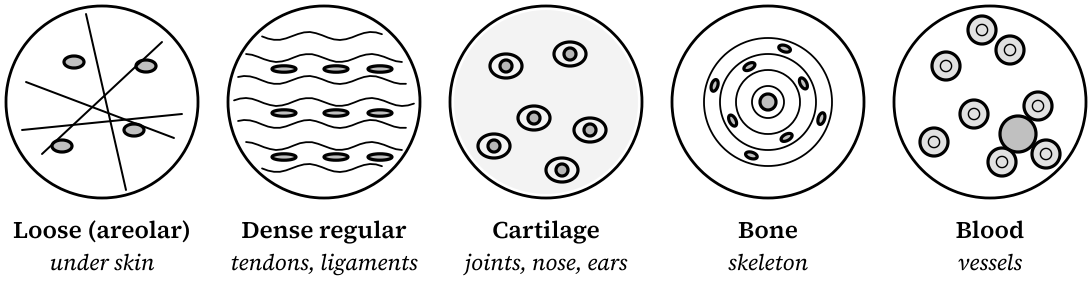
Connective tissue. Here the cells are scattered and the material between them, the *matrix*, does most of the work. The matrix has *fibers* (strong collagen, stretchy elastic fibers and fine reticular networks) and *ground substance*, a gel that holds water. Loose (areolar) tissue packs and cushions under the skin; adipose tissue stores fat. Dense regular tissue, with parallel collagen, forms tendons and ligaments that pull in one direction; dense irregular tissue, woven in all directions, forms the dermis. Cartilage is firm and smooth but has no blood vessels, so it heals slowly. Bone is matrix hardened with calcium phosphate. Blood is a connective tissue whose matrix is liquid plasma. Collagen is the most abundant protein in the body, and making it requires vitamin C.

Membranes. Tissues combine into sheets called membranes. *Mucous* membranes line passages open to the outside (mouth, airways, gut) and stay moist with mucus. *Serous* membranes line closed cavities (lesson 1.2). The *cutaneous* membrane is the skin. *Synovial* membranes, made of connective tissue only, line movable joints and make lubricating fluid.

Try it. In the lab you will find nearly every tissue in this lesson in a single chicken drumstick.



Epithelium is named by its number of layers and the shape of the cells at the surface. Each shape fits the job done where it is found.



Connective tissues differ mainly in their matrix: loose fibers, parallel collagen, firm gel, mineral or liquid.

> **Safety first.** Raw chicken can carry Salmonella. Wear gloves, keep the chicken on one cutting board, then wash the board, scissors and your hands with hot soapy water and wipe the counter.

LAB

Tissue Tour of a Chicken Drumstick

One drumstick holds epithelium, several connective tissues, muscle and nerve. You will find and test each.

You will need

- A raw chicken drumstick (thigh attached if possible), a cutting board, kitchen scissors, a small sharp knife for the parent, gloves, a magnifying glass, paper towels

Steps

1. Look at and feel the skin. Its outer surface is stratified squamous epithelium; the bumps are feather follicles.
2. Peel the skin back. Find the thin, web-like loose connective tissue that holds it to the muscle, and yellow adipose tissue.
3. Separate two muscles along their thin wrappings. Follow one to its shiny white tendon. Pull the tendon and watch the joint move. Try to stretch the tendon lengthwise, then try to tear it crosswise.
4. Find a fine white thread running near the bone: a nerve. Find small blood vessels.
5. With the parent's help, open the knee joint. Find the smooth, glassy cartilage on the bone ends and the ligaments holding the joint together. Cut the bone end to see the spongy interior and red marrow.
6. List every tissue found and its tissue family.

Check your work

- ☐ Why did the tendon resist stretching along its length? What does that tell you about its collagen?
- ☐ Which tissue did you find that had no visible blood vessels?

LAB NOTEBOOK

1. Labeled sketches of skin, tendon, cartilage and bone from the drumstick.
2. A table of the six kinds of epithelium with a location for each.

From history. Xavier Bichat (1771–1802) worked in Paris hospitals in the years after the French Revolution. Without a microscope, he studied hundreds of bodies and sorted their materials by how they behaved when dried, boiled, soaked or left to decay. His *General Anatomy* appeared in 1801, and he died the next year at only 30, yet his idea that organs are built from tissues founded histology.

Practice habit. Name an epithelium in two words, layers first and then the shape of the surface cells, and check it by asking what job that place must do.

Career connection. Histotechnicians cut tissue samples into slices a few micrometers thick and stain them so that a pathologist can diagnose disease, often while the patient is still in surgery. Most train in an associate-degree or certificate program and earn certification from the American Society for Clinical Pathology; medical laboratory scientists usually hold a bachelor's degree. Recognizing the tissues in this lesson is the first skill they learn.

WORKED EXAMPLES

Example 1. Name the epithelium: many layers of cells, those at the base cuboidal and those at the surface flat; it lines the esophagus.

Show solution

1. Many layers: stratified.
2. Name by the surface cells: flat, so squamous.
3. The esophagus is moist, not dry skin, so it is not keratinized.

Answer: Stratified squamous (non-keratinized) epithelium

Example 2. Oxygen crosses the lung's barrier of simple squamous epithelium about 0.5 µm thick. If the barrier were instead the 50 µm stratified squamous epithelium of thin skin, how much slower would diffusion across it be?

Show solution

1. Diffusion rate is roughly proportional to 1 ÷ thickness.
2. 50 µm ÷ 0.5 µm = 100

Answer: About 100 times slower; this is why gas exchange needs the thinnest possible lining

Example 3. A tendon and the dermis are both dense connective tissue. Why is the collagen of a tendon parallel and that of the dermis woven in all directions?

Show solution

1. A tendon is pulled in one direction only, from muscle to bone: parallel fibers resist that pull best (dense regular).
2. Skin is pulled from every direction: crisscrossed fibers resist all of them (dense irregular).

Answer: Fiber direction matches the direction of the forces each tissue must resist

PRACTICE

CONCEPT CHECKS

1. Easy Name the four tissue types and give one job of each.

   Show answer

   Epithelial (cover, line, secrete), connective (support, bind, store, transport), muscle (move), nervous (sense, control).

2. Easy List four features of epithelial tissue.

   Show answer

   Cells tightly packed with little matrix; rests on a basement membrane; no blood vessels; a free surface; replaces cells quickly.

3. Medium Name the epithelium you would expect in (a) the air sacs of the lungs, (b) a kidney tubule, (c) the small-intestine lining, (d) the trachea, (e) the skin surface.

   Show answer

   (a) Simple squamous, (b) simple cuboidal, (c) simple columnar, (d) pseudostratified ciliated columnar, (e) keratinized stratified squamous.

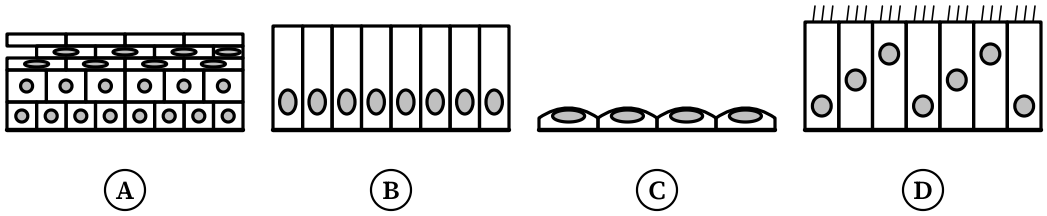
4. Medium Name the three parts of connective tissue. Which fiber gives strength and which gives stretch?

   Show answer

   Cells, fibers and ground substance. Collagen gives strength; elastic fibers give stretch.

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name each kind of epithelium A–D and one place it is found.



Show answer

A stratified squamous (skin, mouth, esophagus); B simple columnar (stomach, intestine); C simple squamous (air sacs, blood-vessel lining); D pseudostratified ciliated columnar (trachea).

6. **Medium** Exocrine or endocrine: (a) sweat gland, (b) thyroid, (c) salivary gland, (d) the pancreas?

Show answer

(a) Exocrine, (b) endocrine, (c) exocrine, (d) both: it sends enzymes through a duct and releases insulin into the blood.

7. **Medium** Fluid in the lungs thickens the air-sac barrier from 0.5 µm to 2.0 µm. By about what factor does the rate of oxygen diffusion fall?

Show answer

About 4 times slower

$2.0 \div 0.5 = 4$

DISORDER AS A BROKEN MECHANISM

8. Hard Sailors on long voyages without fresh fruit got scurvy: bleeding gums, bruising, and old wounds that reopened. Vitamin C is needed by an enzyme that finishes and stabilizes new collagen fibers. Explain the symptoms as a broken mechanism.

Show answer

Without vitamin C, new collagen is weak and falls apart. Connective tissue constantly replaces its collagen, so tissues that depend on it fail: vessel walls leak (bleeding gums, bruises), and the collagen holding healed wounds together weakens until the scars reopen. Fresh fruit restores vitamin C and the collagen.

TEST PREP

9. Easy Which tissue has no blood vessels and therefore heals slowly?

A. bone

B. cartilage

C. areolar tissue

D. blood

Show answer

B. cartilage

10. Hard A broken bone usually heals in weeks, but torn knee cartilage often never heals well. Explain the difference.

Show answer

Bone is richly supplied with blood vessels that bring cells, nutrients and repair signals. Cartilage has no vessels; its few cells are fed by slow diffusion through the matrix, so new tissue forms very slowly.

COMMON MISTAKES

- Naming epithelium by the cells at the bottom; use the shape at the free surface.
- Thinking pseudostratified epithelium has several layers; it has one, with nuclei at different heights.
- Forgetting that blood and bone are connective tissues.
- Thinking “connective” means only things that join; connective tissue also stores fat, transports and protects.

Make it a game · Tissue Detective. The parent names a place in the body: inside of the cheek, Achilles tendon, ear flap, kidney tubule, trachea, fat on the hip, air sac, bladder, a drop of blood. The student scores one point for the tissue family and two more for the exact kind. First to 15 points wins.

Scripture. “From whom the whole body fitly joined together and compacted by that which every joint supplieth, according to the effectual working in the measure of every part, maketh increase of the body unto the edifying of itself in love.” (Ephesians 4:16, KJV)

The body is “fitly joined together and compacted”: tissues bound to tissues by connective fibers, each part supplying something to the whole.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

2.4 Muscle and Nervous Tissue; How Tissues Heal

Mark up this lesson

OBJECTIVES

- Compare skeletal, cardiac and smooth muscle tissue in structure, control and location.
- Describe the parts of a neuron and the jobs of supporting glial cells, including myelin.
- Explain inflammation and tissue repair, and predict which tissues regenerate and which form scars.

> **Warm-up.** Hold a heavy book straight out in front of you until your arm trembles. You chose to use those muscles. Now try to make your heart beat slower, or your stomach churn, just by deciding to. What is different about those muscles?

WATCH

Tissues, Part 1: Crash Course Anatomy & Physiology #2

CrashCourse · 10:43

https://www.youtube.com/watch?v=i5tR3csCWYo

> **WHEN TO WATCH**
> After the muscle and nervous tissue core ideas.

BACKUP VIDEO

Body Tissues (the 4 Types)

Amoeba Sisters · 15:57

https://www.youtube.com/watch?v=5j8j7BhCCEg

As a review of all four tissue types.

KEY TERMS

skeletal muscle

Long, striated, many-nucleated fibers attached to bones; under voluntary control.

cardiac muscle

Striated, branched cells with one nucleus each, joined by intercalated discs; found only in the heart; involuntary.

smooth muscle

Spindle-shaped cells without stripes in the walls of hollow organs and vessels; involuntary.

neuron

A nerve cell that carries electrical signals: dendrites receive, the cell body integrates, the axon sends.

neuroglia (glial cells)

Supporting cells of nervous tissue that nourish, protect and insulate neurons; some make myelin.

myelin sheath

Fatty wrapping around many axons that speeds signals; gaps in it are called nodes.

regeneration and fibrosis

Repair by replacing damaged cells with the same kind of cells, or by filling the gap with collagen scar tissue.

inflammation

The first response to injury: widened, leaky vessels bring blood, fluid and white cells, causing redness, heat, swelling and pain.

CORE IDEAS

The story. In the 1780s in Bologna, Luigi Galvani noticed that the legs of dissected frogs twitched when a metal scalpel touched a nerve while an electrical machine sparked nearby, and later when the legs hung from brass hooks on an iron rail. In 1791 he published his idea of "animal electricity." His friend and rival Alessandro Volta argued that the electricity came from the two metals, and his experiments led him to build the first battery in 1800. Both were partly right: nerves and muscles do run on electricity, carried not by metal wires but by ions crossing membranes.

Muscle tissue: three kinds. Muscle cells, called fibers, shorten and pull. *Skeletal* muscle fibers are long cylinders, some many centimeters long, with many nuclei and cross stripes (striations); they pull on bones through tendons and obey our will. *Cardiac* muscle is also striated, but its cells are short, branched and have one central nucleus; they are joined end to end by *intercalated discs* that pass the electrical signal from cell to cell so the heart contracts as one, and they beat without any command from us. *Smooth* muscle cells are spindle-shaped, unstriped and slow but tireless; they squeeze food through the gut, narrow blood vessels and empty the bladder, all involuntarily.

What the stripes are. The striations of skeletal and cardiac muscle are rows of overlapping protein filaments, actin and myosin, arranged in repeating units called

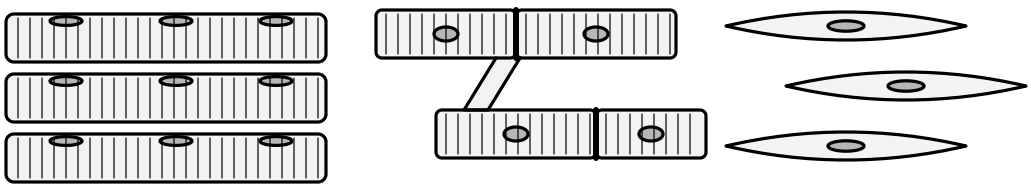
sarcomeres. When the filaments slide past each other, the muscle shortens. The PE course tells the story of the 1954 discovery in PE 9, lesson 4.1, and Unit 4 of this course takes it further.

Nervous tissue. A *neuron* receives signals on its branching dendrites, combines them in its cell body and sends its own signal down a single *axon* to axon terminals that pass it to the next cell. Some axons are a meter long, running from the spine to the toes. Neurons are outnumbered by *glial cells*, which feed, guard and clean up after them. Some glial cells wrap axons in a fatty *myelin sheath*: Schwann cells in the nerves of the body and oligodendrocytes in the brain and spinal cord. The signal jumps from gap to gap (node to node) along a myelinated axon, reaching speeds of around 100 meters per second, against about 1 meter per second in thin unmyelinated fibers.

How tissues heal. Injury first brings *inflammation*. Blood vessels widen and leak, so the area becomes red, hot, swollen and painful; clotting seals torn vessels; white blood cells clear away bacteria and debris. Then comes repair. In *regeneration* the same kind of cells divide and replace what was lost. In *fibrosis* fibroblasts fill the gap with collagen, forming a scar that holds the tissue together but cannot do its work. Epithelium, bone, blood and loose connective tissue regenerate well; smooth muscle and dense connective tissue moderately; skeletal muscle only a little; heart muscle and the neurons of the brain and spinal cord hardly at all. That is why a heart attack leaves a permanent scar and a weaker pump, while a scraped knee heals without a trace.

Helping healing. Repair needs a good blood supply, protein and vitamin C for collagen, and time. Young people heal faster than old. Gentle, guided movement during recovery helps healing tissue line up along the forces it will bear, which is the daily work of physical therapists.

Try it. In the lab you will measure your reaction time with a falling ruler and watch your muscles fatigue with a clothespin.

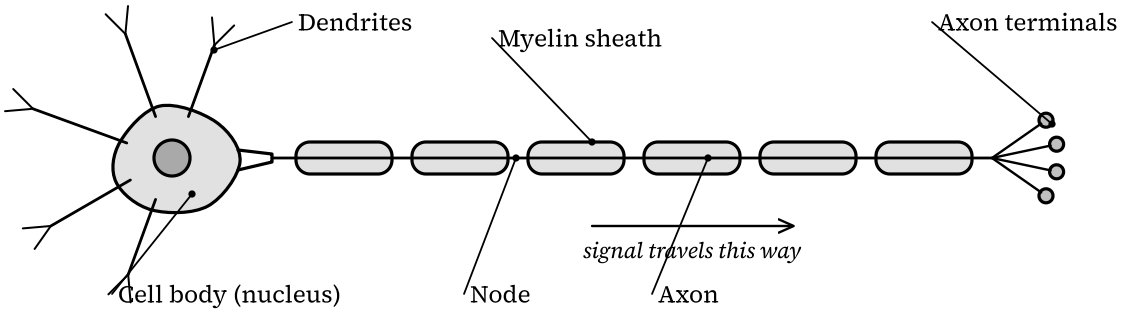


Skeletal
striated, many nuclei, voluntary

Cardiac
striated, branched, discs

Smooth
no stripes, spindle, involuntary

The three kinds of muscle tissue. Stripes mark the regular rows of actin and myosin.



A neuron. Myelin wrapped by glial cells lets the signal jump from node to node.

> **Safety first.** Drop the ruler from just above the catcher's hand and keep it away from faces. Stop the clothespin test if your hand cramps or hurts.

LAB

Reaction Time and Muscle Fatigue

You will time the path from eye to brain to finger muscles, then measure how fast a working muscle tires.

You will need

- A 30-cm ruler, a wooden spring clothespin, a timer, a partner, graph paper

Steps

1. Ruler drop: your partner holds the ruler by the top end with its zero mark between your open thumb and finger. Without warning they let go; catch it as fast as you can. Record the distance it fell in cm. Do five trials with each hand.
2. Convert each average distance to time with $t = \sqrt{(2d \div g)}$, using d in meters and $g = 9.8\ m/s^2$.
3. Clothespin test: count how many times you can squeeze the clothespin fully open with thumb and index finger in 30 seconds. Rest 5 seconds and repeat, for six trials in all.
4. Graph squeezes against trial number.

Check your work

- ☐ Which kind of muscle tissue did you use? Which tissues carried the signal?
- ☐ Describe the fatigue curve. What do you think the muscle fibers were running short of?

LAB NOTEBOOK

1. Reaction-time and fatigue data with your graph.
2. Side-by-side sketches of skeletal, cardiac and smooth muscle and a labeled neuron.

KEY FORMULAS

$$t = \sqrt{\frac{2d}{g}} \qquad g = 9.8\ \text{m/s}^2$$

$$\text{time} = \frac{\text{distance}}{\text{conduction speed}}$$

From history. Galvani's nephew Giovanni Aldini later toured Europe applying electric current to the muscles of animals, which twitched dramatically. Behind the showmanship lay a real discovery: Galvani had shown that a nerve can carry an electrical signal that makes a muscle contract, the foundation of everything in Unit 5.

Practice habit. When you study any injury, first ask whether that tissue can make new cells of its own kind; if not, expect a scar.

Review first. PE 9, lesson 4.1 (how a muscle contracts) and Biology 10.4 (nerves and senses) are good companions to this lesson.

WORKED EXAMPLES

Example 1. A ruler falls 15.0 cm before you catch it. What is your reaction time?

Show solution

1. d = 0.150 m, g = 9.8 m/s²
2. t = √(2 × 0.150 ÷ 9.8) = √0.0306
3. t = 0.175 s

Answer: About 0.17–0.18 s

Example 2. A pain signal travels 1.0 m from a toe to the spinal cord. How long does it take along a myelinated fiber at 100 m/s, and along an unmyelinated fiber at 1 m/s?

Show solution

1. time = distance ÷ speed
2. Myelinated: 1.0 ÷ 100 = 0.010 s = 10 ms
3. Unmyelinated: 1.0 ÷ 1 = 1.0 s

Answer: 10 ms versus 1 s: myelin makes the signal 100 times faster (this is why you feel the sharp first pain of a stubbed toe before the slow ache)

Example 3. Predict how each heals: (a) a scraped knee that removed only the epidermis, (b) heart muscle killed in a heart attack, (c) a broken forearm bone, (d) a cut through the spinal cord.

Show solution

1. Ask: can this tissue make new cells of its own kind?
2. (a) Epithelium regenerates quickly.
3. (b) Cardiac muscle barely divides: the dead area becomes scar.
4. (c) Bone regenerates well.
5. (d) Central nervous system neurons barely regenerate: function below the cut is usually lost.

Answer: (a) regeneration, (b) scar (fibrosis), (c) regeneration, (d) little or no regeneration

PRACTICE

CONCEPT CHECKS

1. Easy For skeletal, cardiac and smooth muscle, state whether each is striated, whether it is voluntary, how many nuclei each cell has, and where it is found.

   Show answer

   Skeletal: striated, voluntary, many nuclei, attached to bones. Cardiac: striated, involuntary, one nucleus, heart wall. Smooth: not striated, involuntary, one nucleus, walls of hollow organs and vessels.

2. **Easy** Name the parts of a neuron in the order a signal passes through them.

Show answer

Dendrites, cell body, axon, axon terminals.

3. **Medium** A ruler falls 21.0 cm before it is caught. Find the reaction time.

Show answer

About 0.21 s

$\sqrt{(2 \times 0.210 \div 9.8)} = 0.207$

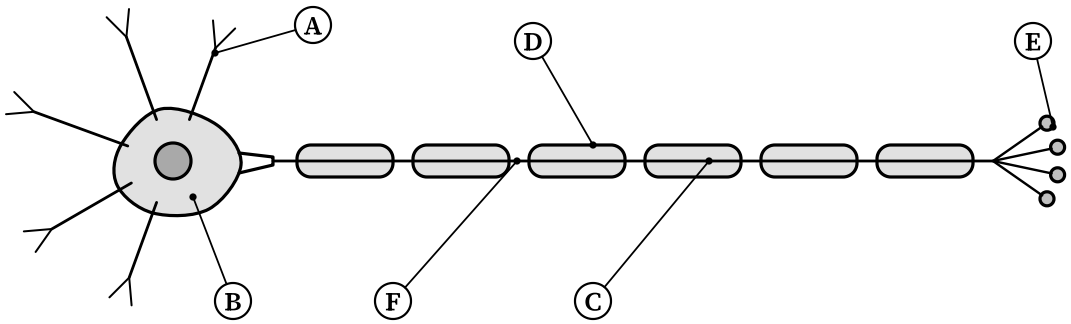
4. **Medium** A signal must travel 0.80 m. How long does it take at 60 m/s? At 0.8 m/s?

Show answer

About 13 ms at 60 m/s (0.80 ÷ 60 = 0.0133 s); 1.0 s at 0.8 m/s.

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the parts of the neuron lettered A–F.



Show answer

A dendrites, B cell body (with nucleus), C axon, D myelin sheath, E axon terminals, F node (gap in the myelin).

6. **Medium** Name the four classic signs of inflammation and explain the cause of each.

Show answer

Redness and heat: widened vessels bring more warm blood. Swelling: leaky capillaries let fluid into the tissue. Pain: swelling presses on nerve endings, and chemicals released by damaged cells stimulate them.

7. Medium Regeneration or scar? (a) liver, (b) cardiac muscle, (c) epidermis, (d) a neuron in the brain, (e) bone.

Show answer

(a) Regeneration, (b) scar, (c) regeneration, (d) little or none, (e) regeneration.

DISORDER AS A BROKEN MECHANISM

8. Hard In multiple sclerosis the immune system attacks the myelin of the brain and spinal cord. Using the job of myelin, explain why patients can have weakness, numbness and blurred vision, and why symptoms differ from person to person.

Show answer

Myelin lets signals jump quickly from node to node. Where it is stripped away, signals slow, weaken or fail to arrive, so commands to muscles (weakness), messages from the skin (numbness) and signals along the optic nerve (blurred vision) are disrupted. The damaged patches occur in different places in different people, so the symptoms depend on which pathways are hit.

TEST PREP

9. Easy Intercalated discs are found in

A. skeletal muscle

B. cardiac muscle

C. smooth muscle

D. nervous tissue

Show answer

B. cardiac muscle

10. Hard Explain why a heart attack leaves a person with a permanently weaker heart, while a broken thigh bone often heals almost as strong as before.

Show answer

Heart-muscle cells barely divide, so dead muscle is replaced by collagen scar, which holds but cannot contract: the pump loses force. Bone has active bone-building cells and a rich blood supply, so it regenerates true bone and then remodels it to its former shape and strength.

COMMON MISTAKES

- Thinking “smooth” muscle is the kind we control; smooth muscle is involuntary.
- Saying lost neurons and heart cells are easily replaced; they are not.
- Thinking a scar is the same tissue as before; it is collagen that holds but does not work.
- Calling myelin part of the neuron; it is made by glial cells wrapped around the axon.

> **Make it a game · Heal or Scar?.** The parent calls an injury (sunburn peel, torn hamstring, heart attack, cut lip, broken wrist, burned-out nerve, liver injury). The student shouts “Heal!” or “Scar!” and names the tissue in five seconds. Wrong answers mean ten clothespin squeezes.

> **Scripture.** “He giveth power to the faint; and to them that have no might he increaseth strength.” (Isaiah 40:29, KJV)
>
> You will measure how quickly working muscle tires. The prophet points past muscle to a strength that does not run out.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

UNIT 2

Cells and Tissues

Every organ is built from a few kinds of tissue, and every tissue from cells. This unit reviews the cell with a clinician's eye, follows water, ions and nutrients across membranes in the body's fluid compartments, and sorts the body's cells into the four tissue families: epithelial, connective, muscle and nervous. It ends with how tissues heal and why some heal without a trace while others scar.

Labs: cheek cells under the microscope, gummy-bear osmosis and IV fluids, a tissue tour of a chicken drumstick, and a reaction-time and muscle-fatigue lab.

PREREQUISITES

- Unit 1 (levels of organization, homeostasis)
- Biology 3.1–3.4 (cells and membranes) and 6.3 (protein synthesis), or equivalent

MASTERY CHECKLIST

- ☐ I can name the main organelles and explain how a cell's structure fits its job.
- ☐ I can explain diffusion, osmosis and active transport and choose an isotonic IV fluid.
- ☐ I can classify epithelium and connective tissue and say where each is found.
- ☐ I can compare the three muscle tissues, describe a neuron and predict whether an injured tissue will regenerate or scar.

LESSONS IN THIS UNIT

2.1	**The Cell Reviewed for Anatomy and Physiology**	3 sessions of 45 minutes
2.2	**Membrane Transport in the Body**	4 sessions of 45 minutes
2.3	**Epithelial and Connective Tissue**	4 sessions of 45 minutes
2.4	**Muscle and Nervous Tissue; How Tissues Heal**	4 sessions of 45 minutes

Unit 2 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. 8 pts **Lesson 2.1**

   Match each organelle to its job: mitochondrion, rough ER, Golgi apparatus, lysosome. Jobs: packages proteins; makes ATP; digests worn-out parts; makes proteins for export.

2. 8 pts **Lesson 2.1**

   Explain how the structure of a red blood cell and of an intestinal lining cell each fit their jobs.

3. 8 pts **Lesson 2.2**

   Distinguish simple diffusion, facilitated diffusion and active transport, with one example of a substance moved by each.

4. 8 pts **Lesson 2.2**

   A nurse is about to hang a liter of sterile water as an IV. Explain what would happen to the patient’s red blood cells and name a safe fluid instead.

5. 8 pts **Lesson 2.2**

   Find the osmolarity of a 0.45 percent NaCl solution (4.5 g per liter; molar mass 58.44 g/mol). Is it isotonic, hypotonic or hypertonic to plasma (about 290 mOsm/L)?

6. 8 pts **Lesson 2.3**

   Name the epithelium and explain how its structure fits its job: (a) the air sacs of the lungs, (b) the skin surface.

7. 8 pts **Lesson 2.3**

   Name the kind of connective tissue: (a) tendon, (b) the matrix is liquid plasma, (c) stores fat under the skin, (d) glassy and smooth on bone ends, with no blood vessels.

8. **8 pts** **Lesson 2.4**

   Which muscle tissue: (a) branched cells with intercalated discs, (b) spindle cells in the wall of the intestine, (c) long multinucleate striated fibers attached to bones?

9. **8 pts** **Lesson 2.4**

   A ruler falls 18.0 cm before a student catches it. Find the reaction time ($g = 9.8\ m/s^2$).

10. **8 pts** **Lesson 2.4**

    Explain why a cut in the epidermis heals without a trace while damage to heart muscle leaves a scar.

LAB AND DATA

11. **8 pts** **Lesson 2.2**

    Gummy bears were soaked for 24 hours. Mass before and after: plain water 2.50 g → 5.75 g; 0.9% salt 2.48 g → 4.22 g; 10% salt 2.52 g → 2.27 g. (a) Find the percent change for each. (b) Which solution made the bear lose mass, and why?

SHORT ESSAY

12. **12 pts**

    Virchow said that every disease is a disease of cells. Choose one disease from this unit (sickle-cell disease, Tay-Sachs, cholera, scurvy or multiple sclerosis) and explain it as a broken mechanism, tracing the fault from molecule or cell to tissue and to the whole person.

ANSWER KEY

1. Mitochondrion: makes ATP. Rough ER: makes proteins for export. Golgi: packages proteins. Lysosome: digests worn-out parts.
2. Red cell: no nucleus or mitochondria, leaving room for hemoglobin and not using the oxygen it carries; small flexible disc for passing through capillaries. Intestinal cell: microvilli multiply the surface area for absorption.
3. Simple diffusion: through the lipid bilayer, downhill (oxygen, CO_2). Facilitated: downhill through a channel or carrier (Na^+ through a channel, glucose on a carrier). Active: uphill using ATP (Na^+ out and K^+ in by the pump).
4. Sterile water is hypotonic, so water would rush into red cells by osmosis and many would swell and burst (hemolysis). Use an isotonic fluid such as 0.9% saline or lactated Ringer's.
5. About 154 mOsm/L: hypotonic

   $4.5 \div 58.44 = 0.0770$ mol/L $\times 2 = 0.154$ osmol/L
6. (a) Simple squamous: one thin layer for fast diffusion of gases. (b) Keratinized stratified squamous: many layers, tough surface cells that resist rubbing and water loss and are replaced from below.
7. (a) Dense regular, (b) blood, (c) adipose, (d) hyaline cartilage.
8. (a) Cardiac, (b) smooth, (c) skeletal.
9. About 0.19 s

   $\sqrt{(2 \times 0.180 \div 9.8)} = 0.192$
10. Epidermal cells divide readily and regenerate the same tissue. Cardiac muscle cells barely divide, so fibroblasts fill the gap with collagen scar tissue.
11. (a) Plain water +130%; 0.9% salt +70.2%; 10% salt −9.9%. (b) The 10% salt water: it was hypertonic to the bear, so water moved out.
12. Look for: the normal mechanism stated correctly; the exact fault (changed hemoglobin, missing lysosomal enzyme, channels locked open, unstable collagen, stripped myelin); a clear chain from cell to tissue to organ and symptoms; and, where fitting, how treatment restores or bypasses the broken step.

UNIT 3

Skin and Bones

The skin is the body's largest organ and its first defense; bone is living tissue that grows, heals and stores minerals. This unit builds the integumentary system layer by layer, treats burns and wounds the way nurses and EMTs do, with the rule of nines, then studies bone tissue, growth and fracture repair, and names the 80 bones of the axial skeleton and the 126 of the appendicular skeleton.

Labs: fingerprints and the two-point touch test, a hand-tracing burn-area lab, the baked bone and the vinegar bone, a spool spine with a morning-and-evening height test, and body landmarks and proportions.

PREREQUISITES

- Units 1–2
- Biology 10.1 (Vesalius and the skeleton) is helpful but not required

MASTERY CHECKLIST

- ☐ I can describe the layers of the skin and the jobs of its cells, glands and hair, and explain how skin helps regulate temperature.
- ☐ I can classify burns by depth, estimate burned area with the rule of nines and describe the phases of wound healing.
- ☐ I can describe bone tissue, bone growth, calcium balance and fracture repair.
- ☐ I can name the major bones of the axial and appendicular skeleton and find key landmarks on my own body.

LESSONS IN THIS UNIT

3.1	**Skin: Layers and Accessory Structures**	4 sessions of 45 minutes
3.2	**Burns, Wounds and Healing**	4 sessions of 45 minutes
3.3	**Bone Tissue, Growth and Fracture Repair**	4 sessions of 45 minutes
3.4	**The Axial Skeleton**	4 sessions of 45 minutes

Unit 3 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **7 pts** **Lesson 3.1**

   Name the three layers of the skin and one important feature of each.

2. **7 pts** **Lesson 3.1**

   Explain how the skin acts as an effector when the body overheats and when it is chilled.

3. **7 pts** **Lesson 3.1**

   What does melanin do, and where is it made?

4. **8 pts** **Lesson 3.2**

   An adult has partial-thickness burns of the whole head, the front of the trunk and the front of both arms, and a superficial sunburn on the back. Estimate the TBSA to count.

5. **8 pts** **Lesson 3.2**

   A 70 kg patient has 30% TBSA burns. Using the Parkland formula, find the 24-hour fluid and the hourly rate for the first 8 hours.

6. **7 pts** **Lesson 3.2**

   Name the four phases of wound healing in order.

7. **7 pts** **Lesson 3.3**

   Where does a long bone grow in length, and why does growth in height stop in the late teens or early twenties?

8. **8 pts** **Lesson 3.3**

   Trace the negative feedback loop that restores blood calcium when it falls.

9. **7 pts** **Lesson 3.3**

   List the four stages of fracture repair in order.

10. **7 pts** **Lesson 3.4**

    Give the number of vertebrae in each region of the adult spine and name the two curves present at birth.

11. **7 pts** **Lesson 3.4**

    Name the bones that form (a) the forehead, (b) the back of the skull, (c) the lower jaw, (d) the cheek.

12. **7 pts** **Lesson 3.5**

    Name the bones of the upper limb from shoulder to fingertip, with the number of each in the hand.

SHORT ESSAY

13. **13 pts**

    Bone is “living tissue.” Defend this statement using bone cells, remodeling and Wolff’s law, calcium homeostasis, growth at the epiphyseal plates and fracture repair. End with one practical way a teenager can build strong bones for life.

ANSWER KEY

1. Epidermis: stratified squamous epithelium with no blood vessels, renewed from below. Dermis: connective tissue with vessels, nerves, glands and follicles. Hypodermis: loose and fat tissue that anchors, insulates and cushions.
2. Overheating: dermal vessels widen to bring heat to the surface and sweat glands secrete; evaporation removes heat. Chilled: dermal vessels narrow to keep warm blood in the core; arrector pili raise goose bumps.
3. It absorbs ultraviolet light, shielding the nuclei of epidermal cells from DNA damage. It is made by melanocytes in the stratum basale and passed to keratinocytes.
4. 36%

   head 9 + front trunk 18 + front of arms 4.5 + 4.5 = 36; the superficial burn is not counted
5. 8,400 mL; 525 mL/h

   4 × 70 × 30 = 8,400; 4,200 ÷ 8 = 525
6. Hemostasis, inflammation, proliferation, remodeling.
7. At the epiphyseal (growth) plates of cartilage. The plates are eventually replaced by bone and close into epiphyseal lines, so no more cartilage remains to grow.
8. Low blood calcium is sensed by the parathyroid glands, which release PTH; osteoclasts release calcium from bone, the kidneys keep calcium and activated vitamin D increases absorption in the gut; blood calcium rises and PTH falls.
9. Hematoma, soft (fibrocartilaginous) callus, hard (bony) callus, remodeling.
10. Cervical 7, thoracic 12, lumbar 5, sacrum (5 fused), coccyx (about 4 fused). The thoracic and sacral curves are present at birth.
11. (a) Frontal, (b) occipital, (c) mandible, (d) zygomatic.
12. Humerus; radius and ulna; 8 carpals; 5 metacarpals; 14 phalanges.
13. Look for: osteoblasts, osteocytes and osteoclasts and their jobs; continual remodeling (about 10% a year) and adaptation to load (tennis arm, astronauts); PTH and vitamin D keeping blood calcium steady; growth in length at the plates; the four-stage repair of a fracture; and weight-bearing exercise with enough calcium and vitamin D while peak bone mass is being built.

3.1 Skin: Layers and Accessory Structures

Mark up this lesson

OBJECTIVES

- Name the layers of the skin and the strata of the epidermis, and the job of each kind of epidermal cell.
- Describe the dermis and hypodermis and the accessory structures: hair, nails, oil and sweat glands.
- Explain how the skin protects, senses, regulates temperature and makes vitamin D.

> **Warm-up.** Press a fingertip onto a clean drinking glass and look at the print with a magnifying glass. Why do you think fingertips have ridges at all? Write two guesses.

WATCH

The Integumentary System, Part 1 - Skin Deep: Crash Course Anatomy & Physiology #6

CrashCourse · 9:40

https://www.youtube.com/watch?v=Orumw-PyNjw

> **WHEN TO WATCH**
> After the epidermis core idea.

BACKUP VIDEO

The Integumentary System, Part 2 - Skin Deeper: Crash Course Anatomy & Physiology #7

CrashCourse · 9:57

https://www.youtube.com/watch?v=EN-x-zXXVwQ

With the dermis and accessory structures.

KEY TERMS

integumentary system

The skin and its accessory structures: hair, nails and glands.

epidermis

The outer layer of skin: keratinized stratified squamous epithelium with no blood vessels.

keratinocyte

The main epidermal cell; it fills with the tough protein keratin and dies as it is pushed to the surface.

melanocyte

A cell in the deepest epidermal layer that makes the pigment melanin, which shields cell nuclei from ultraviolet light.

dermis

The thick connective-tissue layer under the epidermis, holding blood vessels, nerves, glands and hair follicles.

hypodermis

The layer of loose connective and fat tissue under the dermis (subcutaneous layer); it anchors, insulates and cushions.

sebaceous gland

An oil gland that empties sebum into a hair follicle, keeping hair and skin supple.

eccrine sweat gland

A coiled gland that releases watery sweat onto the skin; evaporation cools the body.

CORE IDEAS

Why the skin matters. The skin is the body's largest organ: in an adult it covers roughly 1.5 to 2 square meters. It keeps water in and germs out, blocks much ultraviolet light, senses touch, pressure, pain and temperature, helps hold body temperature near 37 °C, and starts the making of vitamin D. Nurses read it constantly: its color, warmth, moisture and the way it springs back tell them about circulation, fever and hydration.

The epidermis. The epidermis is keratinized stratified squamous epithelium with no blood vessels of its own. In its deepest layer, the *stratum basale*, stem cells divide constantly. New keratinocytes are pushed upward through the *stratum spinosum* and *stratum granulosum*, filling with keratin and sealing lipids as they go, until they die and form the *stratum corneum*, a tough, waterproof wall of flat dead cells that are shed and replaced. The trip takes about a month. Palms and soles add a clear *stratum lucidum* and a much thicker corneum. Among the keratinocytes are melanocytes, immune sentinel cells (dendritic or Langerhans cells) that catch invaders, and Merkel cells that sense light touch.

Pigment as an umbrella. Melanocytes pass packets of melanin to nearby keratinocytes, where the pigment gathers over the nucleus like an umbrella against

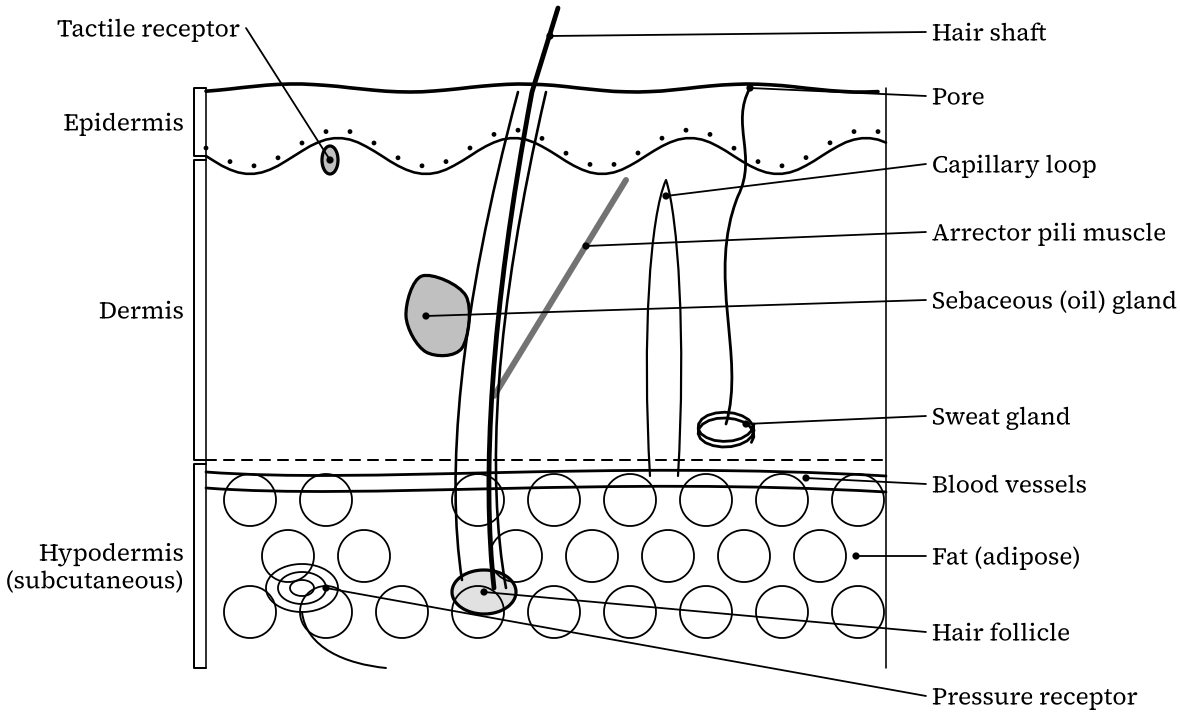
ultraviolet light. People of every complexion have about the same number of melanocytes; differences in skin color come from how much and what kind of melanin they make. Sun exposure increases melanin production, which is why skin tans.

The dermis. Beneath the epidermis lies the *dermis*. Its upper, papillary layer of loose connective tissue rises in small ridges (dermal papillae) that hold capillary loops and touch receptors and that shape the ridges of fingerprints, which help grip. Its deeper, reticular layer of dense irregular connective tissue, crisscrossed with collagen and elastic fibers, gives skin its strength and spring; stretch marks are small tears in it. The dermis carries blood vessels, nerves, glands and hair follicles. Under it, the *hypodermis* of loose and fat tissue anchors the skin, insulates and cushions; "subcutaneous" injections such as insulin go here.

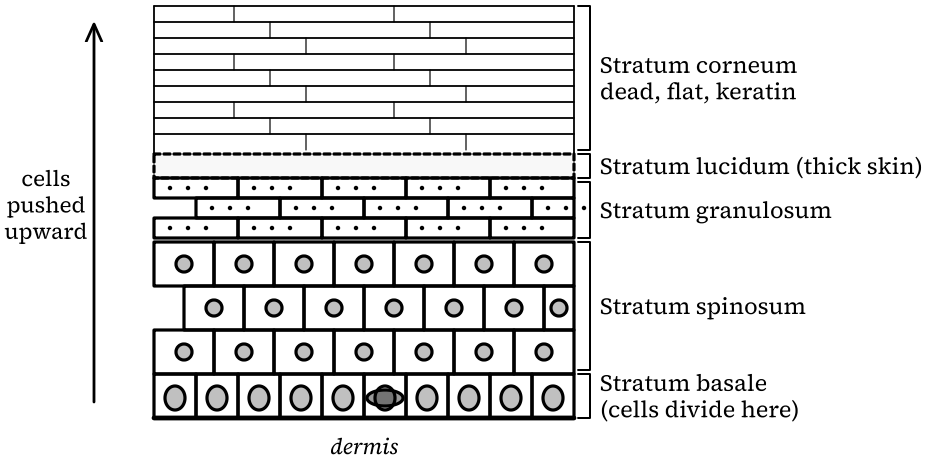
Accessory structures. A hair grows from a follicle that reaches deep into the dermis; a tiny *arrector pili* muscle can pull it upright, raising goose bumps. *Sebaceous glands* oil each hair and the skin; when a follicle plugs with oil and dead cells, acne results. *Eccrine* sweat glands, spread over the whole body, release watery sweat for cooling. *Apocrine* glands in the armpits and groin, active after puberty, empty into follicles; odor comes from bacteria breaking down their secretion. Nails are plates of hard keratin.

Skin and homeostasis. Skin is the main effector of the temperature loop from lesson 1.3. When you overheat, dermal vessels widen and sweat glands pour out sweat; every liter that evaporates carries away about 2,400 kilojoules of heat. When you are cold, the vessels narrow to keep warm blood in the core. Skin also makes vitamin D: ultraviolet B light converts a cholesterol-based molecule in the epidermis into vitamin D_3, which the liver and kidneys activate. Without it the gut cannot absorb enough calcium for bone (lesson 3.3).

Try it. In the lab you will classify your fingerprints and map how finely different parts of your skin can feel.



A block of skin. The epidermis has no vessels; everything else lives in the dermis and hypodermis.



The epidermis renews itself from the bottom up; cells die as they reach the surface.

> **Safety first.** Use a blunt paper clip, never a pin, for the touch test, and press gently. Wash graphite off with soap and water.

LAB

Fingerprints and the Two-Point Touch Test

You will classify the ridges shaped by your dermal papillae and measure how densely touch receptors are packed in different places.

You will need

- A soft pencil, clear tape, white paper, a magnifying glass, a large paper clip, a ruler, a partner

Steps

1. Rub a patch of pencil graphite on paper, roll a fingertip in it, press clear tape on the fingertip and stick the tape to white paper. Do all ten fingers.
2. Classify each print as a loop, whorl or arch. Tally your family's prints. (Loops are most common, then whorls; arches are rare.)
3. Bend the paper clip into a U with points 2 mm apart. With the partner's eyes closed, touch either one point or both points at once to the fingertip; ask "one or two?" Widen the gap (5, 10, 20, 40 mm) until two points are reliably felt.
4. Repeat on the palm, the back of the hand, the forearm and the back of the neck. Record the smallest distance felt as two at each place.

Check your work

- ☐ Where are touch receptors most densely packed? Why is that useful?
- ☐ Why can a blind reader use a fingertip, not a forearm, to read Braille?

LAB NOTEBOOK

1. A labeled block of skin: layers, glands, follicle, vessels and receptors.
2. Your fingerprint chart and two-point data table.

> **From history.** Henry Faulds, a Scottish medical missionary at a hospital in Tokyo, noticed ancient fingerprints pressed into Japanese pottery and began studying living ones. In 1880 he published a letter in the journal *Nature* proposing that fingerprints left at a crime scene could identify the criminal. Twelve years later Francis Galton's book *Finger Prints* showed that the ridge patterns stay the same for life and differ from person to person, and police forces soon adopted them.

> **Practice habit.** Say the epidermal layers both ways every day this week: from the top, "Come, Let's Get Sun Burned" (corneum, lucidum, granulosum, spinosum, basale), then from the bottom.

WORKED EXAMPLES

Example 1. Cells take about 28 days to travel from the stratum basale to the surface through an epidermis 0.1 mm (100 µm) thick. About how fast do they move?

Show solution

1. speed = distance ÷ time
2. = 100 µm ÷ 28 days ≈ 3.6 µm per day

Answer: About 3.6 µm per day, roughly half a red blood cell's width

Example 2. During a summer run, 0.50 L of sweat evaporates from a runner's skin. Each liter carries away about 2,400 kJ. How much heat is removed?

Show solution

1. heat = 0.50 L × 2,400 kJ/L
2. = 1,200 kJ

Answer: About 1,200 kJ (only sweat that evaporates cools; sweat that drips off does not)

Example 3. In the two-point test a student feels two points 3 mm apart on the fingertip but needs 36 mm on the forearm. Compare and explain.

Show solution

1. 36 ÷ 3 = 12
2. Each touch receptor covers a smaller patch of skin on the fingertip, so two nearby points land on different receptors.

Answer: The fingertip discriminates about 12 times more finely because its receptors are far more densely packed

PRACTICE

CONCEPT CHECKS

1. **Easy** List four functions of the skin.

   Show answer

   Any four: barrier to water loss and germs; protection from ultraviolet light; sensation; temperature regulation; making vitamin D; small amounts of excretion.

2. **Easy** List the five strata of thick-skin epidermis from deepest to most superficial.

   Show answer

   Stratum basale, spinosum, granulosum, lucidum, corneum.

3. **Medium** Which epidermal cell (a) makes keratin, (b) makes melanin, (c) catches invading microbes, (d) senses light touch?

   Show answer

   (a) Keratinocyte, (b) melanocyte, (c) dendritic (Langerhans) cell, (d) Merkel cell.

4. **Medium** During a hike, 0.80 L of sweat evaporates. At about 2,400 kJ per liter, how much heat is removed?

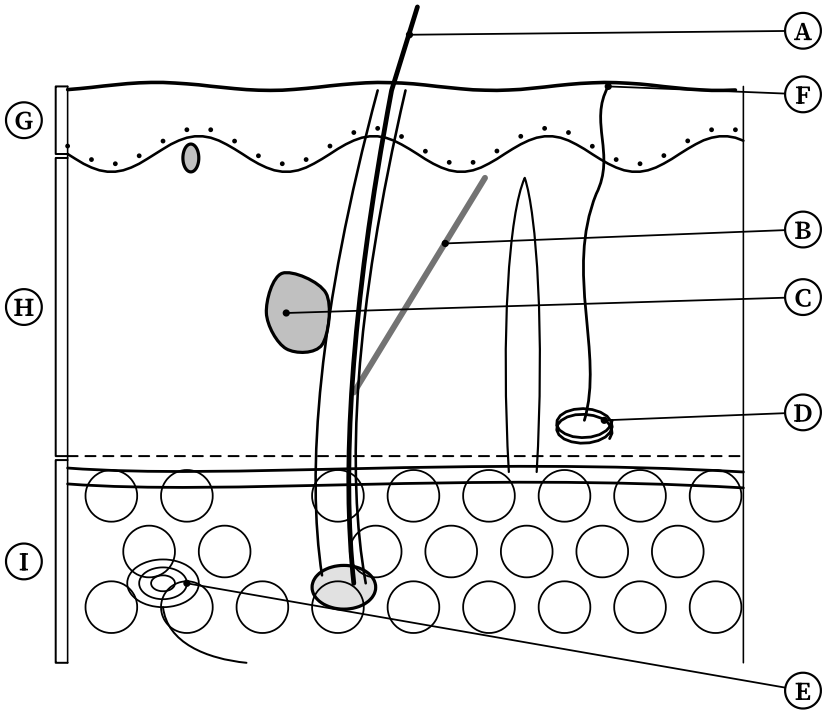
   Show answer

   1,920 kJ

   $0.80 \times 2{,}400 = 1{,}920$

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the structures lettered A–F and the layers G, H and I.



Show answer

A hair shaft, B arrector pili muscle, C sebaceous (oil) gland, D eccrine sweat gland, E lamellated (pressure) receptor, F sweat pore. G epidermis, H dermis, I hypodermis.

6. **Medium** Two-point thresholds: fingertip 2 mm, palm 10 mm, forearm 38 mm, back 45 mm. Rank the sites from most to least densely supplied with touch receptors, and say how many times finer the fingertip is than the back.

Show answer

Fingertip, palm, forearm, back. The fingertip is about 22 times finer (45 ÷ 2 = 22.5).

7. **Medium** A paper cut stings but does not bleed. How deep did it go? Explain.

Show answer

Only into the epidermis (or barely into the dermis). The epidermis has no blood vessels; it does have nerve endings near its base, so the cut stings without bleeding.

DISORDER AS A BROKEN MECHANISM

8. Hard In the most common form of albinism, melanocytes are present but lack a working enzyme (tyrosinase) needed to make melanin. Explain the effects on skin, hair and eyes, and why sunburn risk is high.

Show answer

Without the enzyme no melanin is made, so skin and hair are very pale and the iris and retina lack pigment (light sensitivity and poor vision). With no melanin umbrella over the keratinocyte nuclei, ultraviolet light reaches their DNA, so the skin burns easily and skin-cancer risk rises; protection must come from clothing, hats and sunscreen.

TEST PREP

9. Easy A subcutaneous insulin injection delivers the drug into the

A. epidermis

B. dermis

C. hypodermis

D. muscle

Show answer

C. hypodermis

10. Hard On a cold morning your arms show goose bumps. What causes them, and which other responses to cold do far more to keep you warm?

Show answer

Arrector pili muscles contract and pull hairs upright, lifting the skin around each follicle. Narrowing of dermal blood vessels (keeping warm blood in the core) and shivering (heat from muscle work) do much more to hold core temperature.

COMMON MISTAKES

- Saying the epidermis has blood vessels; it is fed by diffusion from the dermis.
- Thinking sweat cools by being wet; it cools as it evaporates.
- Thinking people with darker skin have more melanocytes; they make more or different melanin.
- Mixing up sebaceous glands (oil) and sweat glands (water).

Make it a game · Skin-Deep Floor Map. Lay three sheets of paper on the floor in a column labeled epidermis, dermis and hypodermis. The parent calls a structure (melanocyte, sweat-gland coil, fat cell, capillary loop, stratum corneum, hair bulb, pressure receptor, oil gland). The student jumps onto the right layer within three seconds. Miss twice and swap roles.

Scripture. “Thou hast clothed me with skin and flesh, and hast fenced me with bones and sinews.” (Job 10:11, KJV)

Job speaks of being clothed with skin and fenced with bones, the very subjects of this unit: a covering that protects and a frame that holds.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

3.2 Burns, Wounds and Healing

Mark up this lesson

OBJECTIVES

- Classify burns by depth and explain why deep burns hurt less but are more dangerous.
- Estimate burned body-surface area with the rule of nines and the palm method, and explain why burned patients need fluid.
- Describe the four phases of wound healing and correct first aid for burns and cuts.

> **Warm-up.** You grab the handle of a hot pan for about one second. Which layers of skin were probably harmed? What should you do in the next minute, and what should you not do?

WATCH

How a wound heals itself - Sarthak Sinha

TED-Ed · 4:01

https://www.youtube.com/watch?v=TLVwELDMDWs

> **WHEN TO WATCH**
> After the wound-healing core idea.

BACKUP VIDEO

Rule of Nines for Burns in Adults Nursing NCLEX Lecture w/ Examples

RegisteredNurseRN · 7:42

https://www.youtube.com/watch?v=JRa9F2PVmL0

Before Worked Example 1.

KEY TERMS

superficial (first-degree) burn
A burn of the epidermis only: red, painful, dry, no blisters.

partial-thickness (second-degree) burn
A burn through the epidermis into the dermis: blisters, moist, very painful.

full-thickness (third-degree) burn

A burn that destroys the whole dermis: white, brown or leathery, often painless at the center; usually needs skin grafting.

total body surface area (TBSA)

The percent of the body's skin that is burned; only partial- and full-thickness burns are counted.

rule of nines

A quick adult estimate dividing the body into areas of 9 percent or multiples of 9, plus 1 percent for the groin.

granulation tissue

Red, bumpy new tissue full of capillaries and fibroblasts that fills a wound during healing.

phases of wound healing

Hemostasis (clotting), inflammation, proliferation (rebuilding) and remodeling (strengthening the scar).

CORE IDEAS

Why burns are dangerous. A burn takes away every job of the skin at once. Damaged capillaries leak plasma into the tissue and out of the wound, so a large burn can drain the blood of fluid and send the patient into shock within hours. The lost barrier lets bacteria in, so infection is the great danger in the days that follow. Without skin, water and heat escape, and the patient grows cold. Severity depends on depth, area, location (face, hands, feet, groin and major joints are always serious) and age.

Depth. A *superficial* burn (a mild sunburn) harms only the epidermis: red, painful, no blisters, healing in about a week. A *partial-thickness* burn reaches into the dermis: blisters, a moist pink surface and severe pain, because the nerve endings are irritated but alive; shallow ones heal in two or three weeks from surviving follicles and glands, deeper ones may scar. A *full-thickness* burn destroys the whole dermis: the surface is white, brown or leathery and may be painless at the center, because the nerve endings themselves are destroyed. With no follicles or glands left to regrow from, it can heal only slowly from the edges and usually needs a skin graft.

Area: the rule of nines. In the late 1940s and early 1950s burn surgeons began dividing the adult body into areas worth 9 percent: the head 9, each arm 9, the front

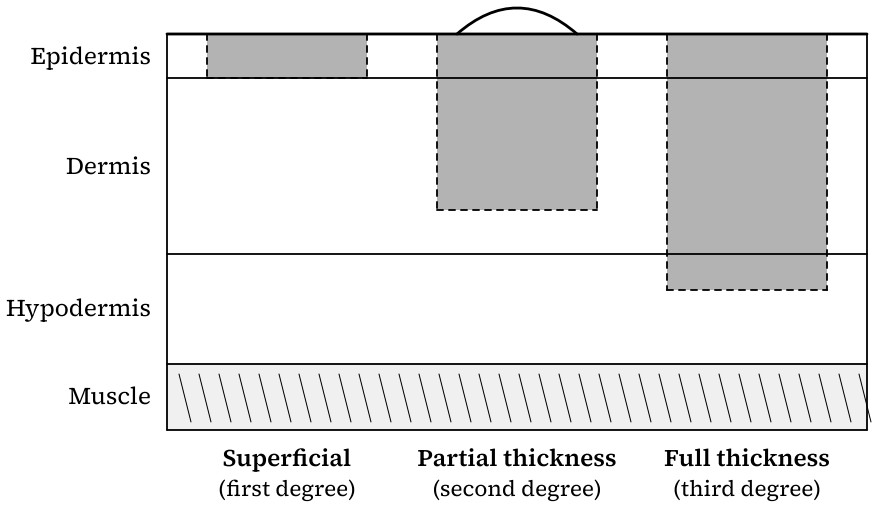
of the trunk 18, the back of the trunk 18, each leg 18, and the groin 1, for a total of 100. For small or scattered burns, the patient's own palm with fingers is about 1 percent. Children have much larger heads and smaller legs, so they need a different chart. Only partial- and full-thickness burns are counted. Burn centers in the United States advise referring patients with partial-thickness burns over more than 10 percent of the body.

Fluid. Because burned skin leaks plasma, large burns are treated with IV fluid, and the amount is calculated from weight and burned area. The widely taught Parkland formula gives 4 mL × body mass in kg × %TBSA over the first 24 hours, with half in the first 8 hours. Nurses then adjust the rate by watching the patient's urine output.

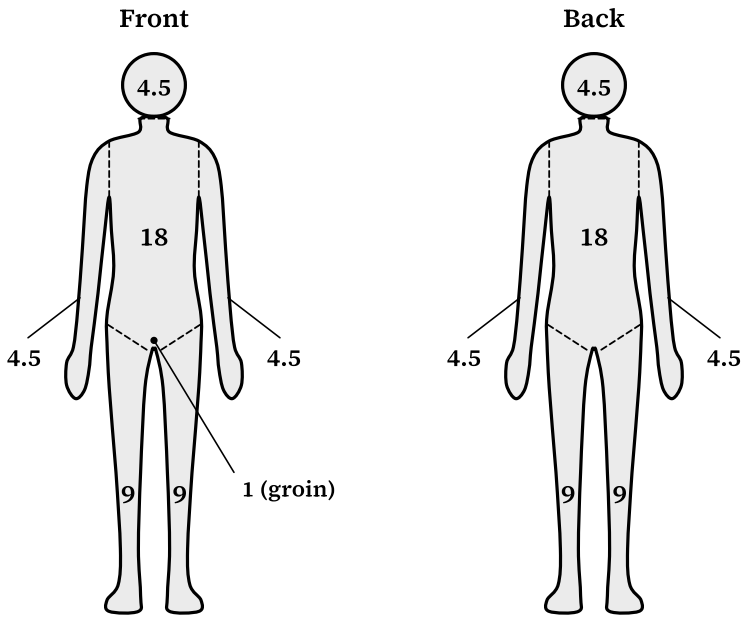
First aid. Stop the burning: remove the heat, put out flames (stop, drop and roll) and take off hot or soaked clothing and rings before swelling starts, unless they are stuck to the skin. Cool the burn under cool running water, not ice, for at least 10 minutes (many burn centers say 20). Cover it loosely with clean plastic wrap or a clean, dry cloth. Do not use butter, oil or ointment, and do not pop blisters. Get medical care for any burn that is large, deep, on the face, hands, feet, groin or a joint, or caused by chemicals or electricity, and call 911 for major burns.

How a wound heals. Every wound passes through four overlapping phases. *Hemostasis* (minutes): vessels narrow and platelets and fibrin form a clot. *Inflammation* (the first few days): white cells clear bacteria and debris. *Proliferation* (days to weeks): fibroblasts lay down collagen, new capillaries form red, bumpy granulation tissue, the edges pull together and epithelium crawls across the surface. *Remodeling* (weeks to a year or more): the collagen is reorganized and the scar grows stronger and paler, though it reaches only about 80 percent of the original strength and has no hair follicles or sweat glands.

Try it. In the lab you will find out how big "one percent of your body" really is.



Burn depth decides how a burn looks, how much it hurts and whether skin can regrow.



Adult: each arm 9, each leg 18, trunk 36, head 9, groin 1 = 100%

The adult rule of nines. Only partial- and full-thickness burns are counted.

> **Safety first.** This lab uses no heat or burning of any kind. Never test burns on yourself or anyone else.

LAB

How Big Is One Percent?

You will measure your own hand and body surface area and test the palm rule, then make a first-aid card for your kitchen.

You will need

- 1-cm graph paper, a pencil, a tape measure, a bathroom scale, a calculator, an index card

Steps

1. Trace your hand, fingers together, on 1-cm graph paper. Count the whole squares inside, and add half the partial squares. This is your hand area in cm^2.
2. Measure your height in cm and mass in kg. Estimate your body surface area with the Mosteller formula, BSA (m^2) = √(height × mass ÷ 3600), then convert to cm^2 (× 10,000).
3. Find what percent of your body your hand covers: hand area ÷ BSA × 100.
4. Repeat for two family members of different sizes.
5. Write a burn first-aid card (cool, cover, call) and post it near the stove.

Check your work

- ☐ How close to 1 percent was each hand?
- ☐ Why is a rule of thumb that is only roughly right still useful in an emergency?

LAB NOTEBOOK

1. Your hand tracing, calculations and family data table.
2. A front-and-back rule-of-nines outline with the percentages written in.

KEY FORMULAS

$$\text{Parkland: fluid (mL in 24 h)} = 4 \times \text{mass (kg)} \times \%\text{TBSA}$$

$$\text{BSA } (\text{m}^2) = \sqrt{\frac{\text{height (cm)} \times \text{mass (kg)}}{3600}}$$

From history. In August 1865 the Glasgow surgeon Joseph Lister, who had read Louis Pasteur's work on germs, dressed the open leg fracture of James Greenlees, an 11-year-old boy run over by a cart, with lint soaked in carbolic acid. At the time such wounds usually festered, and many patients lost the limb or died. The boy's leg healed cleanly. Lister's 1867 papers in *The Lancet* launched antiseptic surgery, and his habit of keeping wounds clean is still the first rule of every dressing.

Practice habit. Before you add up a burn, cross out every superficial area first; then add the nines.

Career connection. Burn-unit nurses calculate fluids, change dressings, watch for infection and comfort patients through long recoveries. Registered nurses train through a two-year associate degree or a four-year bachelor's degree and pass the NCLEX-RN licensing exam; certified nursing assistants can start after a course of a few weeks. Both use this lesson's rule of nines and healing phases.

WORKED EXAMPLES

Example 1. An adult has partial-thickness burns covering the front of both legs and the front of the trunk. Estimate the TBSA.

Show solution

1. Front of each leg: half of 18 = 9, so both legs = 9 + 9 = 18.
2. Front of trunk = 18.
3. Total = 18 + 18 = 36.

Answer: 36% TBSA

Example 2. An 80 kg adult has partial- and full-thickness burns of the entire left arm (front and back) and the front of the trunk. Estimate TBSA and use the Parkland formula to find the 24-hour fluid and the hourly rate for the first 8 hours.

Show solution

1. TBSA = 9 (whole arm) + 18 (front trunk) = 27%
2. 24-hour fluid = 4 × 80 × 27 = 8,640 mL
3. First 8 hours: half = 4,320 mL
4. Rate = 4,320 ÷ 8 = 540 mL per hour

Answer: 27% TBSA; 8,640 mL in 24 hours; 540 mL/h for the first 8 hours

Example 3. Classify each burn: (a) red, dry and painful, like a sunburn; (b) blistered, moist and very painful; (c) white and leathery, with little pain at the center.

Show solution

1. Match the signs to the depth of damage.
2. (a) Epidermis only: superficial.
3. (b) Into the dermis, nerves irritated: partial thickness.
4. (c) Whole dermis destroyed, nerve endings gone: full thickness.

Answer: (a) superficial, (b) partial thickness, (c) full thickness

PRACTICE

CONCEPT CHECKS

1. Easy Name the three main burn depths and the deepest layer each reaches.

Show answer

Superficial: epidermis. Partial thickness: into the dermis. Full thickness: through the whole dermis to the hypodermis.

2. **Easy** Why can the center of a full-thickness burn hurt less than a partial-thickness burn?

Show answer

The full-thickness burn has destroyed the nerve endings in the dermis, so they can no longer send pain signals; in a partial-thickness burn they are alive and irritated.

3. **Medium** Use the rule of nines: an adult burns the whole right leg and the whole right arm (partial thickness). Estimate the TBSA.

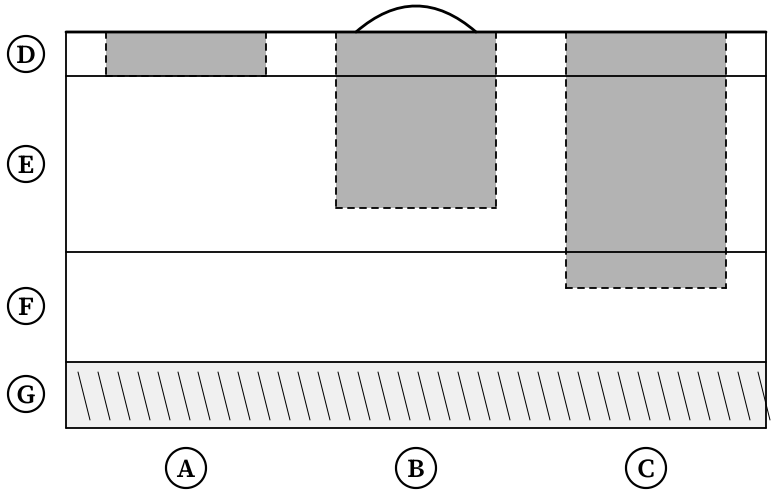
Show answer

27%

18 + 9 = 27

DIAGRAM AND DATA QUESTIONS

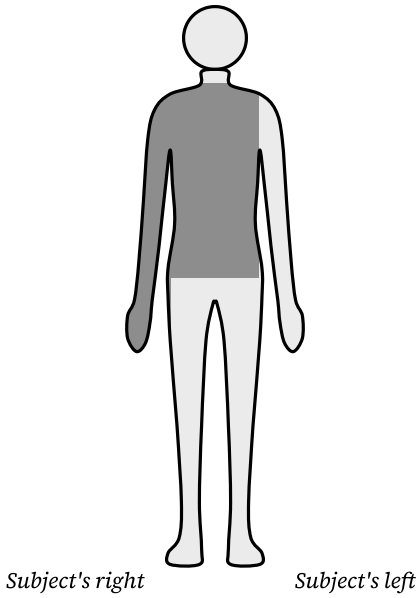
4. **Easy** Name burn depths A, B and C and tissue layers D, E, F and G.



Show answer

A superficial (first degree), B partial thickness (second degree), C full thickness (third degree). D epidermis, E dermis, F hypodermis, G muscle.

5. **Medium** The shaded areas show partial-thickness burns on the front of an adult; the back is not burned. Estimate the TBSA.



Show answer

22.5%

front of trunk 18 + front of right arm 4.5 = 22.5

6. **Medium** A 60 kg patient has 25% TBSA partial-thickness burns. Use the Parkland formula to find the 24-hour fluid and the rate for the first 8 hours.

Show answer

6,000 mL in 24 h; 375 mL/h for the first 8 hours

4 × 60 × 25 = 6,000; 3,000 ÷ 8 = 375

7. **Medium** A child spills hot water and has three palm-sized blistered areas and one palm-sized red, unblistered area. Estimate the TBSA to count.

Show answer

About 3%: three partial-thickness palms at about 1% each; the superficial area is not counted.

8. Medium Put the phases of wound healing in order and give one event of each.

Show answer

Hemostasis (a clot forms), inflammation (white cells clear debris and bacteria), proliferation (granulation tissue, collagen, new epithelium), remodeling (collagen reorganized, scar strengthens).

DISORDER AS A BROKEN MECHANISM

9. Hard Explain why a patient with burns over 40 percent of the body can go into shock within hours and develop dangerous infections days later.

Show answer

Burned capillaries leak plasma into the tissue and out through the wound, and the missing skin lets water evaporate freely; blood volume falls, so blood pressure drops and organs are poorly supplied (shock). Later, with the skin barrier gone and dead tissue as food, bacteria invade, and the stressed immune system struggles to stop them.

TEST PREP

10. Easy The best first aid for a small kitchen burn is to

A. hold ice on it

B. spread butter on it

C. cool it under cool running water

D. pop the blisters

Show answer

C. cool it under cool running water

11. Hard A healed scar on the forearm has no hair and never sweats, and it can tear more easily than the skin around it. Explain why.

Show answer

The wound was filled by fibrosis: fibroblasts laid down collagen scar instead of regrowing dermis with its follicles and glands, so no hair or sweat glands return. Scar collagen is less organized than normal dermis and reaches only about 80 percent of its strength.

COMMON MISTAKES

- Counting superficial (first-degree) burns in the TBSA.

- Using the adult rule of nines for a small child, whose head is a much larger share of the body.
- Putting ice, butter or ointment on a fresh burn, or popping blisters.
- Assuming a painless burn is a minor one; it may be full thickness.

Make it a game · Nines Race. Draw front and back outlines on paper. The parent shades "burns" with a highlighter and says whether each is red only or blistered. The student calls the TBSA within ten seconds, remembering to skip red-only areas. Score a point for each answer within 2 percent.

Scripture. "And went to him, and bound up his wounds, pouring in oil and wine, and set him on his own beast, and brought him to an inn, and took care of him." (Luke 10:34, KJV)

The Good Samaritan cleaned and bound a stranger's wounds and paid for his care. Every lesson on first aid is a lesson in how to be that neighbor.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

3.3 Bone Tissue, Growth and Fracture Repair

Mark up this lesson

OBJECTIVES

- Name the functions of bone and the parts of a long bone, and describe compact bone, spongy bone and the osteon.
- Explain how bones form and grow in length and width, and how remodeling and hormones keep blood calcium steady.
- Classify common fractures and describe the stages of fracture repair.

> **Warm-up.** Press hard on your shin, then on the end of your nose. One is bone and one is cartilage. Which could carry your weight, and which can bend? Why might a growing child need both?

WATCH

The Skeletal System: Crash Course Anatomy & Physiology #19

CrashCourse · 10:38

https://www.youtube.com/watch?v=rDGqkMHPDqE

> **WHEN TO WATCH**
> After the bone-tissue core ideas.

BACKUP VIDEO

What happens when you break a bone? - Gurpreet Baht and Natalie Pang

TED-Ed · 4:12

https://www.youtube.com/watch?v=gVXoAbeB8QI

With fracture repair.

KEY TERMS

diaphysis and epiphysis
The shaft of a long bone and its knobbed ends.

periosteum
The tough membrane covering bone, with blood vessels and bone-forming cells; it is essential for growth in width and for repair.

osteon

The unit of compact bone: rings of mineralized matrix (lamellae) around a central canal holding blood vessels and nerves.

osteoblast, osteocyte, osteoclast

Bone-building cell; mature bone cell trapped in the matrix that maintains it; large bone-dissolving cell.

epiphyseal plate

The growth plate of cartilage between epiphysis and diaphysis where a bone grows in length; it closes into the epiphyseal line in the late teens or early twenties.

remodeling

The continual removal of old bone by osteoclasts and its replacement by osteoblasts.

callus

The mass of repair tissue that bridges a fracture: first soft (fibrous tissue and cartilage), then hard (bony).

CORE IDEAS

Why bone is remarkable. Bone is living tissue with blood vessels, nerves and cells that work every day. It supports the body, protects the brain, heart and lungs, works with muscles as levers, stores about 99 percent of the body's calcium along with phosphate, makes blood cells in its red marrow, and stores fat in its yellow marrow. Bones are classed by shape: long (femur), short (wrist bones), flat (skull, sternum), irregular (vertebrae) and sesamoid (kneecap).

A long bone. The shaft (*diaphysis*) is a tube of compact bone around a hollow *medullary cavity* of yellow marrow; a tube resists bending nearly as well as a solid rod at a fraction of the weight. The knobbed ends (*epiphyses*) are filled with spongy bone and red marrow and capped with smooth articular cartilage. The *periosteum* covers the outside and anchors tendons and ligaments.

Bone tissue. Bone matrix is about one-third organic (mostly collagen, which gives flexibility) and two-thirds mineral (calcium phosphate crystals, which give hardness). Remove the mineral with vinegar and a bone bends like rubber; remove the collagen by baking and it shatters like chalk. Compact bone is built of *osteons*: rings of matrix around a central canal with vessels and nerves. Bone cells (*osteocytes*)

live in small spaces between the rings and reach one another through hair-thin canals. Spongy bone is a lattice of struts (trabeculae) lined up along the lines of stress, light and strong like the trusses of a bridge.

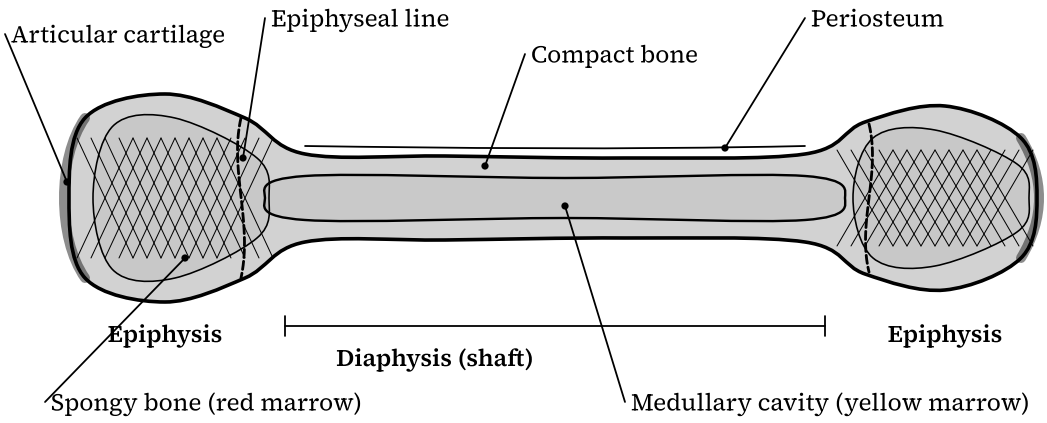
Build, keep, cut. *Osteoblasts* lay down new matrix; those that become trapped in it become *osteocytes*, which sense strain and maintain the bone; *osteoclasts* dissolve bone with acid and enzymes. Together they *remodel* the skeleton throughout life, replacing roughly a tenth of it each year. In 1892 the German surgeon Julius Wolff described what we now call Wolff's law: bone adapts to the loads placed on it. A tennis player's racket-arm bones grow thicker, while astronauts in weightlessness lose roughly 1 percent of the bone in their hips and spine each month.

Growth. Flat skull bones and the clavicles form directly from sheets of tissue (intramembranous ossification). Most bones first form as cartilage models that are replaced by bone (endochondral ossification). Bones lengthen at the *epiphyseal plates*, where cartilage cells keep dividing on the epiphysis side while the cartilage on the shaft side is replaced by bone. In the late teens or early twenties the plates are used up and close into epiphyseal lines, and growth in height stops. Bones grow wider as osteoblasts beneath the periosteum add bone to the outside while osteoclasts widen the cavity within.

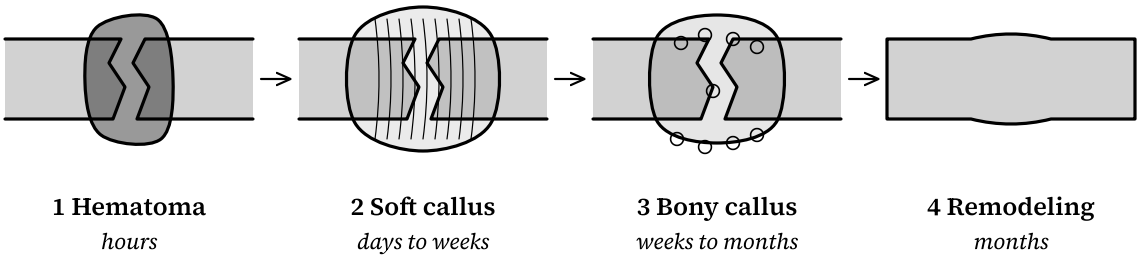
Calcium homeostasis. Nerves, muscles and blood clotting need blood calcium kept in a narrow range. When it falls, the parathyroid glands release parathyroid hormone (PTH), which stirs osteoclasts to release calcium from bone, makes the kidneys keep calcium, and activates vitamin D so the gut absorbs more. When calcium returns to normal, PTH falls: a negative feedback loop like those in lesson 1.3. Enough calcium and vitamin D and regular weight-bearing exercise during the teens build the peak bone mass that must last a lifetime.

Fractures and repair. A fracture is *closed* if the skin is intact and *open* (compound) if bone breaks through it; it may be transverse, spiral, comminuted (in pieces), a compression fracture, or a *greenstick* fracture that bends and cracks on one side, common in children's flexible bones. Repair follows four stages: a blood clot (hematoma) fills the break; over days to weeks a soft callus of fibrous tissue and cartilage bridges it; over weeks to months a bony callus replaces it; and over months remodeling restores the bone's shape. Setting the bone (reduction) and holding it

still (a cast or splint) let the stages proceed; a simple adult fracture often takes six to twelve weeks to knit.



A long bone cut open lengthwise.



Fracture repair in four stages, from blood clot to remodeled bone.

> **Safety first.** Use cooked, cleaned chicken bones. A parent handles the oven; use oven mitts and let the bones cool. Wash hands after handling bones.

LAB

The Baked Bone and the Vinegar Bone

You will take bone apart into its two ingredients, mineral and collagen, and test what each contributes.

You will need

- Three cooked, cleaned and dried chicken leg bones of similar size, a jar of white vinegar, a baking sheet, an oven, a kitchen scale (0.1 g), paper towels

Steps

1. Weigh all three bones. Keep one as a control.
2. Soak the second in vinegar for 5 days, changing the vinegar once. Rinse it, let it dry for a day and weigh it again.
3. A parent bakes the third bone at about 120 °C (250 °F) for 3 hours. Let it cool and weigh it again.
4. Try to bend each bone gently, then harder. Record what happens.
5. Calculate the percent mass lost by each treated bone.

Check your work

- ☐ Which bone bent? Which crumbled? Which ingredient did each treatment remove?
- ☐ Why does a healthy bone need both ingredients?

LAB NOTEBOOK

1. A labeled long bone and a labeled osteon.
2. The four stages of fracture repair, with your bone-lab data table.

KEY FORMULAS

$$\%\ \text{mass lost} = \frac{\text{initial} - \text{final}}{\text{initial}} \times 100$$

From history. In the early 1850s the Dutch army surgeon Antonius Mathijsen rubbed dry plaster of Paris into coarse cotton bandages. Dipped in water and wrapped around a broken limb, they hardened within minutes into a light, close-fitting cast that could be applied on the battlefield. Before his invention fractures were held with splints of wood or bandages stiffened with starch or egg white that took hours to dry. Plaster casts are still used, alongside lighter fiberglass ones.

Practice habit. Remember bone cells by their endings and say the rule whenever you meet one: -blast builds, -cyte keeps, -clast cuts.

Review first. Biology 10.1 tells how Vesalius corrected Galen by studying real skeletons and includes a vinegar-bone lab; this lesson goes deeper into bone tissue, growth and repair.

WORKED EXAMPLES

Example 1. A dried chicken bone weighed 8.0 g. After a week in vinegar and drying again, it weighed 3.1 g. What percent of its mass was mineral dissolved by the vinegar?

Show solution

1. mass lost = 8.0 − 3.1 = 4.9 g
2. 4.9 ÷ 8.0 × 100 = 61%

Answer: About 61%, close to the two-thirds expected for bone mineral

Example 2. Remodeling replaces about 10 percent of the adult skeleton each year. About how long would it take to replace the equivalent of the whole skeleton? An astronaut loses about 1 percent of hip bone a month. About how much is lost on a 6-month mission?

Show solution

1. 100% ÷ 10% per year = 10 years
2. 6 months × 1% per month ≈ 6%

Answer: About 10 years; about 6% of hip bone

Example 3. Trace the feedback loop that corrects low blood calcium.

Show solution

1. Stimulus: blood calcium falls.
2. Receptors and control center: cells of the parathyroid glands sense it.
3. Signal: parathyroid hormone (PTH) is released.
4. Effectors: osteoclasts release calcium from bone; kidneys keep calcium; activated vitamin D raises absorption in the gut.
5. Response: blood calcium rises, so PTH release falls (negative feedback).

Answer: Low Ca^{2+} → parathyroids → PTH → bone, kidneys and gut → Ca^{2+} restored

PRACTICE

CONCEPT CHECKS

1. Easy List five functions of the skeleton.

   Show answer

   Support, protection, movement (levers), mineral storage (calcium and phosphate), blood-cell formation; also fat storage.

2. Easy Tell the jobs of osteoblasts, osteocytes and osteoclasts.

   Show answer

   Osteoblasts build new bone matrix; osteocytes maintain bone and sense strain; osteoclasts dissolve bone.

3. Medium Compare compact and spongy bone: structure and where each is found in a long bone.

   Show answer

   Compact bone is dense, built of osteons, and forms the walls of the shaft and the outer shell everywhere. Spongy bone is a lattice of trabeculae with red marrow between them, filling the epiphyses.

4. **Medium** A dried bone weighed 6.4 g before and 2.4 g after vinegar treatment. What percent of its mass was mineral?

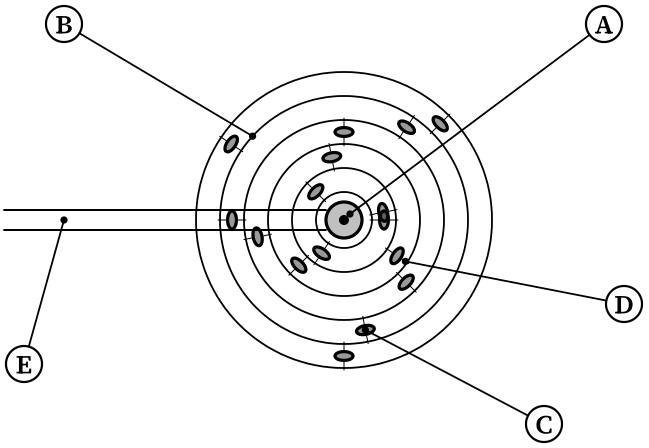
Show answer

62.5%

(6.4 − 2.4) ÷ 6.4 × 100 = 62.5

DIAGRAM AND DATA QUESTIONS

5. **Medium** Name the parts of the osteon lettered A–E.



Show answer

A central canal (with blood vessel), B lamella (ring of matrix), C osteocyte in its lacuna, D canaliculi (hair-thin channels), E perforating canal.

6. **Medium** An X-ray of a 13-year-old's knee shows a dark band across each end of the femur and tibia that an adult's X-ray lacks. What is it, and what does it tell you?

Show answer

The epiphyseal (growth) plates, made of cartilage, which absorbs fewer X-rays than bone and so looks dark. They are still open, so the bones are still growing in length.

7. Medium Put the stages of fracture repair in order and say roughly how long each lasts.

Show answer

Hematoma (hours), soft callus of fibrous tissue and cartilage (days to weeks), bony callus (weeks to months), remodeling (months).

DISORDER AS A BROKEN MECHANISM

8. Hard In osteoporosis, osteoclasts remove bone faster than osteoblasts replace it. Explain why the hip, wrist and spine break easily, and name two ways to lower the risk.

Show answer

Spongy bone loses trabeculae and compact bone thins, so the bone has less mineral and fewer struts to carry load; the hip, wrist and vertebrae, rich in spongy bone, can break in a simple fall or even collapse under body weight. Lower the risk with weight-bearing exercise, enough calcium and vitamin D, and (in older adults) fall prevention and medication when prescribed.

TEST PREP

9. Easy Which hormone raises blood calcium by stimulating osteoclasts?

A. insulin

B. calcitonin

C. parathyroid hormone

D. glucagon

Show answer

C. parathyroid hormone

10. Hard Why are greenstick fractures common in children but rare in adults?

Show answer

Children’s bones contain relatively more collagen and less mineral, so they bend before they break, cracking only on the stretched side; their thick periosteum also holds the pieces together.

11. **Medium** A professional tennis player's racket-arm humerus is thicker than the other. Explain using Wolff's law.

Show answer

Bone adapts to the loads on it. Repeated stress on the racket arm signals osteoblasts to add bone, so that humerus grows thicker and stronger.

COMMON MISTAKES

- Thinking bone is dead material; it is living tissue that remodels constantly.
- Saying bones grow longer in the middle of the shaft; they lengthen at the epiphyseal plates.
- Mixing up osteoblasts (build) and osteoclasts (cut).
- Thinking the vinegar bone shows bone is "mostly calcium"; it shows bone needs both mineral and collagen.

Make it a game · Build or Break. The parent calls a situation: lifting weights, low blood calcium, a cast coming off, an astronaut in orbit, PTH rising, a 12-year-old's growth spurt, a long hospital stay in bed. The student shouts "Build!" (osteoblasts), "Break!" (osteoclasts) or "Both!" and gives the reason in one sentence.

Scripture. "As thou knowest not what is the way of the spirit, nor how the bones do grow in the womb of her that is with child: even so thou knowest not the works of God who maketh all." (Ecclesiastes 11:5, KJV)

The Preacher named the growth of bones as a mystery beyond us. We now know some of the steps, cartilage models and growth plates, and the wonder has only grown.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

3.4 The Axial Skeleton

Mark up this lesson

OBJECTIVES

- Name the parts of the axial skeleton and account for its 80 bones.
- Name the main bones and sutures of the skull and describe the fontanelles.
- Describe the regions, curves and parts of the vertebral column, the intervertebral discs and the thoracic cage.

> **Warm-up.** Bend your head forward and run your fingers down the back of your neck. Which bump sticks out the most? Count how many bumps you can feel below it before they become hard to find.

WATCH

Human Skeleton | AXIAL SKELETON

Miss Angler · 15:47

https://www.youtube.com/watch?v=a_2Dr0K0NKo

> **WHEN TO WATCH**
> After the skull and spine core ideas.

BACKUP VIDEO

Skull Bones Mnemonic (Cranial and Facial Bones) | Anatomy and Physiology

RegisteredNurseRN · 7:07

https://www.youtube.com/watch?v=ocqoZyY12GM

With the skull core idea.

KEY TERMS

axial skeleton

The 80 bones along the body's axis: skull, middle-ear bones, hyoid, vertebral column and thoracic cage.

cranium

The eight bones enclosing the brain: frontal, two parietal, two temporal, occipital, sphenoid and ethmoid.

suture

An immovable joint between skull bones (coronal, sagittal, lambdoid, squamous).

fontanelle

A soft, membrane-covered gap between an infant's skull bones, which closes as the bones grow.

vertebra

One bone of the spine: a weight-bearing body, an arch around the vertebral foramen and processes for muscles.

intervertebral disc

A pad of fibrocartilage with a gel center between vertebral bodies that absorbs shock.

true, false and floating ribs

Ribs 1–7 join the sternum by their own cartilage; ribs 8–12 do not, and ribs 11–12 have no front attachment at all.

CORE IDEAS

The axis. The skeleton has two divisions. The *axial* skeleton runs along the body's central axis and protects the brain, spinal cord, heart and lungs. Its 80 bones are the skull (22), the six tiny bones of the middle ears, the hyoid, the vertebral column (26) and the thoracic cage (24 ribs and the sternum). The *appendicular* skeleton of the next lesson hangs the limbs from it.

The skull. Eight cranial bones form a vault around the brain: the frontal bone (forehead), two parietal bones (top and sides), two temporal bones (around the ears), the occipital bone (back, with the large opening where the spinal cord leaves) and the sphenoid and ethmoid deep inside. They meet at immovable *sutures*: the coronal between frontal and parietals, the sagittal between the two parietals, the lambdoid at the back and the squamous above each ear. Fourteen facial bones form the face, including the two maxillae (upper jaw), two zygomatic bones (cheeks), two nasal bones and the mandible, the only skull bone that moves. Air-filled sinuses lighten the skull and warm the air we breathe.

Built to grow. At birth the skull bones are separated by soft *fontanelles*, which let the head mold slightly during birth and give the brain room to grow; the largest, at the top, usually closes by about 18 to 24 months. Nurses feel it to check a baby: sunken can mean dehydration, bulging can mean raised pressure inside the skull. The *hyoid*,

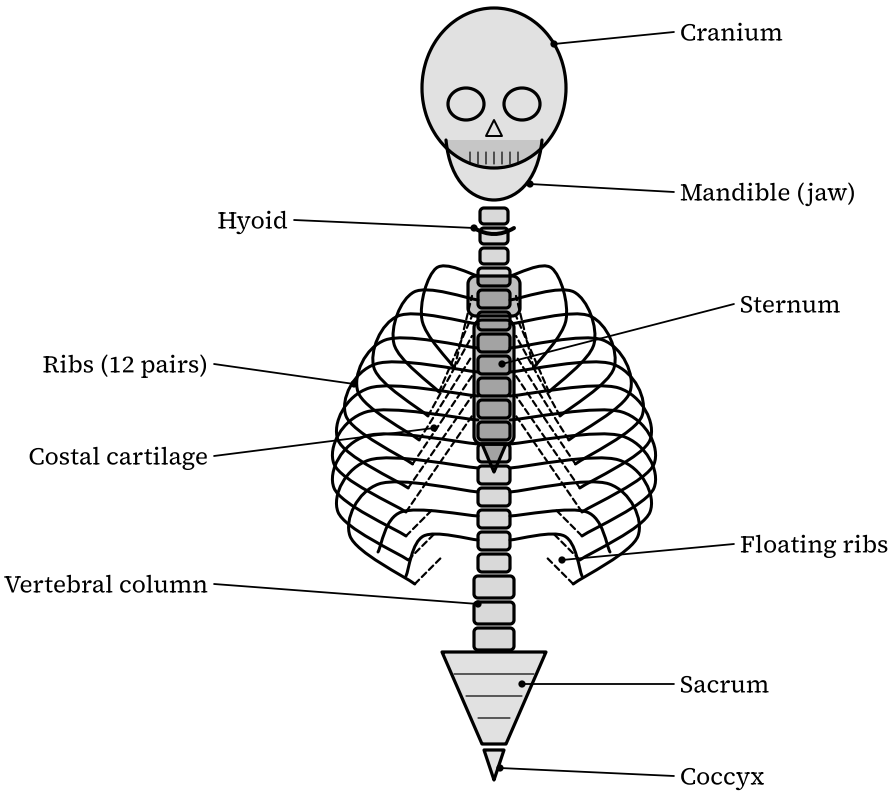
a small horseshoe-shaped bone in the neck, touches no other bone; it anchors the tongue and helps in swallowing.

The vertebral column. A child has 33 vertebrae; in an adult the lower ones have fused, leaving 26: 7 cervical (neck), 12 thoracic (chest), 5 lumbar (lower back), the sacrum (5 fused) and the coccyx (usually 4 fused). A memory aid: breakfast at 7, lunch at 12, dinner at 5. Seen from the side the column has four curves. The thoracic and sacral curves bend backward and are present at birth; the cervical curve forms as a baby learns to hold up its head and the lumbar curve as it learns to stand and walk. The S-shape works like a spring, absorbing the shock of each step and keeping the head balanced over the feet.

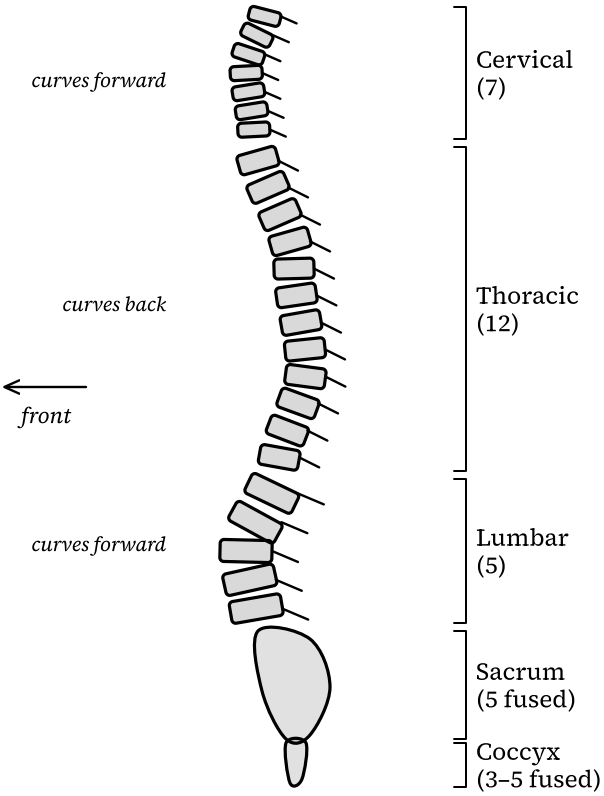
A vertebra. A typical vertebra has a *body* in front that bears weight, an *arch* behind that encloses the vertebral foramen for the spinal cord, and *processes* for muscles and joints; the spinous process is the bump you feel down your back. Vertebrae grow larger toward the bottom, because each carries all the weight above it. The first cervical vertebra (atlas) holds up the skull and lets you nod "yes"; the second (axis) has a peg that the atlas pivots around when you shake your head "no." The seventh cervical is the bump you found in the warm-up. Between the bodies lie *intervertebral discs*: a tough ring of fibrocartilage around a gel-like center. They make up about a quarter of the column's length and lose a little water under load during the day, so most people are around a centimeter shorter at bedtime than when they wake.

The thoracic cage. The sternum (manubrium, body and the small xiphoid process) and 12 pairs of ribs form a cage around the heart and lungs that also moves with every breath. Ribs 1–7 are *true ribs*, each joined to the sternum by its own costal cartilage. Ribs 8–10 are *false ribs* that join the cartilage of the rib above. Ribs 11 and 12 are *floating ribs* with no front attachment, though like all ribs they join the vertebrae behind. In CPR, rescuers press on the lower half of the sternum, avoiding the fragile xiphoid tip.

Try it. In the lab you will build a spool model of the spine and measure how much shorter you are at night.



The axial skeleton: skull, hyoid, vertebral column and thoracic cage.



The vertebral column from the side, with its four curves and the number of vertebrae in each region.

LAB

The Spool Spine and the Shrinking Student

You will build a working model of the spine and measure your own discs at work.

You will need

- 24 empty thread spools or short cardboard tubes in three sizes (7 small, 12 medium, 5 large), 23 thin kitchen sponge squares, a flexible cord or pipe cleaners, a paper-cup “sacrum”
- A tape measure, a flat book and a doorframe for height marks

Steps

1. Thread the spools on the cord in order (7 small, 12 medium, 5 large) with a sponge “disc” between each pair, ending in the cup. Bend the model into the four curves.
2. Press down on the top. Watch which parts give: the discs or the vertebrae?
3. For three days, measure your height first thing in the morning and again just before bed, with a book held flat on your head and a pencil mark on the doorframe. Record to the nearest millimeter.
4. Find your average morning-to-evening change.

Check your work

- ☐ Why are the lumbar spools the biggest?
- ☐ Where did the height you lost during the day go, and how did you get it back?

LAB NOTEBOOK

1. A front view of the axial skeleton and a side view of the spine with its curves labeled.
2. Your height data table with the average change.

From history. In Vesalius's day many people believed that men have one fewer rib than women, because God made Eve from one of Adam's ribs. In his *Fabrica* of 1543 Vesalius reported what he actually counted: twelve pairs of ribs in men and in women alike. Genesis says God took a rib from Adam; it nowhere says that Adam's sons would be born short of one, and a change made to one man's body is not passed to his children.

Practice habit. Touch it as you name it: say each skull bone and spinal landmark aloud while touching it on your own head and back.

WORKED EXAMPLES

Example 1. Account for the 80 bones of the axial skeleton.

Show solution

1. Skull: 8 cranial + 14 facial = 22
2. Middle-ear bones: 3 per ear × 2 = 6
3. Hyoid: 1
4. Vertebral column: 7 + 12 + 5 + sacrum + coccyx = 26
5. Thoracic cage: 24 ribs + 1 sternum = 25
6. 22 + 6 + 1 + 26 + 25 = 80

Answer: 80 bones

Example 2. A student measured 172.4 cm in the morning and 171.3 cm at bedtime. Find the change in centimeters and as a percent of morning height.

Show solution

1. 172.4 − 171.3 = 1.1 cm
2. 1.1 ÷ 172.4 × 100 = 0.64%

Answer: 1.1 cm, about 0.6% of height

Example 3. Identify the region of each vertebra: (a) a small vertebra with a hole in each transverse process for an artery; (b) a vertebra with facets on its body for ribs; (c) a large, heavy vertebra with no rib facets and no holes in its transverse processes.

Show solution

1. Holes in the transverse processes carry arteries to the brain: cervical.
2. Rib facets: thoracic.
3. Largest bodies, no rib facets: lumbar.

Answer: (a) cervical, (b) thoracic, (c) lumbar

PRACTICE

CONCEPT CHECKS

1. Easy Name the eight cranial bones.

   Show answer

   Frontal, two parietal, two temporal, occipital, sphenoid, ethmoid.

2. Easy How many vertebrae are in each region of the adult column? How many vertebrae does a child have, and why the difference?

   Show answer

   Cervical 7, thoracic 12, lumbar 5, sacrum 1 (5 fused), coccyx 1 (about 4 fused): 26. A child has 33 because the sacral and coccygeal vertebrae have not yet fused.

3. Medium Explain the difference between true, false and floating ribs, with rib numbers.

   Show answer

   True ribs (1–7) join the sternum through their own costal cartilage. False ribs (8–12) do not: 8–10 join the cartilage of the rib above, and 11–12 (floating ribs) have no front attachment.

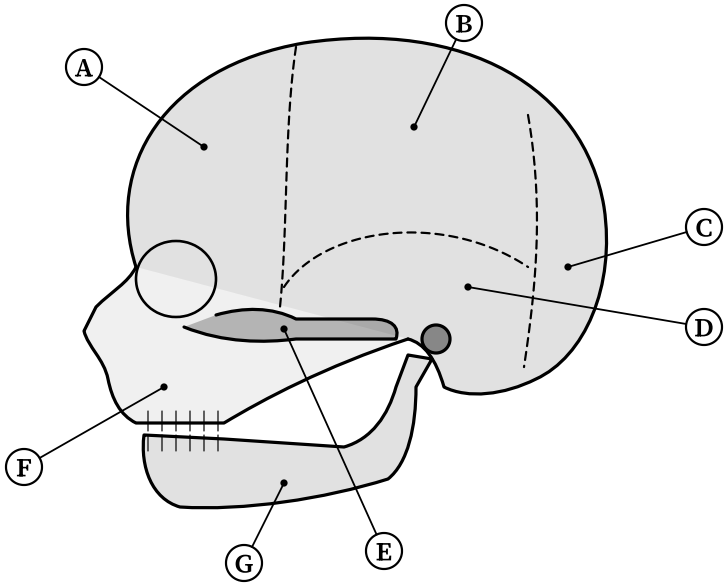
4. Medium Name the suture between (a) the frontal and parietal bones, (b) the two parietal bones, (c) the parietal and occipital bones.

   Show answer

   (a) Coronal, (b) sagittal, (c) lambdoid.

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the skull bones lettered A–G.



Show answer

A frontal, B parietal, C occipital, D temporal, E zygomatic, F maxilla, G mandible.

6. **Medium** Morning and evening heights over three days were 168.0 and 167.0 cm, 168.3 and 167.1 cm, 167.9 and 166.8 cm. Find the average daily change.

Show answer

1.1 cm

$(1.0 + 1.2 + 1.1) \div 3 = 1.1$

7. **Medium** Which two vertebrae let you nod “yes” and shake your head “no,” and how?

Show answer

The atlas (C1) cradles the skull, which rocks on it to nod “yes.” The atlas pivots around the peg (dens) of the axis (C2) to turn the head “no.”

DISORDER AS A BROKEN MECHANISM

8. Hard A disc between L4 and L5 is herniated: its gel center has pushed out through a weakened outer ring. The patient feels pain shooting down the back of one leg. Explain the mechanism.

Show answer

The bulging gel presses on a spinal nerve root as it leaves the column at that level. The compressed, inflamed nerve sends pain signals that the brain reads as coming from the area that nerve supplies, here along the sciatic nerve down the back of the leg (sciatica). Numbness or weakness can follow if the pressure continues.

TEST PREP

9. Easy Which region has the largest vertebral bodies?

A. cervical

B. thoracic

C. lumbar

D. coccygeal

Show answer

C. lumbar: they carry the most weight

10. Medium Why are an infant's skull bones separated by fontanelles, and what might a sunken fontanelle tell a nurse?

Show answer

Fontanelles let the skull mold slightly at birth and give the brain room to grow. A sunken fontanelle can be a sign of dehydration.

11. Hard The thoracic and sacral curves are present at birth, but the cervical and lumbar curves are not. When and why do they form?

Show answer

The cervical curve forms as the baby begins to hold up its head (a few months old), and the lumbar curve as the child sits, stands and walks (around the first year). The new loads shape the growing spine so that the head and trunk balance over the hips and feet.

COMMON MISTAKES

- Counting the fused sacrum and coccyx as separate vertebrae in an adult.

- Forgetting that the hyoid and the middle-ear bones belong to the axial skeleton.
- Thinking floating ribs float free at both ends; they attach to the vertebrae behind.
- Calling the mandible a cranial bone; it is a facial bone, and the only movable one.

Make it a game · Breakfast, Lunch and Dinner. The parent calls a number or a name: “7!”, “12!”, “5!”, “atlas!”, “xiphoid!”, “lambdoid!”. The student answers with the region, bone or suture and touches the spot on his or her own head, neck, back or chest. Two seconds per answer; three misses and roles swap.

Scripture. “He keepeth all his bones: not one of them is broken.” (Psalm 34:20, KJV)

The skull, spine and ribs are the body’s keepers, closing a guard of bone around brain, spinal cord, heart and lungs. John 19:36 sees this verse fulfilled at the cross.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

3.5 The Appendicular Skeleton

Mark up this lesson

OBJECTIVES

- Name the bones of the pectoral girdle and upper limb and of the pelvic girdle and lower limb, and account for the 126 appendicular bones.
- Find major bony landmarks on your own body.
- Explain how the girdles and limbs trade mobility against stability.

> **Warm-up.** Shrug your shoulders up and around in a big circle. Now try to do the same with your hips. Why can your shoulders move so much more freely?

WATCH

Human Skeleton | APPENDICULAR SKELETON

Miss Angler · 9:54

https://www.youtube.com/watch?v=52VdWyO-9_8

> **WHEN TO WATCH**
> After the core ideas.

BACKUP VIDEO

Appendicular Skeleton Anatomy | Pectoral Girdle, Pelvic Girdle, Upper Limb & Lower Limb Bones

Scientist Cindy · 12:10

https://www.youtube.com/watch?v=gtMAkrRbpus

As review before the practice.

KEY TERMS

appendicular skeleton
The 126 bones of the limbs and the girdles that attach them to the axial skeleton.

pectoral girdle
The clavicle and scapula on each side, which attach the arm to the trunk.

radius and ulna

The forearm bones: the radius on the thumb side (lateral), the ulna on the little-finger side (medial), with the olecranon at the elbow.

carpals, metacarpals, phalanges

The 8 wrist bones, 5 palm bones and 14 finger bones of each hand.

pelvic girdle

The two hip bones (each made of the fused ilium, ischium and pubis), which with the sacrum form the pelvis.

femur and patella

The thigh bone, the longest and strongest bone, and the kneecap, which sits inside the quadriceps tendon.

tibia and fibula

The leg bones: the large weight-bearing tibia on the inner side and the slender fibula on the outer side.

tarsals and metatarsals

The 7 ankle and heel bones and the 5 long bones of the foot.

CORE IDEAS

The limbs and their girdles. The appendicular skeleton is the moving part of the frame: 126 bones in the arms, legs and the two girdles that join them to the axis. Hands and feet alone hold 106 bones, more than half of the whole skeleton, which shows how much of our design is given to fine movement and balance.

The pectoral girdle: built for reach. Each shoulder has an S-shaped *clavicle*, a strut from the sternum to the shoulder, and a flat triangular *scapula* that rides on the back of the rib cage, held mostly by muscles. The clavicle is the arm's only bony link to the trunk, and it is one of the most often broken bones in falls. The shallow shoulder socket lets the arm swing through a huge range, but the price is stability: the shoulder dislocates more often than any other large joint.

The upper limb. The *humerus* runs from shoulder to elbow. In the forearm the *radius* lies on the thumb side (lateral in anatomical position) and the *ulna* on the little-finger side; the ulna's olecranon is the point of the elbow. The radius can roll over the ulna, turning the palm down and up. The wrist has 8 *carpals*, the palm 5 *metacarpals* and the fingers 14 *phalanges* (two in the thumb, three in each finger), 27 bones in each hand. A memory aid for the carpals, from the thumb side of the near

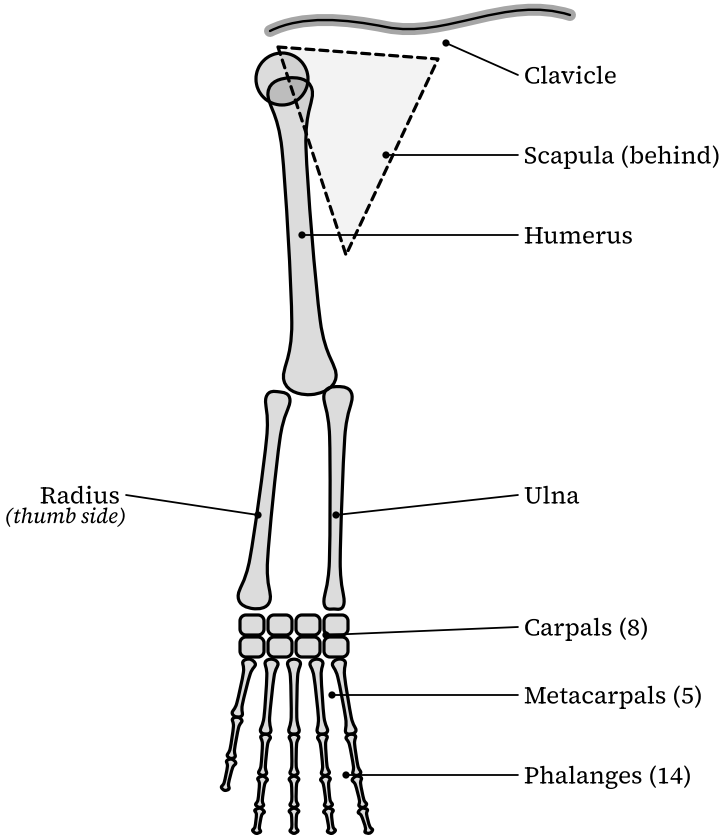
row: Sally Left The Party To Take Cathy Home (scaphoid, lunate, triquetrum, pisiform, trapezium, trapezoid, capitate, hamate).

The pelvic girdle: built for stability. Each hip bone is three bones fused in the teens: the flaring *ilium* (the crest you rest your hands on), the *ischium* (which you sit on) and the *pubis* in front. They meet in a deep socket, the acetabulum, which grips the head of the femur far more securely than the shoulder socket holds the humerus. The two hip bones and the sacrum form a sturdy basin that carries the weight of the upper body to the legs and protects the bladder and other pelvic organs. The female pelvis is generally wider and shallower, with a larger opening, suited to childbirth.

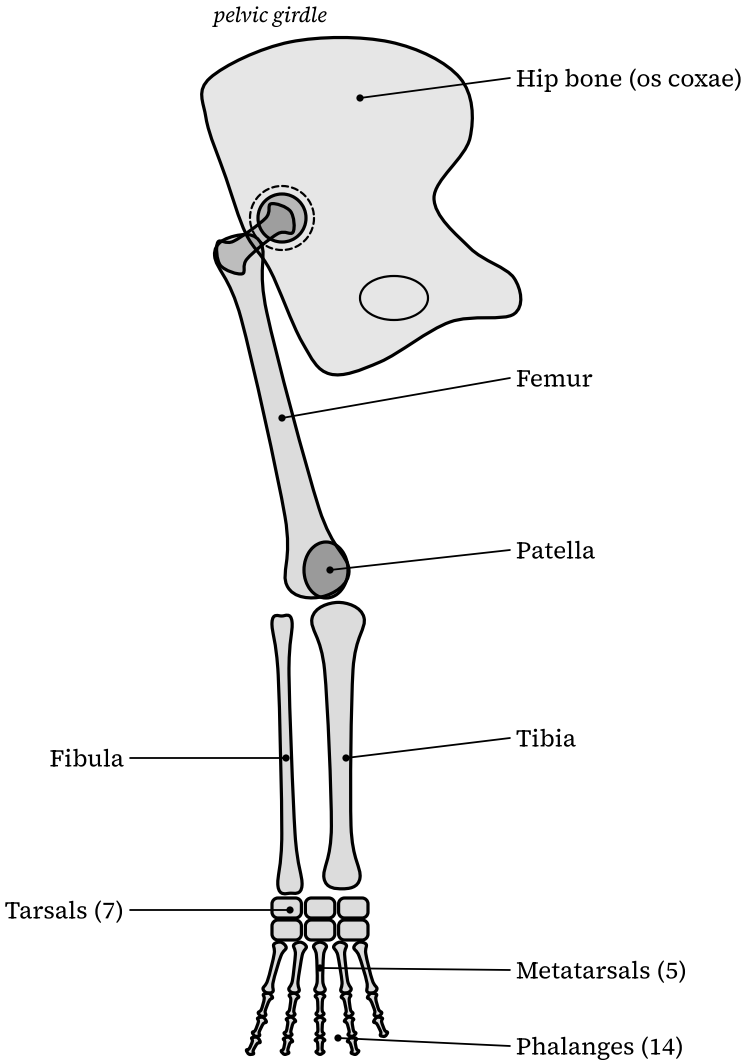
The lower limb. The *femur*, the longest and strongest bone, angles inward from hip to knee. Its narrow neck is where older people with weak bones most often break a hip. The *patella* sits inside the quadriceps tendon and improves the muscle's leverage. The *tibia* carries the body's weight; the slender *fibula* beside it mainly anchors muscles. The bumps on each side of the ankle are the end of the tibia (medial malleolus) and of the fibula (lateral malleolus). The foot has 7 *tarsals*, including the talus (which carries the leg's weight) and the calcaneus (the heel), 5 *metatarsals* and 14 phalanges, 26 bones arranged in arches that spread the load and spring with each step.

One plan, two jobs. Arm and leg follow the same plan: one bone, then two bones, then a cluster of small bones, then five long ones, then fourteen phalanges. On that common plan the arm is shaped for reach and skill and the leg for weight and walking, the same design adjusted for two different callings.

Try it. In the lab you will find landmarks on your own body and test the classic proportions between bone lengths and height.



The right upper limb and pectoral girdle, palm forward: the radius is on the thumb side.



The right lower limb and pelvic girdle: the tibia is on the inner side and the fibula on the outer side.

LAB

Landmarks and Proportions

Physical therapists and coaches find bones by touch. You will learn the landmarks and test body proportions on your family.

You will need

- A tape measure, a partner, washable marker or sticky dots, a data table

Steps

1. Find and touch each landmark on yourself: clavicle, acromion (tip of the shoulder), spine of the scapula, olecranon, the bumps on each side of the elbow, the styloid processes on each side of the wrist, iliac crest, greater trochanter (the bump on the side of the hip), patella, tibial tuberosity just below the knee, the medial and lateral malleoli, the calcaneus. Mark three with sticky dots and have your partner name the bone.
2. Measure height, arm span (fingertip to fingertip), foot length and thigh length (greater trochanter to the outer side of the knee joint) for at least four people.
3. For each person compute arm span ÷ height, foot length ÷ height and thigh length ÷ height.

Check your work

- ☐ Was arm span close to height? Was foot length close to 15 percent of height?
- ☐ How might a forensic scientist use a single femur?

LAB NOTEBOOK

1. Labeled sketches of the upper and lower limbs with their girdles.
2. Your proportions table with the class or family averages.

From history. On a November day in 1962 at Wrightington Hospital in the north of England, the surgeon John Charnley replaced a worn-out hip with a small polished steel ball on a stem set into the femur and a socket of tough plastic in the pelvis, both fixed with acrylic cement. He had tested the plastic for years on machines of his own design. His “low-friction arthroplasty” let crippled patients walk without pain, and hip replacement has since become one of the most successful operations in medicine.

Practice habit. Recite each limb by the same plan, one bone, two bones, a cluster, five, fourteen, and touch each part on your own arm or leg as you say it.

Career connection. Physical therapists help patients recover movement after fractures, joint replacements and strokes, and they find bony landmarks by touch dozens of times a day. In the United States a physical therapist earns a Doctor of Physical Therapy degree (about three years after a bachelor’s degree) and passes a national licensing exam; physical therapist assistants complete a two-year associate degree.

WORKED EXAMPLES

Example 1. Account for the 126 appendicular bones and the 206 bones of the skeleton.

Show solution

1. Each upper limb: humerus, radius, ulna, 8 carpals, 5 metacarpals, 14 phalanges = 30
2. Each lower limb: femur, patella, tibia, fibula, 7 tarsals, 5 metatarsals, 14 phalanges = 30
3. Pectoral girdles: 2 × (clavicle + scapula) = 4; pelvic girdle: 2 hip bones
4. 4 + 60 + 2 + 60 = 126
5. Axial 80 + appendicular 126 = 206

Answer: 126 appendicular bones; 206 in all

Example 2. A femur 45 cm long is found. If femur length is about 26 percent of height, estimate the person's height.

Show solution

1. height ≈ femur ÷ 0.26
2. = 45 ÷ 0.26 ≈ 173 cm

Answer: About 173 cm (about 5 ft 8 in)

Example 3. A woman falls on her outstretched hand and breaks the forearm bone just above the wrist on the thumb side. Which bone is it?

Show solution

1. In anatomical position the thumb is lateral.
2. The lateral forearm bone is the radius.
3. The end of the radius near the wrist takes the force of a fall on an outstretched hand.

Answer: The distal radius (a very common fracture)

PRACTICE

CONCEPT CHECKS

1. Easy Name the bones of the pectoral girdle and of the pelvic girdle.

   Show answer

   Pectoral: clavicle and scapula (on each side). Pelvic: the two hip bones, each formed from the fused ilium, ischium and pubis.

2. Easy In anatomical position, which forearm bone is lateral? Which leg bone carries most of the weight?

   Show answer

   The radius; the tibia.

3. **Medium** Each hand has 27 bones and each foot 26. How many bones are in both hands and both feet, and what percent of the 206-bone skeleton is that?

   Show answer

   106 bones, about 51%

   $2 \times 27 + 2 \times 26 = 106$; $106 \div 206 \times 100 = 51.5$

4. **Medium** Use the 26 percent rule to estimate the height of a person whose femur is 41 cm long.

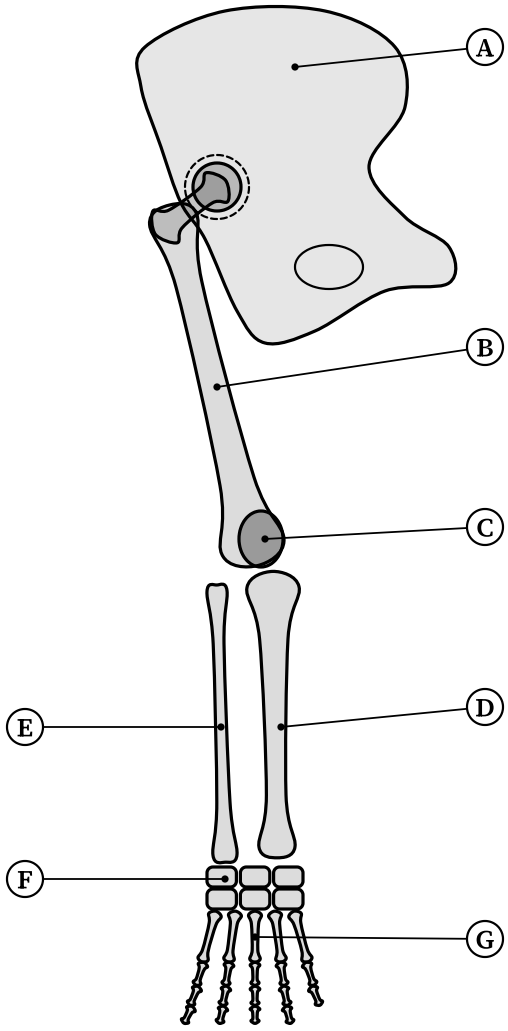
   Show answer

   About 158 cm

   $41 \div 0.26 = 157.7$

DIAGRAM AND DATA QUESTIONS

5. **Easy** Name the bones lettered A–G.



Show answer

A hip bone (os coxae), B femur, C patella, D tibia, E fibula, F tarsals, G metatarsals.

6. **Medium** A student is 160 cm tall, with a foot 24.0 cm long and an arm span of 162 cm. Find foot length as a percent of height and arm span ÷ height.

Show answer

Foot 15.0% of height (24.0 ÷ 160); arm span ÷ height = 1.01 (162 ÷ 160).

7. Medium Explain why the shoulder dislocates far more often than the hip.

Show answer

The shoulder socket is shallow and the scapula is held mainly by muscles, which gives a wide range of motion but little bony security. The hip's acetabulum is a deep cup that grips the femoral head, trading range for stability.

DISORDER AS A BROKEN MECHANISM

8. Hard An 82-year-old with osteoporosis falls and breaks the neck of her femur. The blood vessels that feed the femoral head run along that neck. Explain why surgeons often replace the femoral head instead of pinning it.

Show answer

Osteoporosis has thinned the femoral neck so a simple fall breaks it. The break can tear the vessels that run along the neck to the head, cutting off its blood supply; without blood the bone of the head dies (avascular necrosis) and will not heal even if pinned. Replacing it lets her walk again quickly and avoids a long time in bed.

TEST PREP

9. Easy Which of these is a sesamoid bone, formed inside a tendon?

A. scapula

B. patella

C. talus

D. clavicle

Show answer

B. patella

10. Hard After rolling an ankle, a player has a tender bump on the outer side of the ankle. Which bone forms that bump, and which bone forms the bump on the inner side?

Show answer

The outer bump is the lateral malleolus, the lower end of the fibula. The inner bump is the medial malleolus, the lower end of the tibia.

COMMON MISTAKES

- Swapping the radius and ulna; the radius is on the thumb side.
- Calling one hip bone “the pelvis”; the pelvis is both hip bones plus the sacrum.
- Thinking the fibula carries most of the weight; the tibia does.
- Giving the thumb or big toe three phalanges; each has two.

Make it a game · Touch and Tell. The parent calls a landmark or bone: lateral malleolus, olecranon, iliac crest, patella, clavicle, calcaneus, styloid process of the radius, greater trochanter. The student touches it on his or her own body within three seconds and names the bone it belongs to. Then swap roles.

Scripture. “He maketh my feet like hinds’ feet, and setteth me upon my high places.” (Psalm 18:33, KJV)

Each foot is 26 bones arched like a spring. David praised God for feet as sure as a deer’s on the rocky heights.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

UNIT 3

Skin and Bones

The skin is the body's largest organ and its first defense; bone is living tissue that grows, heals and stores minerals. This unit builds the integumentary system layer by layer, treats burns and wounds the way nurses and EMTs do, with the rule of nines, then studies bone tissue, growth and fracture repair, and names the 80 bones of the axial skeleton and the 126 of the appendicular skeleton.

Labs: fingerprints and the two-point touch test, a hand-tracing burn-area lab, the baked bone and the vinegar bone, a spool spine with a morning-and-evening height test, and body landmarks and proportions.

PREREQUISITES

- Units 1–2
- Biology 10.1 (Vesalius and the skeleton) is helpful but not required

MASTERY CHECKLIST

- ☐ I can describe the layers of the skin and the jobs of its cells, glands and hair, and explain how skin helps regulate temperature.
- ☐ I can classify burns by depth, estimate burned area with the rule of nines and describe the phases of wound healing.
- ☐ I can describe bone tissue, bone growth, calcium balance and fracture repair.
- ☐ I can name the major bones of the axial and appendicular skeleton and find key landmarks on my own body.

LESSONS IN THIS UNIT

3.1	**Skin: Layers and Accessory Structures**	4 sessions of 45 minutes
3.2	**Burns, Wounds and Healing**	4 sessions of 45 minutes
3.3	**Bone Tissue, Growth and Fracture Repair**	4 sessions of 45 minutes
3.4	**The Axial Skeleton**	4 sessions of 45 minutes

Unit 3 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **7 pts** **Lesson 3.1**

   Name the three layers of the skin and one important feature of each.

2. **7 pts** **Lesson 3.1**

   Explain how the skin acts as an effector when the body overheats and when it is chilled.

3. **7 pts** **Lesson 3.1**

   What does melanin do, and where is it made?

4. **8 pts** **Lesson 3.2**

   An adult has partial-thickness burns of the whole head, the front of the trunk and the front of both arms, and a superficial sunburn on the back. Estimate the TBSA to count.

5. **8 pts** **Lesson 3.2**

   A 70 kg patient has 30% TBSA burns. Using the Parkland formula, find the 24-hour fluid and the hourly rate for the first 8 hours.

6. **7 pts** **Lesson 3.2**

   Name the four phases of wound healing in order.

7. **7 pts** **Lesson 3.3**

   Where does a long bone grow in length, and why does growth in height stop in the late teens or early twenties?

8. **8 pts** **Lesson 3.3**

   Trace the negative feedback loop that restores blood calcium when it falls.

9. **7 pts** **Lesson 3.3**

   List the four stages of fracture repair in order.

10. **7 pts** **Lesson 3.4**

    Give the number of vertebrae in each region of the adult spine and name the two curves present at birth.

11. **7 pts** **Lesson 3.4**

    Name the bones that form (a) the forehead, (b) the back of the skull, (c) the lower jaw, (d) the cheek.

12. **7 pts** **Lesson 3.5**

    Name the bones of the upper limb from shoulder to fingertip, with the number of each in the hand.

SHORT ESSAY

13. **13 pts**

    Bone is “living tissue.” Defend this statement using bone cells, remodeling and Wolff’s law, calcium homeostasis, growth at the epiphyseal plates and fracture repair. End with one practical way a teenager can build strong bones for life.

ANSWER KEY

1. Epidermis: stratified squamous epithelium with no blood vessels, renewed from below. Dermis: connective tissue with vessels, nerves, glands and follicles. Hypodermis: loose and fat tissue that anchors, insulates and cushions.
2. Overheating: dermal vessels widen to bring heat to the surface and sweat glands secrete; evaporation removes heat. Chilled: dermal vessels narrow to keep warm blood in the core; arrector pili raise goose bumps.
3. It absorbs ultraviolet light, shielding the nuclei of epidermal cells from DNA damage. It is made by melanocytes in the stratum basale and passed to keratinocytes.
4. 36%

   head 9 + front trunk 18 + front of arms 4.5 + 4.5 = 36; the superficial burn is not counted
5. 8,400 mL; 525 mL/h

   4 × 70 × 30 = 8,400; 4,200 ÷ 8 = 525
6. Hemostasis, inflammation, proliferation, remodeling.
7. At the epiphyseal (growth) plates of cartilage. The plates are eventually replaced by bone and close into epiphyseal lines, so no more cartilage remains to grow.
8. Low blood calcium is sensed by the parathyroid glands, which release PTH; osteoclasts release calcium from bone, the kidneys keep calcium and activated vitamin D increases absorption in the gut; blood calcium rises and PTH falls.
9. Hematoma, soft (fibrocartilaginous) callus, hard (bony) callus, remodeling.
10. Cervical 7, thoracic 12, lumbar 5, sacrum (5 fused), coccyx (about 4 fused). The thoracic and sacral curves are present at birth.
11. (a) Frontal, (b) occipital, (c) mandible, (d) zygomatic.
12. Humerus; radius and ulna; 8 carpals; 5 metacarpals; 14 phalanges.
13. Look for: osteoblasts, osteocytes and osteoclasts and their jobs; continual remodeling (about 10% a year) and adaptation to load (tennis arm, astronauts); PTH and vitamin D keeping blood calcium steady; growth in length at the plates; the four-stage repair of a fracture; and weight-bearing exercise with enough calcium and vitamin D while peak bone mass is being built.

UNIT 4

Joints and Muscles

Bones give the body a frame, but joints and muscles make it move. This unit follows five discoveries: William Hunter's study of joint cartilage (1743) and John Charnley's artificial hip (1962), the chemists and microscopists who found how actin, myosin, ATP and calcium make a muscle fiber shorten, Giovanni Borelli's muscle levers (1680), Duchenne's electrical map of the muscles (1860s), and A. V. Hill's measurements of the energy of exercise.

Students classify joints and name movements, trace excitation–contraction coupling step by step, calculate the forces in the body's levers, learn the major muscles by place and action, and run a four-week training study on themselves. Labs use a homemade goniometer, paper sarcomere models, a ruler lever and a cardboard forearm, and simple bodyweight exercises.

PREREQUISITES

- Unit 1 (anatomical position, directional terms and planes)
- Unit 2, especially Lesson 2.4 (muscle and nervous tissue)
- Unit 3 (the skeleton)
- Basic algebra for lever calculations

MASTERY CHECKLIST

- ☐ I can classify joints by structure and function, name the six kinds of synovial joint, and use movement terms correctly.
- ☐ I can trace muscle contraction from the motor neuron's signal through calcium release to the cross-bridge cycle, and explain the roles of ATP.
- ☐ I can identify lever classes in the body and calculate muscle force and mechanical advantage.
- ☐ I can locate the major muscles, state their actions and name their antagonists.
- ☐ I can describe the three energy systems, fiber types and how muscle adapts to training.
- ☐ I can explain a joint or muscle disorder as a failure of a specific part.

LESSONS IN THIS UNIT

4.1 Joints and Body Movements: Hunter's Cartilage (1743) and Charnley's Hip (1962)

4 sessions of 45 minutes

4.2 How a Muscle Fiber Contracts: From Nerve Signal to Sliding Filaments

4 sessions of 45 minutes

4.3 Levers and Naming Muscles: Borelli's Muscle Machines (1680)

4 sessions of 45 minutes

4.4 The Major Muscle Groups: Duchenne's Electrical Map (1860s)

4 sessions of 45 minutes

4.5 Exercise and Muscle: A. V. Hill, Energy Systems and Training

4 sessions of 45 minutes

Unit 4 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **6 pts** **Lesson 4.1**

   Name the type of synovial joint and one movement it allows: (a) shoulder, (b) elbow, (c) base of the thumb, (d) the joint between the atlas and axis.

2. **7 pts** **Lesson 4.1**

   A knee reads 0° straight and 135° fully bent. After surgery it bends to 108°. What percent of the range of motion has returned?

3. **7 pts** **Lesson 4.2**

   List in order the steps from a motor neuron impulse to the first power stroke.

4. **7 pts** **Lesson 4.2**

   A sarcomere shortens from 2.4 µm to 2.0 µm. The thick filaments are 1.6 µm and each thin filament is 1.0 µm. Give the A band, I band and H zone before and after.

5. **7 pts** **Lesson 4.2**

   Why does a muscle stay contracted (rigor) when the cell runs out of ATP?

6. **8 pts** **Lesson 4.3**

   The biceps inserts 4.5 cm from the elbow. A 9.0 kg dumbbell (weight 88 N) is held 30 cm from the elbow with the forearm level. Find the biceps force and the mechanical advantage. Ignore the weight of the forearm.

7. **7 pts** **Lesson 4.3**

   Classify each as a first-, second- or third-class lever: (a) nodding the head, (b) rising onto the toes, (c) the biceps curling a weight.

8. **7 pts** **Lesson 4.3**

   Decode the names: (a) adductor longus, (b) sternocleidomastoid, (c) external oblique.

9. **8 pts** **Lesson 4.4**

   For each movement, name the prime mover and its antagonist: (a) straightening the knee, (b) bending the elbow, (c) pulling the toes up toward the shin.

10. **6 pts** **Lesson 4.4**

    What does the rotator cuff do, and why does the shoulder need it more than the hip needs similar muscles?

11. **8 pts** **Lesson 4.5**

    Compare the phosphagen system, anaerobic glycolysis and aerobic respiration: for each give how fast it supplies ATP, how long it can last at high effort, and one sport that relies on it.

12. **6 pts** **Lesson 4.5**

    Estimate the 1RM of a student who lifts 50 kg for 5 repetitions, using the Epley formula.

DISORDERS AND DATA

13. **8 pts** **Lesson 4.2**

    Explain why a person with myasthenia gravis has drooping eyelids by evening that improve after rest. Name the part that is broken.

14. **8 pts** **Lesson 4.5**

    A student records max push-ups: week 0, 15; week 2, 21; week 4, 24. (a) Find the percent increase from week 0 to week 2 and from week 2 to week 4. (b) Explain the pattern using nervous-system and muscle adaptations.

ANSWER KEY

1. (a) ball-and-socket: abduction, rotation, flexion and more; (b) hinge: flexion and extension; (c) saddle: opposition; (d) pivot: rotation.
2. 108/135 = 0.80, so 80%.
3. ACh released at the neuromuscular junction → ACh binds receptors on the sarcolemma → impulse spreads along the membrane and down the T tubules → sarcoplasmic reticulum releases calcium → calcium binds troponin → tropomyosin uncovers actin's binding sites → cocked myosin heads bind actin and make the power stroke.
4. Before: A band 1.6 µm, I band 0.8 µm, H zone 0.4 µm. After: A band 1.6 µm, I band 0.4 µm, H zone 0.
5. ATP must bind the myosin head to release it from actin (and to pump calcium back). Without ATP the heads stay attached.
6. E = 88 × 30 / 4.5 ≈ 587 N (about 590 N); MA = 4.5/30 = 0.15.
7. (a) first, (b) second, (c) third.
8. (a) a long muscle that adducts (the thigh); (b) runs from the sternum and clavicle to the mastoid process of the skull; (c) an outer abdominal muscle with slanting fibers.
9. (a) quadriceps femoris / hamstrings; (b) biceps brachii (with the brachialis) / triceps brachii; (c) tibialis anterior / gastrocnemius and soleus.
10. Its four muscles hold the head of the humerus in the shallow glenoid socket and rotate the arm. The hip's deep socket holds the femur securely by its shape, so it relies less on muscles for stability.
11. Phosphagen: fastest, about 10 s, sprint start or a heavy lift. Anaerobic glycolysis: fast, about 10 s to 2 min, a 400 m run. Aerobic: slowest but largest yield, minutes to hours, a marathon or long bike ride.
12. 50 × (1 + 5/30) ≈ 58 kg.
13. The ACh receptors at the neuromuscular junction are blocked and destroyed by the person's own antibodies. Each impulse gives a weaker signal; with repeated use the signal fails to reach threshold in more fibers, so muscles such as the eyelid lifters weaken through the day; rest lets the junction recover.
14. (a) (21 − 15)/15 = 40%; (24 − 21)/21 ≈ 14%. (b) Early gains come quickly from the nervous system learning to recruit and coordinate motor units; later gains depend on slower growth of the fibers, so the rate of improvement slows.

4.1 Joints and Body Movements: Hunter's Cartilage (1743) and Charnley's Hip (1962)

Mark up this lesson

OBJECTIVES

- Classify joints by structure (fibrous, cartilaginous, synovial) and by how much they move.
- Describe the parts of a synovial joint and the six kinds of synovial joint, with an example of each.
- Name body movements correctly (flexion, abduction, rotation, supination and the rest) and measure range of motion with a goniometer.

> **Warm-up.** Without moving your upper arm, bend and straighten your elbow. Now swing your whole arm in a circle at the shoulder. Why can the shoulder do something the elbow cannot? Write one guess about what is different inside the two joints.

WATCH

Joints: Crash Course Anatomy & Physiology #20

CrashCourse · 9:22

https://www.youtube.com/watch?v=DLxYDoN634c

> **WHEN TO WATCH**
> After the parts of a synovial joint. Watch for the three structural classes and the six synovial joint types.

BACKUP VIDEO

Synovial Joints

Dr Matt & Dr Mike · 10:52

https://www.youtube.com/watch?v=JO_N1apvidE

With the six kinds of synovial joint.

KEY TERMS

articulation

A joint: any place where two bones (or a bone and cartilage) meet.

fibrous, cartilaginous and synovial joints

The three structural classes: bones joined by dense connective tissue, by cartilage, or separated by a fluid-filled cavity.

synovial joint

A freely movable joint with articular cartilage on the bone ends, a joint cavity of synovial fluid, and a capsule lined by a synovial membrane.

ligament

A band of dense connective tissue that joins bone to bone and steadies a joint; a tendon joins muscle to bone.

flexion and extension

Bending a joint so the angle between the bones decreases, and straightening it so the angle increases.

abduction and adduction

Moving a limb away from the midline of the body, and bringing it back toward the midline.

range of motion (ROM)

The number of degrees a joint can move from one end of its motion to the other, measured with a goniometer.

CORE IDEAS

The story. In 1743 the Scottish anatomist William Hunter read a paper to the Royal Society in London on the cartilage that covers the ends of bones inside joints. He described its smooth surface and its fibers, and he warned that once this cartilage is worn or ulcerated it does not grow back. For two hundred years surgeons had little to offer people whose hip cartilage had worn away. Then in the late 1950s the English surgeon John Charnley, working at Wrightington Hospital in Lancashire, began building artificial hips. His first plastic sockets wore out within a few years, so he tested materials on a machine in his own workshop, and in 1962 he settled on a small polished steel ball turning in a socket of high-density polyethylene, both fixed to the bone with acrylic cement. Millions of people now walk on hips descended from his design.

How they figured it out. Charnley's key idea came from engineering: friction. A large ball rubbing in a socket wastes effort and wears the surface, so he made the ball small (22 mm across) to reduce the turning force at the rubbing surface, and he measured wear on test rigs before any patient received an implant. He also noticed that a healthy joint is more slippery than ice on ice, because its cartilage is lubricated by synovial fluid. His long follow-up records of patients, kept for decades, showed which designs lasted and which failed. Careful measurement, honest records and patience turned a hopeless problem into one of the most successful operations in medicine.

The anatomy. Joints are grouped two ways. By *structure*: **fibrous joints**, such as the sutures of the skull and the joint holding a tooth in its socket, are bound by dense connective tissue and hardly move; **cartilaginous joints**, such as the discs between the vertebrae and the pubic symphysis, are joined by cartilage and move a little; **synovial joints**, such as the knee and shoulder, have a fluid-filled cavity and move freely. By *function* the same joints are called immovable (synarthrosis), slightly movable (amphiarthrosis) and freely movable (diarthrosis). Every synovial joint has articular cartilage (hyaline cartilage) capping the bone ends, a joint cavity of slippery synovial fluid, a two-layer capsule (a tough fibrous outer layer lined by the synovial membrane that makes the fluid) and ligaments that hold the bones together. Some also have pads of cartilage (the menisci of the knee) and fluid-filled sacs called bursae that cushion tendons.

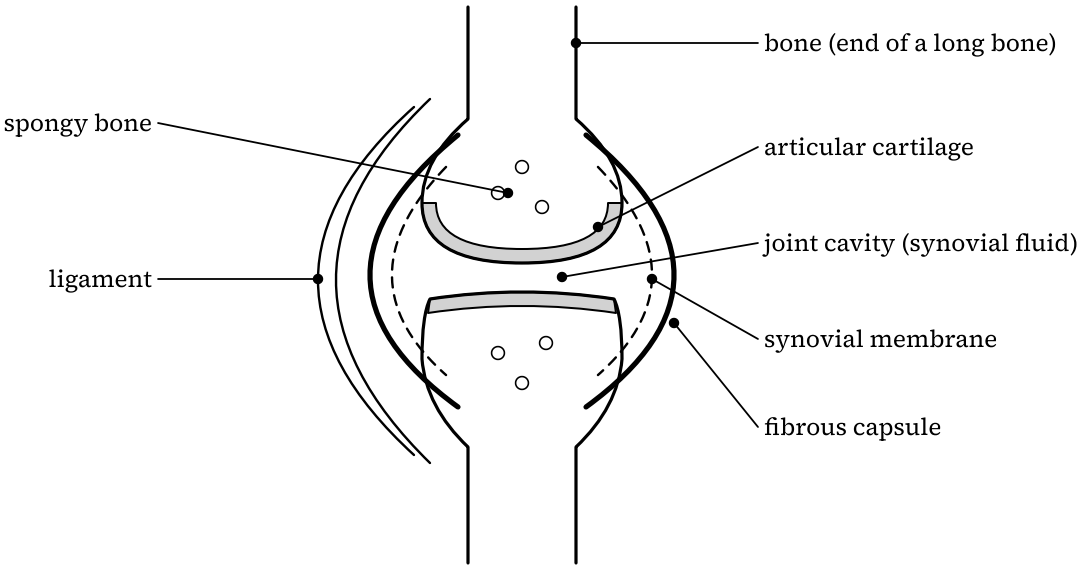
The six synovial joints. The shape of the bone ends sets the movement. A **plane joint** lets flat surfaces glide (between the small bones of the wrist). A **hinge joint** bends one way (elbow, finger joints). A **pivot joint** turns around one axis (the atlas turning on the axis when you shake your head "no"; the radius turning on the ulna). A **condyloid joint** lets an oval surface move in two directions (the wrist, the knuckles). A **saddle joint** has two saddle-shaped surfaces (the base of the thumb, which lets you touch your thumb to each finger). A **ball-and-socket joint** moves in every direction (shoulder and hip). The more freely a joint moves, the less stable it usually is: the shallow shoulder socket gives the greatest range of any joint and also dislocates most often, while the deep hip socket is far steadier.

Naming movements. Movements are named from anatomical position (Lesson 1.2). *Flexion* decreases the angle at a joint and *extension* increases it. *Abduction* takes a limb away from the midline and *adduction* brings it back ("add" it to the body);

circumduction traces a cone. *Rotation* turns a bone around its own long axis. The forearm has its own words: *supination* turns the palm up (as if holding soup) and *pronation* turns it down. At the ankle, *dorsiflexion* lifts the toes and *plantar flexion* points them; *inversion* turns the sole inward and *eversion* outward. Others are elevation and depression (shrugging), protraction and retraction (jaw or shoulder blades forward and back), and *opposition* of the thumb. A goniometer, a protractor with two arms, measures how many degrees a joint moves: its range of motion.

When it goes wrong. In **osteoarthritis**, the most common joint disease, articular cartilage slowly wears thin, bone rubs on bone and grows rough spurs, and the joint becomes painful and stiff. In **rheumatoid arthritis** the body's own immune system attacks the synovial membrane, which swells and damages the cartilage, often in matching joints on both sides of the body. A **sprain** is a stretched or torn ligament; a **dislocation** is when the bone ends are forced out of line. In **gout**, crystals of uric acid collect in a joint, classically the big toe. Each is a failure of a particular part you can point to on the diagram.

Where it is used. Physical therapists measure range of motion before and after an injury to show progress. Orthopedic surgeons repair torn ligaments and replace worn hips and knees. Athletic trainers tape ankles to limit inversion, the movement that causes most ankle sprains. Weight-bearing exercise, a healthy weight and good technique protect joint cartilage for life. In the lab you will build a goniometer and measure the range of motion of your own joints.



A synovial joint. The fibrous capsule and ligaments hold the bones together; the synovial membrane makes the fluid that lubricates the cartilage.

> **Safety first.** Move only as far as is comfortable, and never push or pull on a partner's joint. Skip any joint that is injured or recovering from surgery.

LAB

Range-of-Motion Lab with a Homemade Goniometer

You will build a simple goniometer, measure the range of motion of several joints, and name each movement correctly.

You will need

- A clear plastic protractor, two cardboard strips or craft sticks about 20 cm long, a brass paper fastener, tape
- A partner, a pencil and a data table

Steps

1. Tape one strip to the protractor's straight edge so it lines up with 0°. Fasten the second strip at the protractor's center hole with the paper fastener so it swings freely: that is the moving arm.
2. Elbow flexion: your partner lies or stands with the arm straight. Put the pivot over the elbow joint, the fixed arm along the upper arm and the moving arm along the forearm. Read the angle with the elbow straight, then fully bent. Subtract to get the range of motion.
3. Measure knee flexion (lying on your stomach), shoulder abduction (arm raised sideways) and wrist flexion and extension the same way. Take each measurement three times and average.
4. Repeat on the other side of the body and record which movement term (flexion, abduction and so on) and which synovial joint type each measurement uses.

Check your work

- ☐ Which joint had the largest range of motion? What kind of synovial joint is it?
- ☐ Were your left and right sides the same? Why might they differ?
- ☐ Why is a single reading less trustworthy than the average of three?

LAB NOTEBOOK

1. A labeled drawing of a synovial joint, from the core figure.

2. A range-of-motion table for at least four joints, both sides, with averages and movement names.

From history. Charnley was so set on cutting infection that he had surgeons work inside a clean-air enclosure and wear a hooded gown with its own exhaust, ideas that spread to operating rooms everywhere. He was knighted in 1977. William Hunter's younger brother John became even more famous as a surgeon and collector of anatomical specimens.

Practice habit. Each time you meet a movement term, do the movement with your own body and say the word aloud. Your joints remember what your eyes forget.

Career connection. Physical therapists help people recover movement after injuries, strokes and joint replacements. In the United States a physical therapist earns a Doctor of Physical Therapy degree (about three years after college) and passes a national licensing exam; a physical therapist assistant needs a two-year associate degree. Measuring range of motion, as you did in this lesson, is one of the first skills they learn.

WORKED EXAMPLES

Example 1. During a jumping jack, your arms swing from your sides up over your head and back. Name the movement at the shoulder in each half, and the joint type.

Show solution

1. Arms move away from the midline of the body in the frontal plane: abduction.
2. Arms come back toward the midline: adduction.
3. The shoulder is a ball-and-socket synovial joint (head of the humerus in the glenoid cavity).

Answer: Abduction on the way up, adduction on the way down, at a ball-and-socket joint

Example 2. A goniometer reads 5° with a patient's knee straight and 130° fully bent. Six weeks after a knee injury the same knee reaches only 95°. What was the original range of motion, and what percent of it has the patient regained?

Show solution

1. Original ROM: $130^\circ - 5^\circ = 125^\circ$
2. Injured ROM: $95^\circ - 5^\circ = 90^\circ$ if the knee still straightens to 5°.
3. Percent: $90/125 = 0.72$

Answer: 125° originally; 72% regained (assuming it still straightens to 5°)

Example 3. Classify each joint by structure and by function: (a) a suture of the skull, (b) an intervertebral disc joint, (c) the elbow.

Show solution

1. (a) Bones joined by dense fibrous tissue, no movement.
2. (b) Bones joined by a pad of fibrocartilage, slight movement.
3. (c) A joint cavity with synovial fluid, free movement.

Answer: (a) fibrous, immovable; (b) cartilaginous, slightly movable; (c) synovial (hinge), freely movable

PRACTICE

CONCEPT CHECKS

1. Easy Name the three structural classes of joints and give an example of each.

   Show answer

   Fibrous (skull sutures), cartilaginous (intervertebral discs, pubic symphysis), synovial (knee, shoulder, elbow).

2. Easy Which kind of synovial joint moves in every direction? Give two examples.

   Show answer

   Ball-and-socket: the shoulder and the hip.

3. **Medium** What is the difference between a ligament and a tendon?

Show answer

A ligament joins bone to bone; a tendon joins muscle to bone.

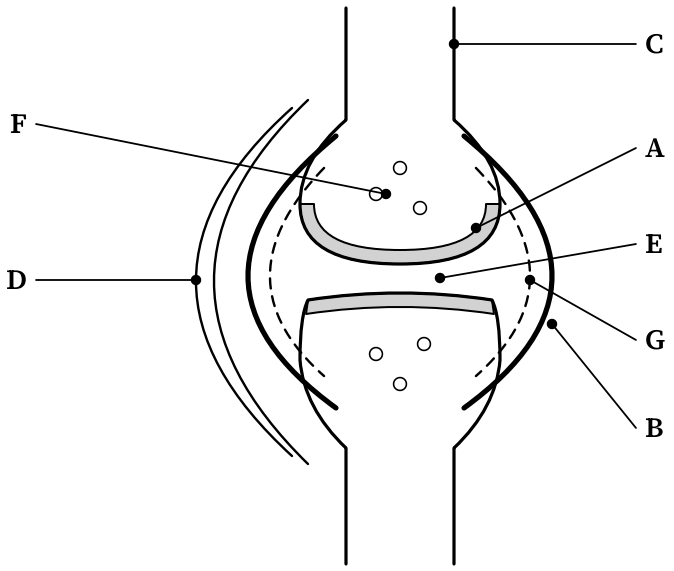
4. **Medium** Name the movement: (a) raising your arm out to the side, (b) pointing your toes, (c) turning your palm up, (d) touching your thumb to your little finger, (e) shaking your head “no”.

Show answer

(a) abduction, (b) plantar flexion, (c) supination, (d) opposition, (e) rotation (at the pivot joint between the atlas and axis).

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of a synovial joint: name each part marked A to G.



Show answer

A, articular cartilage; B, fibrous capsule; C, bone (end of a long bone); D, ligament; E, joint cavity filled with synovial fluid; F, spongy bone; G, synovial membrane.

6. **Medium** An elbow measures 0° straight and 140° fully bent. After a month in a cast it bends only to 98°. What percent of the normal range of motion does it have?

Show answer

98/140 = 0.70, so 70%.

7. Hard The shoulder has a much shallower socket than the hip. Explain the trade-off this creates.

Show answer

The shallow socket lets the shoulder move through the greatest range of any joint, but the bones are held mostly by muscles and ligaments, so it is less stable and dislocates more easily. The deep hip socket is stable for bearing weight but moves less.

DISORDER AS A BROKEN MECHANISM

8. Medium Osteoarthritis and rheumatoid arthritis both cause painful joints. For each, name the part of the synovial joint that fails first and what goes wrong with it.

Show answer

Osteoarthritis: the articular cartilage wears thin until bone rubs on bone (wear and tear). Rheumatoid arthritis: the immune system attacks the synovial membrane, which becomes inflamed and then damages the cartilage and bone.

PREDICT THE EFFECT

9. Hard Predict the effect: suppose an illness made synovial fluid thin and watery. What would happen to the joint over time, and why?

Show answer

The cartilage surfaces would be poorly lubricated, so friction would rise and the cartilage would wear faster, leading to pain and stiffness like osteoarthritis.

10. Challenge A child's growth plate is a cartilaginous joint (a synchondrosis) between the shaft and end of a long bone. What happens to it in adulthood, and why does that end growth in height?

Show answer

At the end of puberty the cartilage of the growth plate is replaced by bone and the two parts fuse (a bony joint, or synostosis). With no cartilage left to grow and turn into bone, the bone can no longer lengthen.

COMMON MISTAKES

- Mixing up ligaments (bone to bone) and tendons (muscle to bone).

- Thinking extension means “stretching”; it means straightening, increasing the joint angle.
- Confusing abduction and adduction; adduction “adds” the limb back to the body.
- Swapping supination and pronation; with the palm up you can hold a bowl of soup (supination).
- Calling every movable joint a hinge; only joints that bend one way (elbow, fingers) are hinges.

Make it a game · Simon Says Joints. The parent calls out “Simon says abduct your hip” or “Simon says pronate.” The student performs the movement and names the joint type used (hinge, pivot, ball-and-socket and so on). Wrong movement or wrong joint type, and the student calls the next three. Switch roles after ten commands.

Scripture. “Thou hast clothed me with skin and flesh, and hast fenced me with bones and sinews.” (Job 10:11, KJV)

Bones and sinews are fastened together at the joints. A good surgeon can replace a worn hip, but no machine yet matches the living cartilage and fluid God designed to last a lifetime.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

4.2 How a Muscle Fiber Contracts: From Nerve Signal to Sliding Filaments

Mark up this lesson

OBJECTIVES

- Describe the structure of a skeletal muscle from the whole muscle down to the sarcomere.
- Trace the steps of excitation–contraction coupling, from the motor neuron's signal to calcium release and the cross-bridge cycle.
- Explain the roles of ATP, calcium, troponin and tropomyosin, and calculate band lengths as a sarcomere shortens.

> **Warm-up.** Squeeze a clothespin between your thumb and finger as many times as you can in 30 seconds. Rest 10 seconds and repeat three more times. Record your counts. Why do the numbers fall? Keep your data for the lab.

WATCH

Muscles, Part 1 - Muscle Cells: Crash Course Anatomy & Physiology #21

CrashCourse · 10:24

https://www.youtube.com/watch?v=Ktv-CaOt6UQ

> **WHEN TO WATCH**
> After the steps from nerve signal to calcium release. Watch for the cross-bridge cycle and the job of ATP.

BACKUP VIDEO

Muscle Tissues and Sliding Filament Model

Amoeba Sisters · 8:20

https://www.youtube.com/watch?v=dpxalWACO7k

With the sarcomere and the sliding filaments.

KEY TERMS

muscle fiber

One long skeletal muscle cell with many nuclei, packed with myofibrils; bundles of fibers form fascicles, and bundles of fascicles form the muscle.

neuromuscular junction

The synapse where a motor neuron releases acetylcholine onto a muscle fiber.

troponin and tropomyosin

Proteins on the thin filament that cover myosin's binding sites; calcium binding to troponin moves tropomyosin aside.

rigor mortis

The stiffening of muscles after death, because without ATP the myosin heads cannot let go of actin.

sarcomere

The repeating unit of a myofibril, from one Z line to the next; it shortens when the muscle contracts.

sarcoplasmic reticulum

The muscle fiber's network of internal membranes that stores calcium ions and releases them when the fiber is stimulated.

cross-bridge cycle

The repeated attach, pull (power stroke), release and re-cock of myosin heads on actin, powered by ATP.

CORE IDEAS

The story. In 1939 the Russian biochemists Vladimir Engelhardt and Militsa Lyubimova showed that myosin, the main protein of muscle, can split ATP. In 1942, in Albert Szent-Györgyi's laboratory in Szeged, Hungary, Bruno Straub discovered a second protein, actin, and Szent-Györgyi showed that threads made of actin and myosin together shortened when ATP was added: muscle contraction in a test tube. In 1954 two pairs of British scientists showed with microscopes that the filaments slide past each other rather than shrinking (see PE Grade 9, Lesson 4.1, which tells that story). The last piece came from the Japanese scientist Setsuro Ebashi, who in the 1960s found that calcium is the switch and discovered troponin, the protein calcium binds to.

How they figured it out. Each step was a careful experiment. Szent-Györgyi's team separated muscle proteins and recombined them one at a time to see which were needed. The 1954 teams measured the bands of living and stretched muscle fibers and found that the dark A band never changed length while the light I band and the H zone shrank: the filaments must be sliding. Ebashi found that purified actin and myosin contracted whether or not calcium was present, but natural thin filaments did not: some extra protein on them was blocking contraction until calcium arrived. Good science often works like this, by taking a system apart and putting it back together.

From muscle to sarcomere. A skeletal muscle is wrapped in connective tissue and divided into bundles called fascicles. Each fascicle holds many **muscle fibers**, long cells with many nuclei. Each fiber is packed with myofibrils, and each myofibril is a chain of **sarcomeres.** In a sarcomere, thin filaments of actin are anchored to the Z lines at each end; thick filaments of myosin sit in the middle, held at the M line, with hundreds of heads sticking out toward the thin filaments. The A band is the length of the thick filaments (about 1.6 μm); the I band is where there are thin filaments only; the H zone is where there are thick filaments only. When the sarcomere shortens, the A band stays the same, while the I band and H zone shrink.

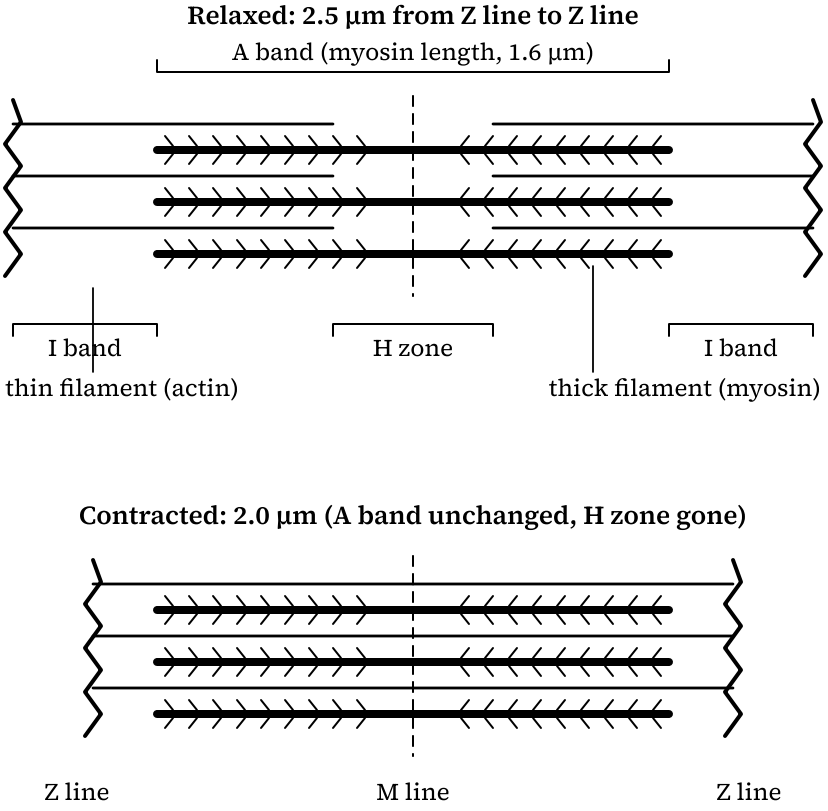
From nerve to calcium. A motor neuron's impulse reaches the **neuromuscular junction** and releases acetylcholine (ACh). ACh binds receptors on the muscle fiber's membrane (the sarcolemma) and starts an electrical impulse that races along the membrane and down tunnels called T tubules into the fiber. The impulse makes the **sarcoplasmic reticulum** release calcium ions. Calcium binds **troponin**, which pulls **tropomyosin** off the binding sites on actin. This whole chain is called excitation–contraction coupling.

The cross-bridge cycle. (1) A myosin head that has already split an ATP into ADP and phosphate is "cocked" and binds to an exposed site on actin, forming a cross-bridge. (2) It releases the ADP and phosphate and swivels, pulling the thin filament toward the M line: the power stroke. (3) A new ATP binds to the head, and the head lets go of actin. (4) The head splits that ATP and re-cocks, ready to grab again farther along. Each stroke moves the filament only about 10 nanometers, but hundreds of heads on each thick filament cycle many times a second, out of step with one another like a team pulling a rope hand over hand. When the nerve signal stops, an enzyme (acetylcholinesterase) breaks down ACh, calcium is pumped back into the

sarcoplasmic reticulum (which also uses ATP), tropomyosin covers the sites again, and the muscle relaxes. ATP is needed both to release the heads and to pump calcium; without it, as after death, the heads stay locked on (rigor mortis).

When it goes wrong. In **myasthenia gravis** the immune system makes antibodies that block and destroy the ACh receptors at neuromuscular junctions. The nerve releases ACh normally, but fewer receptors catch it, so the muscle fiber's signal is weak. Muscles tire very quickly with use, often first the eyelids and eye muscles, and get stronger after rest. Doctors treat it with drugs that slow acetylcholinesterase, so each ACh molecule lasts longer and has more chances to find a working receptor.

Where it is used and try it. Doctors measure muscle enzymes in the blood after injury; anesthesiologists use drugs that block the neuromuscular junction during surgery; athletes know that muscles fatigue partly because calcium release and ATP supply cannot keep up. In the lab you will build a scale model of a sarcomere, measure its bands relaxed and contracted, and graph your clothespin fatigue data.



The sliding filaments. Neither filament gets shorter; they overlap more, so the Z lines are pulled closer together.

LAB

Sarcomere Model and Fatigue Data

You will build a scale model of a sarcomere to see why some bands shrink and others do not, then analyze muscle fatigue.

You will need

- Two colors of paper or card, scissors, tape, a ruler, a sheet of poster board
- A clothespin, a stopwatch, graph paper

Steps

1. Use a scale of 10 cm for 1 µm. Cut two Z-line strips, six thin filaments 10 cm long (1.0 µm) in one color and three thick filaments 16 cm long (1.6 µm) in the other.
2. Tape the thin filaments to the Z lines and set the Z lines 25 cm apart (a relaxed 2.5 µm sarcomere). Center the thick filaments between them, overlapping the thin ones without taping. Measure the A band, I band and H zone.
3. Slide the Z lines to 22 cm and then 20 cm apart. Measure all three bands each time and record them in a table.
4. Graph your clothespin counts from the warm-up against the trial number. Then do four more 30-second trials after a 2-minute rest and add them to the graph.

Check your work

- ☐ Which band never changed length in your model? Why?
- ☐ What would happen to the H zone if the Z lines moved closer than 2.0 µm?
- ☐ How much did rest restore your clothespin count? What does the muscle need to recover?

LAB NOTEBOOK

1. The relaxed and contracted sarcomere, labeled, with your band measurements.
2. A flow chart of the eight steps from nerve impulse to relaxation.

From history. Szent-Györgyi had already won the 1937 Nobel Prize for discovering vitamin C (which he extracted in quantity from Hungarian paprika) before he turned to muscle. During the Second World War his laboratory kept working on actin and myosin, and Straub's discovery was first published in a small Hungarian journal that few outside the country could read until after the war.

Practice habit. When you study a process with many steps, write each step on a separate card, shuffle them and put them back in order until you can do it in under a minute.

WORKED EXAMPLES

Example 1. A sarcomere has thin filaments 1.0 µm long on each side and thick filaments 1.6 µm long. Find the I band and H zone when it is 2.5 µm long and when it has shortened to 2.0 µm.

Show solution

1. I band (total of both halves) = sarcomere length − A band.
2. At 2.5 µm: $2.5 - 1.6 = 0.9\ \mu\text{m}$; at 2.0 µm: $2.0 - 1.6 = 0.4\ \mu\text{m}$
3. H zone = sarcomere length − the two thin filaments: $2.5 - 2(1.0) = 0.5\ \mu\text{m}$; at 2.0 µm: $2.0 - 2.0 = 0$

Answer: Relaxed: I band 0.9 µm, H zone 0.5 µm. Contracted: I band 0.4 µm, H zone gone. The A band stays 1.6 µm.

Example 2. A muscle fiber has 10,000 sarcomeres in a row, each 2.5 µm long. Each shortens to 2.0 µm. How long is the fiber before and after, and by what percent does it shorten?

Show solution

1. Before: $10{,}000 \times 2.5\ \mu\text{m} = 25{,}000\ \mu\text{m} = 25\ \text{mm}$
2. After: $10{,}000 \times 2.0\ \mu\text{m} = 20\ \text{mm}$
3. Percent: $5/25 = 0.20$

Answer: 25 mm to 20 mm, a 20% shortening; many tiny shortenings in series add up

Example 3. Put these in order: calcium binds troponin; ACh binds receptors on the sarcolemma; the power stroke; the impulse travels down the T tubules; the sarcoplasmic reticulum releases calcium; tropomyosin uncovers actin's binding sites; ATP binds and the myosin head detaches.

Show solution

1. Start at the junction: ACh binds receptors.
2. The impulse spreads down T tubules, and the sarcoplasmic reticulum releases calcium.
3. Calcium binds troponin; tropomyosin moves; myosin binds and pulls; ATP releases the head.

Answer: ACh binds → T tubules → calcium released → calcium binds troponin → binding sites uncovered → power stroke → ATP binds and head detaches

PRACTICE

CONCEPT CHECKS

1. Easy List from largest to smallest: myofibril, muscle, sarcomere, fascicle, muscle fiber.

   Show answer

   Muscle, fascicle, muscle fiber, myofibril, sarcomere.

2. Easy What chemical does a motor neuron release at the neuromuscular junction?

   Show answer

   Acetylcholine (ACh).

3. Medium What are the two jobs of ATP in muscle contraction and relaxation?

   Show answer

   It lets the myosin head detach from actin (and re-cock for the next stroke), and it powers the pumps that return calcium to the sarcoplasmic reticulum so the muscle can relax.

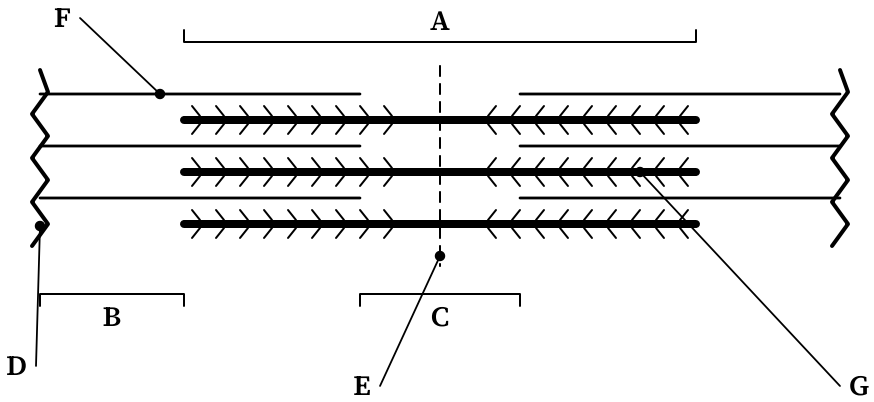
4. Medium What does calcium do in a muscle fiber?

Show answer

It binds troponin, which shifts tropomyosin off the binding sites on actin so myosin heads can attach.

DIAGRAM AND DATA QUESTIONS

5. Medium Label the diagram of a sarcomere: name each line, band or filament marked A to G.



Show answer

A, A band; B, I band; C, H zone; D, Z line; E, M line; F, thin filament (actin); G, thick filament (myosin).

6. Medium With thin filaments 1.0 µm and thick filaments 1.6 µm, find the I band and H zone of a 2.2 µm sarcomere.

Show answer

I band = 2.2 − 1.6 = 0.6 µm; H zone = 2.2 − 2.0 = 0.2 µm.

7. Hard A fiber has 8,000 sarcomeres in a row. It shortens from 2.4 µm to 2.1 µm per sarcomere. By how many millimeters does the fiber shorten?

Show answer

8,000 × 0.3 µm = 2,400 µm = 2.4 mm.

DISORDER AS A BROKEN MECHANISM

8. Medium In myasthenia gravis, antibodies destroy many ACh receptors at the neuromuscular junction. Explain why the patient's muscles tire quickly, and why a drug that slows acetylcholinesterase helps.

Show answer

With fewer receptors, each nerve impulse produces a weaker signal in the muscle fiber; with repeated use the ACh released per impulse falls a little and the signal no longer reaches threshold, so fibers drop out and the muscle weakens. Slowing acetylcholinesterase lets ACh stay in the junction longer, so it has more chances to bind the remaining receptors.

PREDICT THE EFFECT

9. Hard Predict the effect: a poison stops the sarcoplasmic reticulum from pumping calcium back in. What happens to the muscle?

Show answer

Calcium stays high, the binding sites stay uncovered, and the muscle cannot relax; it stays contracted (a cramp or spasm) as long as ATP lasts.

10. Challenge Explain why rigor mortis sets in some hours after death and why it eventually passes.

Show answer

After death the cells stop making ATP, and calcium leaks out of the sarcoplasmic reticulum. Myosin heads bind actin and, with no ATP to release them, stay locked, so the muscles stiffen. Later the proteins themselves break down, and the stiffness goes away.

COMMON MISTAKES

- Saying the filaments get shorter; they slide past each other and overlap more.
- Thinking ATP is needed for the power stroke itself; the stroke releases energy stored when ATP was split earlier, and fresh ATP is needed to let go.
- Forgetting that relaxation also costs ATP (to pump calcium back).
- Mixing up the A band (dark, constant) and the I band (light, shrinks): remember "I" for "lIght."
- Calling a sustained contraction "tetanus" and confusing it with the disease of the same name; the disease is caused by a toxin.

Make it a game · Cross-Bridge Relay. Two family members are "thin filaments" holding a rope; the student is a "myosin head." The parent hands out cards: CALCIUM (you may grab the rope), ATP (let go and re-cock), NO ATP (you must hold on: rigor). The student acts out each card and says what step it is. Then switch: the student calls the cards in the right order from memory while the parent acts them out.

Scripture. "But they that wait upon the LORD shall renew their strength; they shall mount up with wings as eagles; they shall run, and not be weary; and they shall walk, and not faint." (Isaiah 40:31, KJV)

Every muscle contraction spends ATP, and every muscle tires. Strength that never fails comes from the Lord.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

4.3 Levers and Naming Muscles: Borelli's Muscle Machines (1680)

Mark up this lesson

OBJECTIVES

- Identify the fulcrum, effort and load in a body movement and classify it as a first-, second- or third-class lever.
- Calculate mechanical advantage and the force a muscle must produce, using torque balance.
- Explain how muscles are named (location, shape, size, fiber direction, number of heads, attachments and action) and describe origin, insertion, prime mover, antagonist and synergist.

> **Warm-up.** Hold a heavy book in your hand with your elbow bent at a right angle. Then hold it close to your elbow, resting on your forearm. Which is easier? Where is your biceps attached, near the elbow or near the hand? Guess why.

WATCH

Levers | Skeletal System 09 | Anatomy & Physiology

Mike Tyler · 8:37

https://www.youtube.com/watch?v=ykuSpo4taZI

> **WHEN TO WATCH**
> Before Example 1. Watch for the three lever classes and where each appears in the skeleton.

BACKUP VIDEO

How are muscles named? - Terminology - Human Anatomy | Kenhub

Kenhub - Learn Human Anatomy · 11:30

https://www.youtube.com/watch?v=1h5l78st7wQ

With the naming rules.

KEY TERMS

lever

A rigid bar that turns about a fixed point; in the body the bone is the bar, the joint is the fulcrum, the muscle supplies the effort, and the body part or weight is the load.

mechanical advantage

Effort arm divided by load arm; above 1 the lever multiplies force, below 1 it multiplies speed and distance.

torque

The turning effect of a force: force times its perpendicular distance from the fulcrum.

origin and insertion

The fixed attachment of a muscle (usually closer to the trunk) and the attachment on the bone that moves.

prime mover (agonist)

The muscle mainly responsible for a movement.

antagonist and synergist

A muscle that opposes the prime mover, and a muscle that helps it or steadies the joint.

CORE IDEAS

The story. Archimedes boasted that with a lever and a place to stand he could move the earth. Nineteen centuries later the Italian physiologist and mathematician Giovanni Alfonso Borelli, who worked in Pisa and later in Rome, applied the law of the lever to living bodies. His book *De Motu Animalium* (On the Movement of Animals) was printed in 1680 and 1681, just after his death. It analyzed walking, running, jumping, flying and swimming as problems in mechanics, drawing bones as bars, joints as pivots and muscles as ropes. Borelli is often called the father of biomechanics.

How they figured it out. Borelli measured where muscles attach and how far the loads are from the joints, and applied the law of the lever: a lever balances when the torques on each side are equal. He reached a surprising conclusion. Because the biceps attaches only a few centimeters from the elbow while the hand is about thirty centimeters away, the muscle must pull many times harder than the weight in the hand. Muscles are built to be strong because the body's levers mostly trade force for speed and range. (For the physics of torque, see Physics and Engineering, Lesson 7.1: Torque, Archimedes' Lever.)

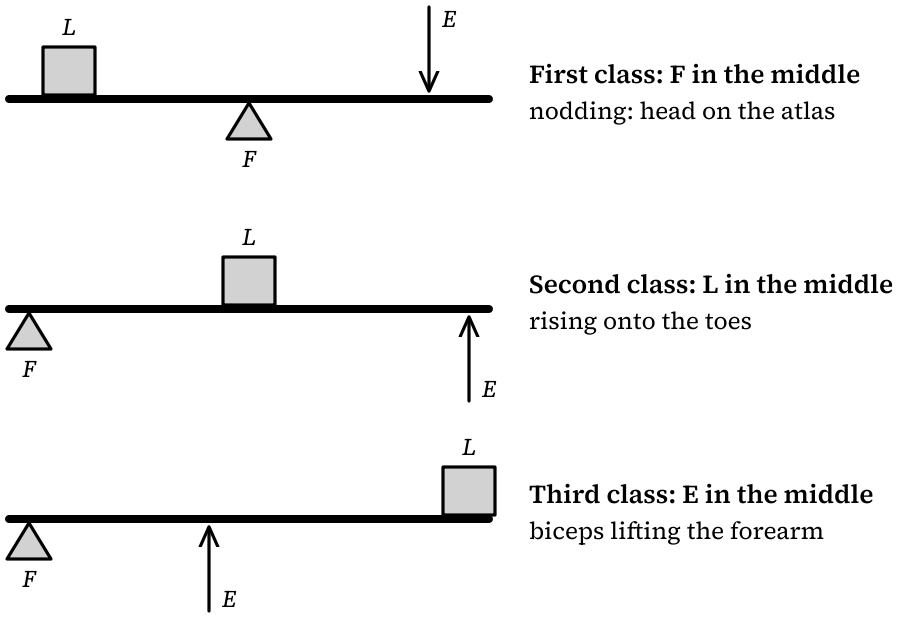
The three classes of lever. Every lever has a fulcrum (F), an effort (E) and a load (L); the class depends on which is in the middle. In a **first-class lever** the fulcrum is in the middle, like a seesaw: nodding your head, where the skull balances on the atlas, the face is the load and the neck muscles at the back pull down. In a **second-class lever** the load is in the middle, like a wheelbarrow: rising onto your toes, where the ball of the foot is the fulcrum, the body's weight acts through the ankle, and the calf muscles pull up on the heel. In a **third-class lever** the effort is in the middle, like tweezers or a fishing rod: the elbow is the fulcrum, the biceps pulls just below it, and the load is in the hand. Most of the body's levers are third-class.

Mechanical advantage. The **effort arm** is the distance from the fulcrum to where the muscle pulls; the **load arm** is the distance from the fulcrum to the load. At balance, $E \times d_E = L \times d_L$, and the mechanical advantage is $MA = d_E / d_L$. A second-class lever always has MA greater than 1 (it multiplies force). A third-class lever always has MA less than 1: the muscle pulls harder than the load, but a small shortening of the muscle swings the hand through a large, fast arc. If the biceps attaches 4 cm from the elbow and the hand is 32 cm away, MA is 1/8: the biceps must pull with eight times the load, and the hand moves eight times as far and as fast as the tendon.

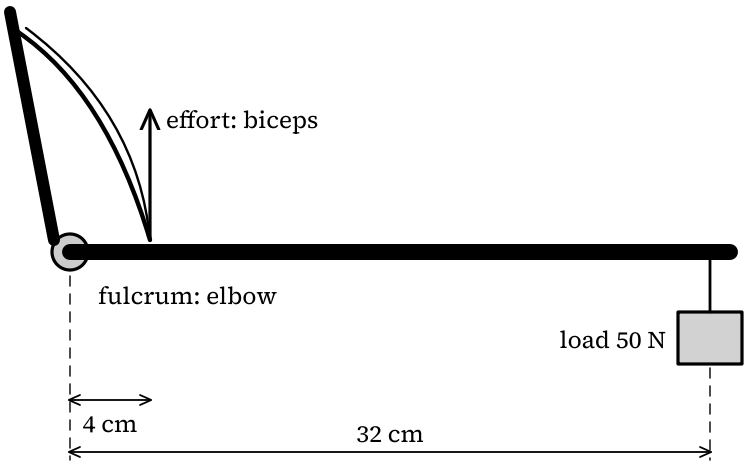
How muscles are named. Muscle names are Latin descriptions, and once you know the code they teach you about the muscle. They may tell *location* (tibialis anterior, at the front of the tibia), *shape* (deltoid, triangular like the Greek letter delta; trapezius, trapezoid), *size* (gluteus maximus, minimus; longus, brevis), *fiber direction* (rectus, straight; oblique, slanting; transversus, across), *number of heads* (biceps, two; triceps, three; quadriceps, four), *attachments* (sternocleidomastoid, from the sternum and clavicle to the mastoid process) or *action* (flexor, extensor, adductor). The **origin** is the attachment that stays put; the **insertion** is on the bone that moves. The muscle that does most of a movement is the **prime mover**; its **antagonist** does the opposite; **synergists** help. Muscles can only pull, so they work in opposing pairs such as biceps and triceps.

When it goes wrong. The Achilles (calcaneal) tendon joins the calf muscles to the heel. If it ruptures, often with a sudden push-off in basketball or tennis, the calf muscles can still contract, but their pull no longer reaches the heel: the effort is disconnected from the lever. The person can usually still point the foot weakly using smaller muscles but cannot rise onto the toes of that foot or push off normally when walking. Surgeons or a long period in a special boot reconnect the effort to the bar.

Where it is used and try it. Physical therapists choose exercises by their levers: an ankle weight hung farther from the knee makes the quadriceps work much harder. Engineers who design prosthetic limbs and robot arms use the same calculations. In the lab you will balance a ruler lever with coins and build a cardboard forearm whose “biceps” string you can move.



The middle item names the class: F in the middle, first class; L in the middle, second; E in the middle, third.



The forearm is a third-class lever with a mechanical advantage of $4/32 = 1/8$.

LAB

Ruler Levers and a Cardboard Forearm

You will measure mechanical advantage with a simple lever, then model the biceps and forearm.

You will need

- A 30 cm ruler, a pencil (fulcrum), a stack of identical coins, tape
- Two strips of stiff cardboard, a brass paper fastener, string, a small paper cup, a spring scale or a luggage scale (optional)

Steps

1. Balance the ruler on the pencil at its 15 cm mark. Put 2 coins 10 cm from the pencil on one side. Find where 1 coin must go on the other side to balance. Repeat with other combinations and test whether coins × distance is equal on both sides.
2. Build a forearm: fasten the two cardboard strips at one end with the paper fastener (the elbow). Tape the upper-arm strip to a box so it stands vertical. Punch holes along the forearm strip at 2, 4 and 6 cm from the elbow.
3. Hang the cup at the far end of the forearm and add 10 coins. Tie the string (the biceps) to the 2 cm hole, run it up over the top of the upper arm and pull until the forearm is level. Feel or measure the pull. Repeat with the 4 cm and 6 cm holes.
4. Calculate the mechanical advantage for each attachment point and compare with how hard you had to pull.

Check your work

- ☐ Which attachment point needed the least pull? Which made the cup move farthest for a short pull of the string?
- ☐ Why might God have placed the real biceps tendon close to the elbow?
- ☐ What class of lever is your model?

LAB NOTEBOOK

1. Your three lever diagrams with a body example for each.
2. A table of ten muscle names with what each part of the name means.

KEY FORMULAS

$$E \times d_E = L \times d_L \qquad MA = \frac{d_E}{d_L}$$

From history. Borelli was a friend of Marcello Malpighi, who discovered the capillaries, and he observed Jupiter's moons and comets as well as muscles. He spent his last years in poverty, living and teaching at a school run by a religious order in Rome. His great book, published after his death, was dedicated to Queen Christina of Sweden, who lived in Rome and had supported his work.

Practice habit. When you meet a new muscle, write its name, split it into its Latin parts and write what each part means. Then touch the muscle on yourself while you do its action.

WORKED EXAMPLES

Example 1. The biceps inserts 4 cm from the elbow. A 50 N load is held in the hand 32 cm from the elbow, with the forearm level. What force must the biceps pull with, and what is the mechanical advantage?

Show solution

1. Torque balance about the elbow: $E \times 4 = 50 \times 32$
2. $E = 1600/4 = 400$ N
3. $MA = d_E/d_L = 4/32 = 0.125$

Answer: 400 N; MA = 0.125 (1/8). The muscle pulls 8 times the load, but the hand moves 8 times as far as the tendon.

Example 2. Rising onto the toes of one foot, a 600 N student's weight acts through the ankle 12 cm from the ball of the foot (the fulcrum). The Achilles tendon pulls up on the heel 16 cm from the ball of the foot. Find the force in the tendon and the MA.

Show solution

1. Load in the middle: second-class lever.
2. $E \times 16 = 600 \times 12$, so $E = 7200/16 = 450$ N
3. $MA = 16/12 \approx 1.33$

Answer: 450 N; MA ≈ 1.33. This simple model ignores the extra force the ankle bones must carry.

Example 3. Decode the name *flexor carpi ulnaris*.

Show solution

1. *Flexor*: its action is flexion.
2. *Carpi*: of the carpus, the wrist.
3. *Ulnaris*: on the ulna side of the forearm.

Answer: A muscle on the ulna (little-finger) side of the forearm that flexes the wrist

PRACTICE

CONCEPT CHECKS

1. Easy In a lever, what are F, E and L, and how does the middle one tell you the class?

   Show answer

   Fulcrum, effort and load. Fulcrum in the middle: first class; load in the middle: second class; effort in the middle: third class.

2. Easy What does each name tell you? (a) gluteus maximus, (b) triceps brachii, (c) rectus abdominis, (d) deltoid.

   Show answer

   (a) the largest buttock muscle (size); (b) three heads, in the arm; (c) straight fibers, in the abdomen; (d) triangle-shaped.

3. **Medium** What is the difference between a muscle's origin and its insertion?

Show answer

The origin is the attachment on the bone that stays fixed; the insertion is on the bone that moves when the muscle contracts.

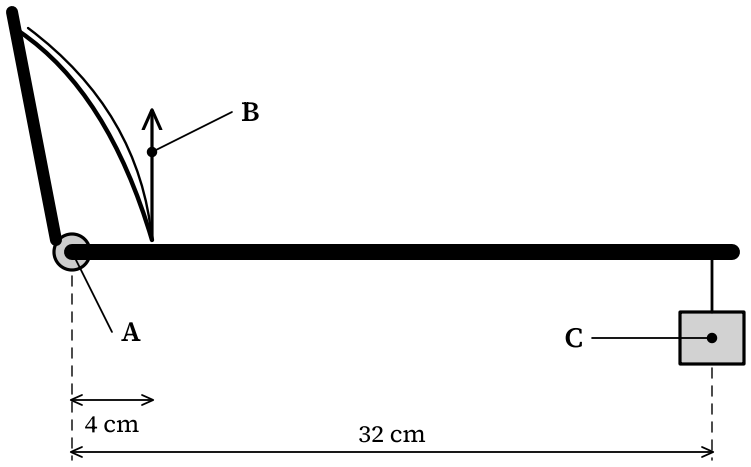
4. **Medium** When you bend your elbow, name the prime mover and the antagonist. When you straighten it, how do their roles change?

Show answer

Bending: the biceps brachii (with the brachialis) is the prime mover and the triceps brachii is the antagonist. Straightening: the triceps is the prime mover and the biceps is the antagonist.

DIAGRAM AND DATA QUESTIONS

5. **Medium** In the diagram of the forearm, identify what is at A, B and C, and the class of lever.



Show answer

A, fulcrum (the elbow joint); B, effort (the biceps pulling up near the elbow); C, load (the weight in the hand). Effort is in the middle, so it is a third-class lever.

6. **Medium** A biceps inserts 5 cm from the elbow. A 20 N load is held 35 cm from the elbow with the forearm level. Find the biceps force and the MA.

Show answer

E = 20 × 35 / 5 = 140 N; MA = 5/35 ≈ 0.14.

7. Hard A physical therapist straps a 40 N ankle weight 40 cm from the knee. The patellar tendon pulls 5 cm from the knee. With the leg held straight out and level, what force must the quadriceps produce to hold the weight (ignore the weight of the leg)?

Show answer

$E = 40 \times 40 / 5 = 320$ N.

DISORDER AS A BROKEN MECHANISM

8. Medium A tennis player ruptures his Achilles tendon. Using the lever model of a calf raise, explain why he cannot rise onto the toes of that foot even though his calf muscles still contract.

Show answer

In a calf raise the ball of the foot is the fulcrum, the body's weight is the load and the calf muscles pull up on the heel through the Achilles tendon (the effort). With the tendon torn, the muscles' pull no longer reaches the heel, so there is no effort on the lever to lift the load.

PREDICT THE EFFECT

9. Hard Predict the effect: if the biceps tendon inserted 8 cm from the elbow instead of 4 cm, how would lifting change? Give one advantage and one disadvantage.

Show answer

The MA would double (8/32 = 1/4), so the muscle would need only half as much force to hold the same load (advantage). But for each centimeter the muscle shortens, the hand would move only half as far, so movements would be slower and smaller (disadvantage).

10. Challenge Explain why most levers in the body are third-class, and why that requires muscles to be very strong.

Show answer

Third-class levers give a large, fast motion at the end of the limb for a small shortening of the muscle, which suits throwing, running and reaching. But the MA is less than 1, so the muscle must pull with several times the force of the load, which is why muscles and tendons are built so strong.

COMMON MISTAKES

- Classifying by where the fulcrum is instead of by which item is in the middle.
- Thinking a mechanical advantage below 1 is a design flaw; it buys speed and range of motion.
- Measuring the effort arm from the hand instead of from the fulcrum (the joint).
- Assuming a muscle can push; muscles only pull, so movements back the other way need an antagonist.
- Reading *biceps* as plural; it is one muscle with two heads ("bi-" two, "-ceps" head).

Make it a game · Name That Muscle Code. The parent says a muscle name (biceps femoris, tibialis anterior, adductor longus, pectoralis major, orbicularis oculi, flexor digitorum). The student must decode every part of the name in 10 seconds and point to where it is on the body. Score a point for each correct part; try to beat your own score next time.

Scripture. "If the iron be blunt, and he do not whet the edge, then must he put to more strength: but wisdom is profitable to direct." (Ecclesiastes 10:10, KJV)

Solomon knew that a poor tool demands more strength and wisdom directs it. Borelli's levers show the body's design trades strength for speed exactly where speed is needed.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

4.4 The Major Muscle Groups: Duchenne's Electrical Map (1860s)

Mark up this lesson

OBJECTIVES

- Locate and name the major skeletal muscles of the head, trunk and limbs on a diagram and on your own body.
- State the main action of each major muscle and identify antagonistic pairs.
- Explain how a muscle disease such as Duchenne muscular dystrophy follows from a broken part.

> **Warm-up.** Put your hand on the front of your thigh and stand up from a chair. Now put it on the back of your thigh and curl your heel toward your seat. What did you feel each time? Which muscles were working?

WATCH

Muscles, Part 2 - Organismal Level: Crash Course Anatomy & Physiology #22

CrashCourse · 10:40

https://www.youtube.com/watch?v=I80Xx7pA9hQ

> **WHEN TO WATCH**
> After the muscles of the trunk. Watch for muscle fiber arrangements and the major groups.

BACKUP VIDEO

FULL VIDEO: Main muscles of the upper limb - Human Anatomy | Kenhub

Kenhub - Learn Human Anatomy · 25:05

https://www.youtube.com/watch?v=LUFkj03iAc4

For students who want more detail on the shoulder, arm and forearm.

KEY TERMS

muscles of facial expression

Small muscles inserting into the skin of the face, such as the orbicularis oculi (closes the eye) and orbicularis oris (closes the lips).

core muscles

The rectus abdominis, obliques, transversus abdominis and back extensors that brace the trunk and spine.

hamstrings

The three muscles on the back of the thigh that flex the knee and extend the hip.

rotator cuff

Four muscles (supraspinatus, infraspinatus, teres minor and subscapularis) whose tendons hold the head of the humerus in its shallow socket.

quadriceps femoris

The four-headed muscle group on the front of the thigh that extends the knee.

dystrophin

A large protein that anchors the inside of a muscle fiber to its membrane; it is missing in Duchenne muscular dystrophy.

CORE IDEAS

The story. Guillaume-Benjamin Duchenne, a French physician who worked in Paris from the 1840s, used small electric currents applied to the skin with damp electrodes to make single muscles contract in living patients. Muscle by muscle he recorded what each one does on its own and what it does with its partners, and in 1867 he published *Physiologie des mouvements* (The Physiology of Motion). He also described a muscle-wasting disease in boys, which now bears his name. Earlier anatomists had worked out muscle actions mostly from dissection; Duchenne watched them work.

How they figured it out. Duchenne's method showed that a muscle's action depends on its attachments and on what else is contracting. Stimulating the deltoid alone raised the arm only so far; full elevation needed the trapezius to rotate the shoulder blade at the same time. He studied patients with paralysis of one muscle to see which movements they lost. Today physical therapists still test single muscles by asking a patient to hold a position against resistance, and electromyography (EMG)

records the electrical activity of muscles during movement, a direct descendant of his work.

Head, neck and trunk. The **muscles of facial expression**, such as the frontalis (raises the eyebrows), orbicularis oculi and orbicularis oris, insert into skin, which is why faces can show so much. The **masseter** and **temporalis** close the jaw. The **sternocleidomastoid** turns and bends the head. On the trunk, the **pectoralis major** pulls the arm across the chest; the **rectus abdominis** flexes the spine (a sit-up), and the **external and internal obliques** twist and bend it; the deep **transversus abdominis** tightens the abdomen like a belt. On the back, the **trapezius** moves and steadies the shoulder blade, the **latissimus dorsi** pulls the arm down and back (a pull-up), and the **erector spinae** straightens the spine. The **diaphragm** is the main muscle of breathing (Unit 8).

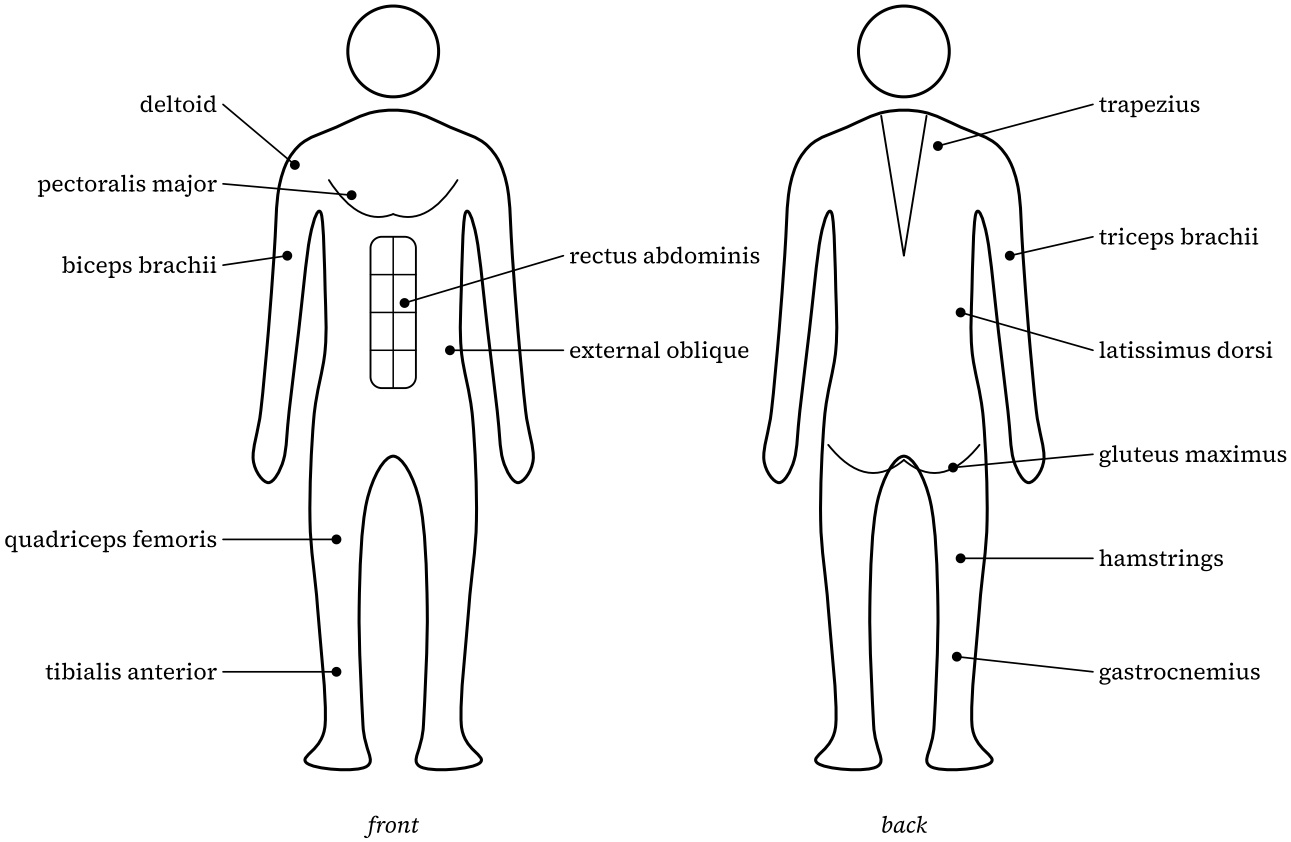
Shoulder and arm. The **deltoid** caps the shoulder and abducts the arm. Four small **rotator cuff** muscles hold the head of the humerus in its shallow socket and rotate it. On the upper arm, the **biceps brachii** flexes the elbow and supinates the forearm, helped by the brachialis beneath it; the **triceps brachii** on the back extends the elbow. Forearm muscles, mostly flexors on the palm side and extensors on the back, send long tendons across the wrist to move the hand and fingers, which keeps the hand slim and nimble.

Hip and leg. The **gluteus maximus** extends the hip (climbing stairs, standing up); the **gluteus medius** abducts it and keeps the pelvis level when you stand on one leg. The **iliopsoas** flexes the hip. On the thigh, the **quadriceps femoris** (four heads, joined in the patellar tendon) extends the knee; the **hamstrings** on the back flex the knee and extend the hip; the **adductors** on the inner thigh pull the legs together; the long strap-like **sartorius** crosses the thigh. On the lower leg, the **gastrocnemius** and **soleus** (the calf) plantar flex the foot through the Achilles tendon, and the **tibialis anterior** dorsiflexes it. Antagonistic pairs to remember: biceps and triceps, quadriceps and hamstrings, gastrocnemius and tibialis anterior, rectus abdominis and erector spinae.

When it goes wrong. Duchenne muscular dystrophy is an inherited disease, almost always in boys, caused by a faulty gene on the X chromosome for the protein **dystrophin**. Dystrophin works like a shock absorber, linking the contracting filaments inside each fiber to the membrane and the tissue outside. Without it, the

membrane tears a little with every contraction, calcium leaks in, and fibers die faster than they can be repaired; fat and scar tissue slowly replace muscle. Boys often show a telltale sign called Gowers' sign: to stand up from the floor they "walk" their hands up their own legs because the hip and thigh muscles are weak. Physicians and researchers are working on treatments, including gene-based therapies.

Where it is used and try it. Nurses give injections into the deltoid and the thigh (vastus lateralis) because these muscles are large and away from major nerves. Coaches and physical therapists design exercises for each group. In the lab you will find and feel each major muscle on yourself while doing its action, then test opposing pairs.



Thirteen major muscles to know by name, place and action. Most work in opposing pairs across a joint.

> **Safety first.** Do the muscle tests gently and stop if anything hurts. Partners press only lightly when giving resistance.

LAB

Muscle Map: Find It, Feel It, Name It

You will find the major muscles on your own body by doing their actions, and test antagonistic pairs against gentle resistance.

You will need

- A partner, a mirror, a washable marker or sticky notes
- The core figure, a chair, a step or stair

Steps

1. For each of the 13 muscles in the core figure, do its main action (for example, shrug for the trapezius, rise onto your toes for the gastrocnemius) and feel the muscle harden under your fingers. Put a sticky note on the spot on your clothing.
2. Antagonist test: sit in a chair. A partner rests a hand on the front of your ankle while you try to straighten the knee (quadriceps), then behind the ankle while you bend it (hamstrings). Note which feels stronger.
3. Repeat for the elbow (biceps and triceps) and the ankle (gastrocnemius and tibialis anterior).
4. Walk up a stair slowly and list every muscle you can feel working, in order.

Check your work

- ☐ Which muscles were hardest to find? Why might deep muscles be hard to feel?
- ☐ In each antagonistic pair, which was stronger? Why might that be?
- ☐ Which muscles were working to keep you balanced while you climbed?

LAB NOTEBOOK

1. Your own front-and-back muscle map with the 13 muscles labeled and one action each.
2. A table of four antagonistic pairs and the joint each pair moves.

From history. Duchenne had no hospital post of his own and visited many Paris hospitals looking for patients with nerve and muscle diseases; he became one of the founders of modern neurology. He took early photographs of the faces of volunteers whose facial muscles he stimulated, and noticed that a true smile uses the muscle around the eyes as well as the mouth; such a smile is still called a "Duchenne smile."

Practice habit. Learn muscles in pairs. Every time you study one, say its antagonist and the joint they share.

WORKED EXAMPLES

Example 1. During a push-up, name the main muscles that (a) straighten the elbows, (b) push the arms forward across the chest, (c) keep the body straight as a plank.

Show solution

1. (a) Elbow extension: triceps brachii.
2. (b) Moving the arms toward the midline in front: pectoralis major, helped by the front of the deltoid.
3. (c) Bracing the trunk: rectus abdominis, obliques and transversus abdominis, with the gluteus maximus.

Answer: (a) triceps brachii, (b) pectoralis major (with deltoid), (c) the core muscles and glutes

Example 2. A runner pushes off: the hip extends, the knee extends, and the foot plantar flexes. Name the prime mover for each joint and its antagonist.

Show solution

1. Hip extension: gluteus maximus (with the hamstrings); antagonist iliopsoas.
2. Knee extension: quadriceps femoris; antagonist hamstrings.
3. Plantar flexion: gastrocnemius and soleus; antagonist tibialis anterior.

Answer: Gluteus maximus vs iliopsoas; quadriceps vs hamstrings; calf (gastrocnemius, soleus) vs tibialis anterior

PRACTICE

CONCEPT CHECKS

1. **Easy** Which muscle abducts the arm at the shoulder?

   Show answer

   The deltoid.

2. **Easy** Name the antagonist of: (a) biceps brachii, (b) quadriceps femoris, (c) tibialis anterior.

   Show answer

   (a) triceps brachii, (b) hamstrings, (c) gastrocnemius (with the soleus).

3. **Medium** Which muscles make up the rotator cuff, and what is its main job?

   Show answer

   Supraspinatus, infraspinatus, teres minor and subscapularis. Their tendons hold the head of the humerus in the shallow shoulder socket and rotate the arm.

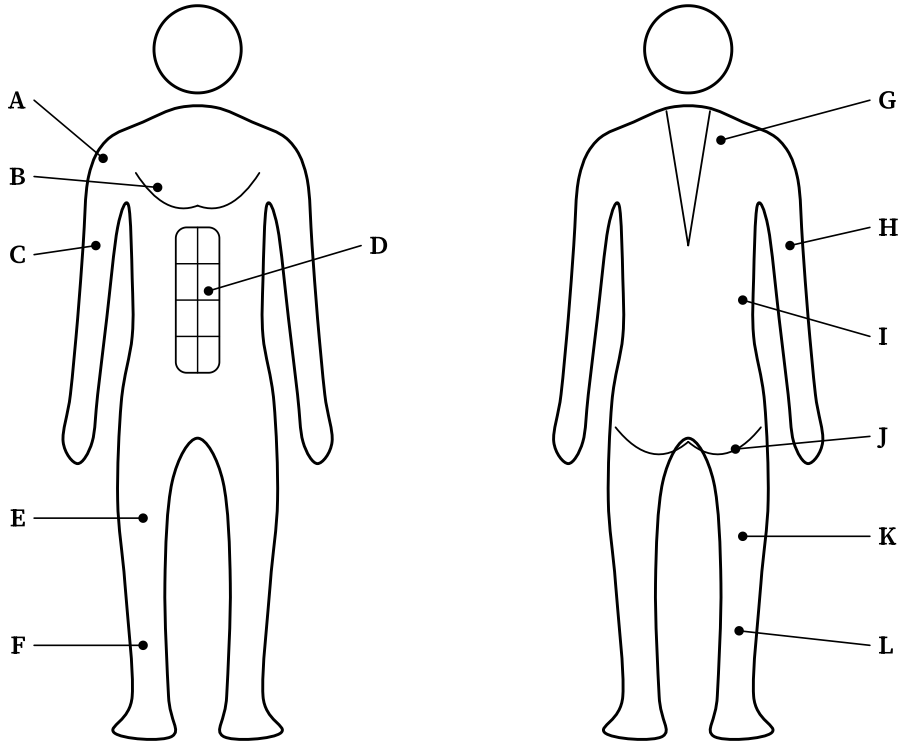
4. **Medium** Why do the muscles that move the fingers sit mostly in the forearm rather than in the hand?

   Show answer

   Long tendons carry their pull across the wrist, so the hand stays slim and nimble while the bulky muscle bellies sit in the forearm.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram: name each muscle marked A to L.



Show answer

A, deltoid; B, pectoralis major; C, biceps brachii; D, rectus abdominis; E, quadriceps femoris; F, tibialis anterior; G, trapezius; H, triceps brachii; I, latissimus dorsi; J, gluteus maximus; K, hamstrings; L, gastrocnemius.

6. **Medium** Which major muscle is the prime mover in each exercise? (a) a pull-up, (b) a sit-up, (c) a calf raise, (d) a squat (standing up out of it).

Show answer

(a) latissimus dorsi (with the biceps), (b) rectus abdominis, (c) gastrocnemius and soleus, (d) quadriceps femoris and gluteus maximus.

7. **Hard** When you stand on your right leg, your left hip would drop if a certain muscle did not work. Which one, on which side, and what is its action?

Show answer

The right gluteus medius, which abducts the hip; standing on the right leg, it pulls on the pelvis to keep the left side from dropping.

DISORDER AS A BROKEN MECHANISM

8. Medium In Duchenne muscular dystrophy the protein dystrophin is missing. Explain step by step why this makes muscle fibers die.

Show answer

Dystrophin links the contractile filaments inside the fiber to the membrane and outer tissue, absorbing the stress of contraction. Without it the membrane is torn slightly by each contraction, calcium leaks in and damages the fiber, and fibers die faster than they can be repaired; fat and scar tissue replace them.

PREDICT THE EFFECT

9. Hard Predict the effect: the nerve to the tibialis anterior is damaged. What happens when the person walks, and how might they compensate?

Show answer

They cannot dorsiflex the foot, so the toes drag or the foot slaps down (foot drop). They may lift the knee higher than usual to clear the toes, or wear a brace that holds the foot up.

10. Challenge Nurses give injections into the deltoid and the vastus lateralis (part of the quadriceps). Suggest two reasons these sites are chosen.

Show answer

They are large, thick muscles that can take the volume, and they are easy to reach and lie away from major nerves and blood vessels.

COMMON MISTAKES

- Thinking the biceps alone flexes the elbow; the brachialis beneath it does much of the work.
- Calling the whole calf the gastrocnemius; the soleus lies beneath it and joins the same Achilles tendon.
- Putting the hamstrings on the front of the thigh; the quadriceps are in front, the hamstrings behind.
- Forgetting that the abdominal muscles also work during breathing out hard and lifting, not just sit-ups.

Make it a game · Muscle Charades. Write the 13 core-figure muscles on cards. The student draws a card and acts out the muscle's action without talking; the family guesses the muscle. Then the guesser must name its antagonist to score. Play until the deck is empty.

Scripture. "But now hath God set the members every one of them in the body, as it hath pleased him." (1 Corinthians 12:18, KJV)

Each muscle has its own place and its own job, and none works alone: every movement needs a team of prime movers, helpers and opposers.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

4.5 Exercise and Muscle: A. V. Hill, Energy Systems and Training

Mark up this lesson

OBJECTIVES

- Describe the three energy systems that supply ATP to working muscle and when each dominates.
- Compare slow-twitch and fast-twitch fibers and explain motor-unit recruitment (the size principle).
- Explain how muscles adapt to training (nervous-system gains, hypertrophy, endurance changes) and estimate a one-repetition maximum safely.

> **Warm-up.** Hold a wall sit (back against a wall, thighs level) for as long as you can, up to 90 seconds. Note when your legs start to shake and burn. What do you think is happening in the muscle?

WATCH

What makes muscles grow? - Jeffrey Siegel

TED-Ed · 4:20

https://www.youtube.com/watch?v=2tM1LFFxeKg

> **WHEN TO WATCH**
> After the section on training adaptations.

BACKUP VIDEO

Aerobic Capacity (VO2max) and Anaerobic Thresholds

Vivo Phys - Evan Matthews · 11:05

https://www.youtube.com/watch?v=doxFSOSHk-0

With the energy systems.

KEY TERMS

creatine phosphate

A molecule stored in muscle that gives its phosphate to ADP to remake ATP instantly, enough for about 10 seconds of all-out effort.

anaerobic glycolysis

Breaking glucose to pyruvate and lactate without oxygen; fast but yields only 2 ATP per glucose.

aerobic respiration

Breaking down glucose and fats with oxygen in the mitochondria; slower but yields about 30 or more ATP per glucose.

slow-twitch and fast-twitch fibers

Type I fibers contract slowly, have many mitochondria and myoglobin, and resist fatigue; type II fibers contract fast and forcefully but tire sooner.

motor unit and size principle

One motor neuron and the fibers it controls; units are recruited from small to large as more force is needed.

hypertrophy and atrophy

Growth of muscle fibers in size with training, and shrinking with disuse.

CORE IDEAS

The story. In the early 1900s the English physiologist Archibald Vivian Hill measured the tiny amounts of heat a frog muscle gives off as it contracts and recovers, using instruments so sensitive they could detect a rise of a few thousandths of a degree. He found that some heat appears at once and more appears afterward, during recovery, when oxygen is used. With the German biochemist Otto Meyerhof, who traced the chemistry of glycogen and lactic acid in muscle, he shared the Nobel Prize in Physiology or Medicine for 1922. Hill later tested human runners and coined ideas we still use, such as the maximum rate at which the body can take up oxygen and the "oxygen debt" after hard exercise.

How they figured it out. Hill's key move was to treat muscle like an engine and measure its inputs and outputs: oxygen used, heat given off, work done. He put runners on a track with bags to collect their breath and measured oxygen uptake at rising speeds; the uptake rose and then leveled off, even though the runners could go faster. The extra energy had to come from processes that do not need oxygen at the moment. Later scientists using needle biopsies of human muscle (from the 1960s)

confirmed that stores of creatine phosphate and glycogen fall during exercise and are rebuilt afterward.

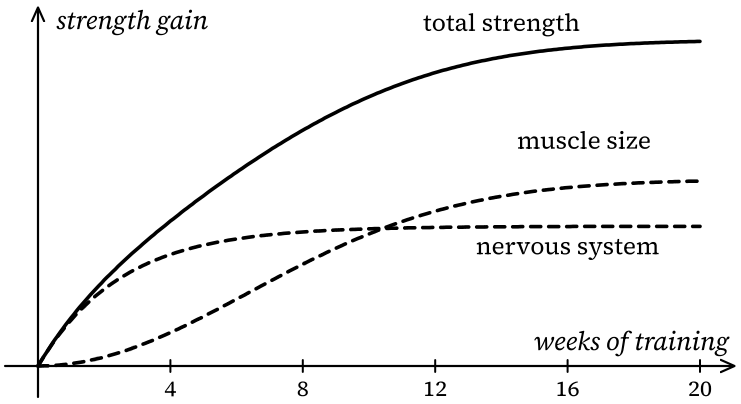
Three energy systems. Muscle stores only enough ATP for a couple of seconds, so it must remake ATP constantly. (1) The **phosphagen system**: creatine phosphate hands its phosphate to ADP, giving instant ATP for about 10 seconds: a sprint start or a heavy lift. (2) **Anaerobic glycolysis** breaks glucose (from glycogen) to pyruvate and then lactate, quickly but yielding only 2 ATP per glucose; it powers efforts lasting from about 10 seconds to 2 minutes, such as a 400 m run. (3) **Aerobic respiration** in the mitochondria (Biology 4.3) breaks glucose and fat completely with oxygen, yielding about 30 or more ATP per glucose; it powers anything longer, from a walk to a marathon. All three work together; the length and intensity of the effort decide which one leads. The burn and shaking of a hard wall sit come from the build-up of hydrogen ions and other products of fast glycolysis and from tiring fibers, not from lactate "poisoning" the muscle.

Fiber types and recruitment. Slow-twitch (type I) fibers are thin, rich in mitochondria, capillaries and the red oxygen-storing protein myoglobin; they contract slowly and can work for hours (posture muscles, marathon runners). **Fast-twitch (type II)** fibers are thicker, store more glycogen and creatine phosphate, and contract fast and hard but tire sooner (sprinters, jumpers). Each **motor unit** is one motor neuron and all the fibers it controls, all of one type. By the **size principle**, the nervous system recruits small, slow units first and adds larger, faster units only as more force is needed. That is why lifting a pencil feels nothing like lifting a heavy box, and why a muscle shakes near exhaustion as large units drop in and out.

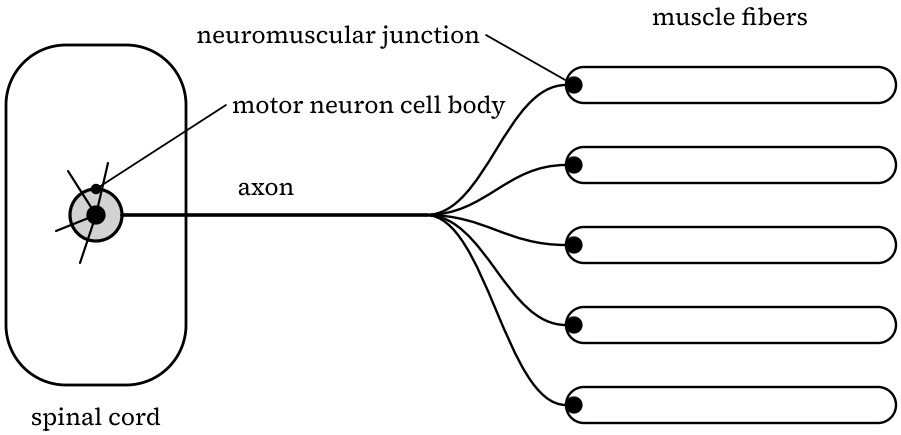
How training changes muscle. In the first few weeks of strength training, most of the gain comes from the **nervous system**: you learn to recruit more motor units at once, fire them faster and relax the antagonists. After that, **hypertrophy** takes over: repeated hard contractions signal fibers to build more actin and myosin, so each fiber grows thicker (resident stem cells called satellite cells donate extra nuclei to help). Endurance training instead adds mitochondria, capillaries and enzymes, so the same muscle uses oxygen better. Muscles adapt only to what they are asked to do: progressive overload, enough protein and sleep, and rest days for repair. Disuse reverses the process (**atrophy**), as anyone knows whose leg has come out of a cast. Training plans are taught in PE Grade 9, Lesson 4.2 (DeLorme's three sets of ten) and the lactate threshold in PE Grade 11, Lesson 5.1.

When it goes wrong. Exertional rhabdomyolysis happens when someone is pushed far beyond their training, often with many repetitions in heat: damaged fibers break open and spill their contents, including myoglobin and potassium, into the blood. Myoglobin can clog the kidneys, and dark, cola-colored urine with severe muscle pain and swelling is a medical emergency. It is a broken mechanism in two places: the fibers are overloaded faster than they can repair, and the kidneys are overloaded by the debris. It is prevented by increasing training gradually, drinking enough, and never treating a workout as a punishment.

Where it is used and try it. Coaches use the energy systems to plan sprints, intervals and long runs; physical therapists use the size principle to rebuild muscle after surgery; nurses watch older adults for sarcopenia, the slow loss of muscle with age, which strength training can slow at any age. In the lab you will run a four-week training study on yourself and graph the results.



Early strength gains are mostly the nervous system learning; later gains are mostly bigger fibers. A schematic, not real data.



A motor unit. When the neuron fires, every fiber in its unit contracts; force is graded by how many units fire, and how often.

> **Safety first.** Check with a doctor before starting a training program if you have a heart, lung or joint condition. Warm up first, keep good form, never train to the point of sharp pain, and drink water. Dark urine with severe muscle pain after exercise needs a doctor the same day.

LAB

Four-Week Training Study

You will measure your own response to a simple, safe bodyweight program and graph the results.

You will need

- A stopwatch, a notebook or spreadsheet, graph paper
- A wall, a sturdy chair, a floor mat

Steps

1. Week 0: test three things on one day with a warm-up first: maximum push-ups with good form (or knee push-ups), maximum wall-sit time, and maximum plank time. Record your resting pulse.
2. Train three days a week for four weeks: 3 sets of push-ups at about two-thirds of your maximum, 3 wall sits and 3 planks at about two-thirds of your best time, with 1 minute of rest between sets. Add one repetition or 5 seconds every week (progressive overload).
3. At the end of week 2 and week 4, retest all three. Calculate the percent change from week 0 for each.
4. Graph each measure against week number. Mark which part of the change you think came from the nervous system and which from the muscle.

Check your work

- ☐ Which test improved most in percent? Why might that be?
- ☐ Why do beginners gain strength faster than they gain muscle size?
- ☐ How did you apply progressive overload? What might happen if you skipped rest days?

LAB NOTEBOOK

1. A data table and line graph of your three tests over four weeks.
2. A chart comparing the three energy systems: speed, ATP yield, how long it lasts, an example sport.

KEY FORMULAS

$$1RM \approx w\left(1 + \frac{r}{30}\right) \qquad \text{volume} = \text{sets} \times \text{reps} \times \text{load}$$

From history. A. V. Hill was also a strong supporter of scientists who had to flee their countries in the 1930s and helped hundreds of them find positions in Britain. Meyerhof was one of the many who escaped, reaching the United States in 1940.

Practice habit. Keep a training log: date, exercise, sets, reps, load and how it felt. Increase only one thing at a time, by a small step, each week.

WORKED EXAMPLES

Example 1. A student lifts 60 kg for 8 repetitions. Estimate the one-repetition maximum with the Epley formula $1RM \approx w\,(1 + r/30)$.

Show solution

1. $1RM \approx 60\,(1 + 8/30)$
2. $= 60 \times 1.267 = 76$

Answer: About 76 kg. Estimating from a set of 8 avoids the risk of testing a true maximum lift.

Example 2. Training volume is sets × reps × load. Week 1: 3 sets of 10 at 40 kg. Week 4: 3 sets of 8 at 45 kg. Find each volume and the percent change.

Show solution

1. Week 1: $3 \times 10 \times 40 = 1200$ kg
2. Week 4: $3 \times 8 \times 45 = 1080$ kg
3. Change: $(1080 - 1200)/1200 = -0.10$

Answer: 1,200 kg and 1,080 kg: the volume fell 10% even though the load rose. Heavier, fewer reps shifts training toward strength.

Example 3. Which energy system leads in each event? (a) a 100 m sprint, (b) an 800 m run, (c) a 5 km run, (d) a single shot put.

Show solution

1. Under 10 seconds: phosphagen.
2. About 2 minutes: anaerobic glycolysis, with much aerobic help.
3. Over 15 minutes: aerobic.

Answer: (a) phosphagen (with glycolysis), (b) anaerobic glycolysis and aerobic together, (c) aerobic, (d) phosphagen

PRACTICE

CONCEPT CHECKS

1. Easy Which energy system gives ATP fastest, and how long does it last at full effort?

   Show answer

   The phosphagen (creatine phosphate) system, for about 10 seconds.

2. Easy Give two differences between slow-twitch and fast-twitch fibers.

   Show answer

   Slow-twitch: slower contraction, more mitochondria, capillaries and myoglobin, resist fatigue. Fast-twitch: faster and more forceful, more glycogen and creatine phosphate, tire quickly.

3. Medium What is the size principle?

   Show answer

   Motor units are recruited in order from small (slow, fatigue-resistant) to large (fast, powerful) as more force is needed.

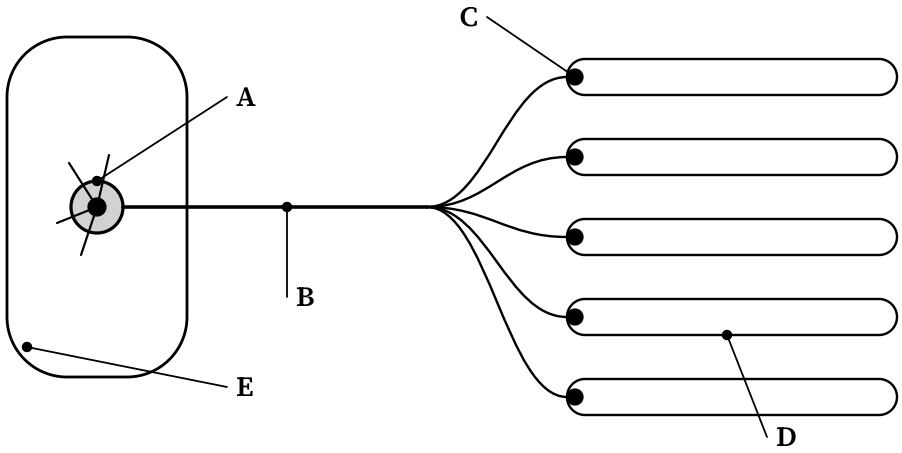
4. Medium Why does a beginner get stronger in the first two weeks of training before the muscle gets bigger?

   Show answer

   The nervous system learns to recruit more motor units, fire them faster and coordinate them better; fiber growth takes longer.

DIAGRAM AND DATA QUESTIONS

5. Medium Label the diagram of a motor unit: name each part marked A to E.



Show answer

A, motor neuron cell body; B, axon; C, neuromuscular junction; D, muscle fiber; E, spinal cord.

6. Medium Estimate the 1RM with the Epley formula for 40 kg lifted 10 times.

Show answer

$40 \times (1 + 10/30) \approx 53.3$ kg.

7. Hard A student's push-up maximum rises from 20 to 32 in four weeks, and her plank time from 45 s to 75 s. Find each percent increase. Which improved more?

Show answer

Push-ups: $(32 - 20)/20 = 60\%$. Plank: $(75 - 45)/45 \approx 67\%$. The plank improved slightly more in percent.

DISORDER AS A BROKEN MECHANISM

8. Medium After a punishing first practice of hundreds of squats in hot weather, a player has severe thigh pain and cola-colored urine. Explain what has broken, and why it endangers the kidneys.

Show answer

Exertional rhabdomyolysis: muscle fibers were overloaded far beyond their training, broke open and released myoglobin, potassium and other contents into the blood. Myoglobin is filtered by the kidneys and can clog and damage them; it also darkens the urine. It needs emergency care.

PREDICT THE EFFECT

9. Hard Predict the effect: a leg is in a cast for six weeks. What happens to the muscles, and why should rehabilitation start with light loads?

Show answer

The unused muscles atrophy: fibers shrink and lose strength, and the nervous system's skill fades. Starting light lets nerves relearn recruitment and fibers rebuild without injuring the weakened muscle, tendons and joint.

10. Challenge A coach says, "Lactic acid is waste that makes your muscles sore for days." Correct the statement using what you learned.

Show answer

Lactate is not just waste: it is made during fast glycolysis and is reused as fuel by the heart, other muscles and the liver within an hour or so. The burning during hard effort comes mainly from hydrogen ions and fatigue of fibers. Soreness one or two days later comes from small injuries in the muscle and their repair, not from lactic acid.

COMMON MISTAKES

- Thinking the three energy systems take turns; they all run at once, and the effort decides which leads.
- Blaming next-day soreness on lactic acid; it comes from tiny injuries and repair.
- Believing you can turn slow-twitch fibers into fast-twitch overnight; training changes fibers only gradually and partly.
- Testing a true one-rep maximum without a coach and spotter; estimate it from a safe set instead.
- Skipping rest days; muscle grows during recovery, not during the workout.

> **Make it a game · Which System?.** The parent names an activity (one jump, climbing three flights of stairs, a soccer game, a 50 m swim, mowing the lawn, a heavy deadlift, a 2-mile walk). The student shouts the leading energy system and does 3 jumping jacks for phosphagen, 10 for glycolysis or a 20-second march for aerobic. A wrong answer costs a 10-second plank.

> **Scripture.** “For bodily exercise profiteth little: but godliness is profitable unto all things, having promise of the life that now is, and of that which is to come.” (1 Timothy 4:8, KJV)
>
> Paul does not say exercise is worthless; it profits a little. Train the body faithfully, and train the soul more.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

UNIT 4

Joints and Muscles

Bones give the body a frame, but joints and muscles make it move. This unit follows five discoveries: William Hunter's study of joint cartilage (1743) and John Charnley's artificial hip (1962), the chemists and microscopists who found how actin, myosin, ATP and calcium make a muscle fiber shorten, Giovanni Borelli's muscle levers (1680), Duchenne's electrical map of the muscles (1860s), and A. V. Hill's measurements of the energy of exercise.

Students classify joints and name movements, trace excitation–contraction coupling step by step, calculate the forces in the body's levers, learn the major muscles by place and action, and run a four-week training study on themselves. Labs use a homemade goniometer, paper sarcomere models, a ruler lever and a cardboard forearm, and simple bodyweight exercises.

PREREQUISITES

- Unit 1 (anatomical position, directional terms and planes)
- Unit 2, especially Lesson 2.4 (muscle and nervous tissue)
- Unit 3 (the skeleton)
- Basic algebra for lever calculations

MASTERY CHECKLIST

- ☐ I can classify joints by structure and function, name the six kinds of synovial joint, and use movement terms correctly.
- ☐ I can trace muscle contraction from the motor neuron's signal through calcium release to the cross-bridge cycle, and explain the roles of ATP.
- ☐ I can identify lever classes in the body and calculate muscle force and mechanical advantage.
- ☐ I can locate the major muscles, state their actions and name their antagonists.
- ☐ I can describe the three energy systems, fiber types and how muscle adapts to training.
- ☐ I can explain a joint or muscle disorder as a failure of a specific part.

LESSONS IN THIS UNIT

4.1 Joints and Body Movements: Hunter's Cartilage (1743) and Charnley's Hip (1962)

4 sessions of 45 minutes

4.2 How a Muscle Fiber Contracts: From Nerve Signal to Sliding Filaments

4 sessions of 45 minutes

4.3 Levers and Naming Muscles: Borelli's Muscle Machines (1680)

4 sessions of 45 minutes

4.4 The Major Muscle Groups: Duchenne's Electrical Map (1860s)

4 sessions of 45 minutes

4.5 Exercise and Muscle: A. V. Hill, Energy Systems and Training

4 sessions of 45 minutes

Unit 4 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **6 pts** **Lesson 4.1**

   Name the type of synovial joint and one movement it allows: (a) shoulder, (b) elbow, (c) base of the thumb, (d) the joint between the atlas and axis.

2. **7 pts** **Lesson 4.1**

   A knee reads 0° straight and 135° fully bent. After surgery it bends to 108°. What percent of the range of motion has returned?

3. **7 pts** **Lesson 4.2**

   List in order the steps from a motor neuron impulse to the first power stroke.

4. **7 pts** **Lesson 4.2**

   A sarcomere shortens from 2.4 µm to 2.0 µm. The thick filaments are 1.6 µm and each thin filament is 1.0 µm. Give the A band, I band and H zone before and after.

5. **7 pts** **Lesson 4.2**

   Why does a muscle stay contracted (rigor) when the cell runs out of ATP?

6. **8 pts** **Lesson 4.3**

   The biceps inserts 4.5 cm from the elbow. A 9.0 kg dumbbell (weight 88 N) is held 30 cm from the elbow with the forearm level. Find the biceps force and the mechanical advantage. Ignore the weight of the forearm.

7. **7 pts** **Lesson 4.3**

   Classify each as a first-, second- or third-class lever: (a) nodding the head, (b) rising onto the toes, (c) the biceps curling a weight.

8. **7 pts** **Lesson 4.3**

   Decode the names: (a) adductor longus, (b) sternocleidomastoid, (c) external oblique.

9. **8 pts** **Lesson 4.4**

   For each movement, name the prime mover and its antagonist: (a) straightening the knee, (b) bending the elbow, (c) pulling the toes up toward the shin.

10. **6 pts** **Lesson 4.4**

    What does the rotator cuff do, and why does the shoulder need it more than the hip needs similar muscles?

11. **8 pts** **Lesson 4.5**

    Compare the phosphagen system, anaerobic glycolysis and aerobic respiration: for each give how fast it supplies ATP, how long it can last at high effort, and one sport that relies on it.

12. **6 pts** **Lesson 4.5**

    Estimate the 1RM of a student who lifts 50 kg for 5 repetitions, using the Epley formula.

DISORDERS AND DATA

13. **8 pts** **Lesson 4.2**

    Explain why a person with myasthenia gravis has drooping eyelids by evening that improve after rest. Name the part that is broken.

14. **8 pts** **Lesson 4.5**

    A student records max push-ups: week 0, 15; week 2, 21; week 4, 24. (a) Find the percent increase from week 0 to week 2 and from week 2 to week 4. (b) Explain the pattern using nervous-system and muscle adaptations.

ANSWER KEY

1. (a) ball-and-socket: abduction, rotation, flexion and more; (b) hinge: flexion and extension; (c) saddle: opposition; (d) pivot: rotation.
2. 108/135 = 0.80, so 80%.
3. ACh released at the neuromuscular junction → ACh binds receptors on the sarcolemma → impulse spreads along the membrane and down the T tubules → sarcoplasmic reticulum releases calcium → calcium binds troponin → tropomyosin uncovers actin's binding sites → cocked myosin heads bind actin and make the power stroke.
4. Before: A band 1.6 µm, I band 0.8 µm, H zone 0.4 µm. After: A band 1.6 µm, I band 0.4 µm, H zone 0.
5. ATP must bind the myosin head to release it from actin (and to pump calcium back). Without ATP the heads stay attached.
6. E = 88 × 30 / 4.5 ≈ 587 N (about 590 N); MA = 4.5/30 = 0.15.
7. (a) first, (b) second, (c) third.
8. (a) a long muscle that adducts (the thigh); (b) runs from the sternum and clavicle to the mastoid process of the skull; (c) an outer abdominal muscle with slanting fibers.
9. (a) quadriceps femoris / hamstrings; (b) biceps brachii (with the brachialis) / triceps brachii; (c) tibialis anterior / gastrocnemius and soleus.
10. Its four muscles hold the head of the humerus in the shallow glenoid socket and rotate the arm. The hip's deep socket holds the femur securely by its shape, so it relies less on muscles for stability.
11. Phosphagen: fastest, about 10 s, sprint start or a heavy lift. Anaerobic glycolysis: fast, about 10 s to 2 min, a 400 m run. Aerobic: slowest but largest yield, minutes to hours, a marathon or long bike ride.
12. 50 × (1 + 5/30) ≈ 58 kg.
13. The ACh receptors at the neuromuscular junction are blocked and destroyed by the person's own antibodies. Each impulse gives a weaker signal; with repeated use the signal fails to reach threshold in more fibers, so muscles such as the eyelid lifters weaken through the day; rest lets the junction recover.
14. (a) (21 − 15)/15 = 40%; (24 − 21)/21 ≈ 14%. (b) Early gains come quickly from the nervous system learning to recruit and coordinate motor units; later gains depend on slower growth of the fibers, so the rate of improvement slows.

UNIT 5

The Nervous System

The nervous system is the body's fast communication network. This unit follows five discoveries: Cajal's drawings of separate neurons (1888) and Hodgkin and Huxley's explanation of the action potential (1952), Otto Loewi's two frog hearts (1921), Broca's speech area (1861) and Penfield's maps of the cortex, Helmholtz's ophthalmoscope (1851), and Walter Cannon's "fight or flight" (1915).

Students trace the action potential millisecond by millisecond, add up synaptic signals, locate the parts of the brain and the cranial nerves, calculate the blind spot and the eye's focusing power, and compare the two divisions of the autonomic system. The unit ends with a clinical-skills lab: a basic neuro check of pupils, eye movements, face, strength, coordination, balance and reflexes, practiced safely on a healthy partner. Labs use dominoes, a ruler, index cards, toothpicks and a penlight.

PREREQUISITES

- Unit 1, especially Lesson 1.3 (homeostasis and feedback)
- Unit 2, especially Lessons 2.2 (membrane transport) and 2.4 (nervous tissue)
- Unit 4, especially Lesson 4.2 (the neuromuscular junction)
- Logarithms for the Nernst equation (optional challenge problems)

MASTERY CHECKLIST

- ☐ I can label a neuron and trace the action potential through each phase, naming the ions and channels.
- ☐ I can describe synaptic transmission step by step and explain summation of EPSPs and IPSPs.
- ☐ I can locate the major parts of the brain, state their jobs, and trace a reflex arc.
- ☐ I can trace light through the eye and sound through the ear, and calculate the blind-spot angle and diopters.
- ☐ I can compare the sympathetic and parasympathetic divisions and predict their effects on organs.
- ☐ I can perform and record a basic neuro check safely, and explain a nervous-system disorder as a broken mechanism.

LESSONS IN THIS UNIT

5.1 Neurons and the Action Potential: Cajal (1888) and Hodgkin and Huxley (1952)
4 sessions of 45 minutes

5.2 The Synapse: Loewi's Dream Experiment (1921) — 4 sessions of 45 minutes

5.3 The Brain and Spinal Cord: Broca (1861) and Penfield's Maps
4 sessions of 45 minutes

5.4 The Senses: Helmholtz's Ophthalmoscope (1851) — 4 sessions of 45 minutes

5.5 The Autonomic Nervous System and the Neuro Check: Cannon's "Fight or Flight" (1915)

4 sessions of 45 minutes, plus the clinical-skills lab

Unit 5 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 5.1**
   Describe the action potential in order: what happens to the voltage and which channels open or close at threshold, at the peak, and during hyperpolarization.

2. **7 pts** **Lesson 5.1**
   An impulse travels along a 1.2 m axon at 60 m/s. How long does it take, in milliseconds? Why would an unmyelinated axon of the same length be much slower?

3. **6 pts** **Lesson 5.1**
   Explain why an action potential cannot travel backward along an axon.

4. **8 pts** **Lesson 5.2**
   List the steps of chemical transmission at a synapse, from the arrival of the action potential to the end of the signal.

5. **7 pts** **Lesson 5.2**
   A neuron rests at −70 mV and fires at −55 mV. At one moment it receives 6 EPSPs of 4 mV each and 2 IPSPs of 3 mV each. Does it fire? Show the sum.

6. **7 pts** **Lesson 5.3**
   Give the main job of: (a) the medulla oblongata, (b) the cerebellum, (c) the hypothalamus, (d) the occipital lobe.

7. **7 pts** **Lesson 5.3**

   Draw or describe the reflex arc for pulling a hand away from a hot pan, naming all five parts.

8. **7 pts** **Lesson 5.4**

   Trace light from outside the eye to the brain, naming each structure.

9. **7 pts** **Lesson 5.4**

   A person holds the blind-spot card 35 cm from the eye. Using a blind-spot angle of 15°, how far from the cross must the dot be to disappear?

10. **8 pts** **Lesson 5.5**

    Compare the sympathetic and parasympathetic divisions: where each leaves the CNS, where the ganglia are, the neurotransmitter at the target, and two effects of each.

11. **6 pts** **Lesson 5.5**

    Clinical skills: A patient's GCS is eye opening 3, verbal 4, motor 5. What is the score? Which cranial nerves are tested when you check that both pupils narrow in light?

DISORDERS AND SHORT ESSAY

12. **10 pts** **Lesson 5.1**

    Choose two of multiple sclerosis, Parkinson's disease, stroke and cataract. For each, name the structure that fails, explain the mechanism, and connect it to the symptoms.

13. **12 pts** **Lesson 5.3**

    Short essay: Cajal, Hodgkin and Huxley, Loewi, Broca and Penfield each discovered something about the nervous system that no one could see directly. Choose two. For each, describe the question, the method and what it showed. What do their methods have in common?

ANSWER KEY

1. Threshold (about −55 mV): voltage-gated Na^+ channels open and Na^+ rushes in, depolarizing to about +30 mV. Peak: Na^+ channels inactivate and voltage-gated K^+ channels open; K^+ flows out and the membrane repolarizes. Hyperpolarization: K^+ channels are slow to close, so the voltage dips to about −80 mV before the pump and leak channels restore −70 mV.
2. 1.2/60 = 0.020 s = 20 ms. Without myelin the action potential must be regenerated at every patch of membrane instead of jumping from node to node, so it travels only about 0.5–2 m/s.
3. The patch of membrane just behind the impulse is in its absolute refractory period: its sodium channels are inactivated and cannot reopen, so only the membrane ahead can fire.
4. Action potential reaches the terminal → voltage-gated Ca^{2+} channels open, Ca^{2+} enters → vesicles fuse and release neurotransmitter → it diffuses across the cleft → binds receptors, opening ion channels → EPSP or IPSP in the next cell → transmitter removed by enzyme breakdown, reuptake or diffusion.
5. Net change = 6 × 4 − 2 × 3 = 24 − 6 = +18 mV, so the membrane reaches −52 mV, above the −55 mV threshold: it fires.
6. (a) heart rate, breathing, blood pressure and other automatic functions; (b) coordination, balance and smooth movement; (c) homeostasis (temperature, hunger, thirst) and control of the pituitary; (d) vision.
7. Receptor (pain and heat receptors in the skin) → sensory neuron into the dorsal spinal cord → interneuron in the gray matter → motor neuron out through the ventral root → effector (the arm's flexor muscles), which pulls the hand away. The brain feels it a moment later.
8. Cornea → aqueous humor → pupil (in the iris) → lens → vitreous humor → retina (rods and cones) → optic nerve (leaving at the optic disc) → brain (occipital lobe).
9. $x = 35 \times \tan 15° \approx 35 \times 0.268 \approx 9.4$ cm.
10. Sympathetic: T1–L2 of the cord; ganglia in a chain near the spine; norepinephrine; e.g. heart speeds up, pupils dilate, airways widen, digestion slows. Parasympathetic: brainstem (cranial nerves III, VII, IX, X) and S2–S4; ganglia in or near the organ; acetylcholine; e.g. heart slows, pupils narrow, digestion speeds up, saliva increases.

11. 3 + 4 + 5 = 12. The optic nerve (II) carries the light signal in, and the oculomotor nerve (III) narrows the pupils.
12. Look for: MS (myelin destroyed, current leaks between nodes, slowed or blocked conduction, changing numbness, weakness or vision problems); Parkinson's (dopamine neurons of the substantia nigra die, too little dopamine at deep brain synapses, tremor, stiffness, slowness; levodopa crosses the blood–brain barrier); stroke (blood supply cut off, neurons die in minutes, symptoms match the region, BE FAST); cataract (lens proteins clump, light scattered, blurry glaring vision, lens replacement).
13. Look for accurate summaries (Cajal: silver stain and drawings, separate neurons; Hodgkin and Huxley: squid giant axon and voltage clamp, sodium and potassium currents, equations; Loewi: two frog hearts, transferred fluid, chemical transmission; Broca: linking lost speech to damage in the left frontal lobe; Penfield: stimulating the cortex of awake patients to map motor and sensory areas) and a thoughtful conclusion about careful observation, controls and measurement.

5.1 Neurons and the Action Potential: Cajal (1888) and Hodgkin and Huxley (1952)

Mark up this lesson

OBJECTIVES

- Describe the parts of a neuron and the main kinds of neurons and glial cells.
- Explain the resting membrane potential and trace the action potential through depolarization, repolarization and hyperpolarization, naming the ion channels involved.
- Explain the all-or-none rule, refractory periods and why myelin speeds conduction, and calculate conduction times.

> **Warm-up.** Line up ten dominoes 2 cm apart and time how long the whole row takes to fall. Now space them 4 cm apart (if they still reach) or use a longer row. A nerve impulse is sometimes compared to falling dominoes. In what ways is the comparison good, and where might it break down?

WATCH

The Nervous System, Part 2 - Action! Potential!: Crash Course Anatomy & Physiology #9

CrashCourse · 11:43

https://www.youtube.com/watch?v=OZG8M_ldA1M

> **WHEN TO WATCH**
> After the resting potential. Watch for the order in which sodium and potassium channels open and close.

BACKUP VIDEO

Nervous System

Amoeba Sisters · 11:32

https://www.youtube.com/watch?v=RNLceVI8jcc

Before the lesson, as an overview of neurons and the parts of the nervous system.

KEY TERMS

neuron

A nerve cell: dendrites receive signals, the cell body holds the nucleus, and the axon carries impulses away to the axon terminals.

glial cells

The support cells of the nervous system; Schwann cells and oligodendrocytes make myelin, astrocytes feed neurons and help form the blood–brain barrier.

resting membrane potential

The voltage across a resting neuron's membrane, about −70 mV (inside negative), kept up by the sodium–potassium pump and leaky potassium channels.

threshold

The voltage, about −55 mV, at which voltage-gated sodium channels open and an action potential fires.

action potential

A brief, all-or-none reversal of membrane voltage (to about +30 mV) that travels along the axon without fading.

refractory period

The short time after an action potential when the neuron cannot fire again (absolute) or needs a stronger stimulus (relative).

myelin and nodes of Ranvier

The fatty insulating wrap around many axons, and the gaps between its segments where the impulse jumps (saltatory conduction).

CORE IDEAS

The story. In the 1880s many scientists believed the nervous system was one continuous net of fused fibers. The Spanish physician Santiago Ramón y Cajal took the silver stain invented by Camillo Golgi, improved it, and in 1888 began publishing drawings of nerve tissue from birds and young mammals in which each neuron stood out alone. He argued that the nervous system is made of separate cells that touch but do not fuse, and that signals flow one way through each: in at the dendrites, out along the axon. He and Golgi, who still believed in the net, shared the 1906 Nobel Prize. Half a century later, in 1952, Alan Hodgkin and Andrew Huxley at

Cambridge and Plymouth explained how the signal itself works, sharing the 1963 Nobel Prize with John Eccles.

How they figured it out. Hodgkin and Huxley used the giant axon of the squid, up to about half a millimeter across, wide enough to slide a thin wire electrode down its middle. With a "voltage clamp" they held the membrane at a chosen voltage and measured the current of ions flowing through it. By changing the sodium in the seawater around the axon they could separate the sodium current from the potassium current. They wrote equations for how each kind of channel opens and closes with voltage and time, then solved them, partly with a hand-cranked calculating machine, and the equations predicted the shape and speed of a real action potential. Channels were later seen directly, but their mathematics came first.

Neurons and their helpers. A neuron has **dendrites** that receive signals, a **cell body** with the nucleus, and one **axon** that starts at the axon hillock (where impulses begin) and ends in **axon terminals**. *Sensory neurons* carry information toward the brain and spinal cord, *motor neurons* carry commands out to muscles and glands, and *interneurons* connect neurons within the brain and spinal cord. Neurons are outnumbered by **glial cells**: astrocytes feed neurons and help form the blood–brain barrier, oligodendrocytes (in the brain and cord) and Schwann cells (in nerves) wrap axons in myelin, microglia clean up debris, and ependymal cells line the fluid spaces. The human brain has about 86 billion neurons.

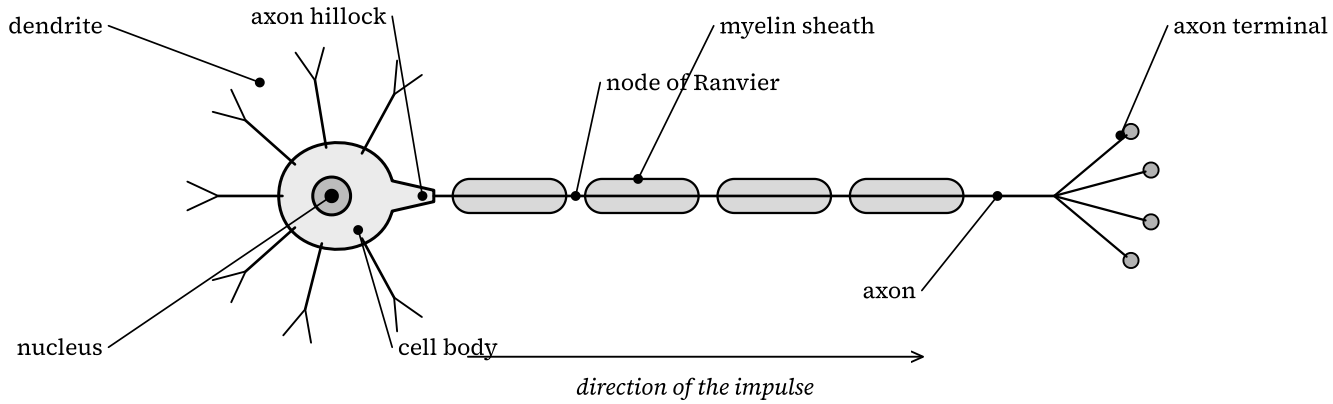
The resting potential. A neuron at rest is like a charged battery. The **sodium–potassium pump** uses ATP to push 3 Na^+ out for every 2 K^+ it brings in, so sodium is concentrated outside and potassium inside. The resting membrane has many open "leak" channels for potassium but few for sodium, so K^+ slowly leaks out, leaving the inside about 70 mV more negative than the outside: the **resting membrane potential** of about −70 mV. (Lesson 2.2 covered pumps and channels.)

The action potential, step by step. (1) A stimulus opens some channels and the inside becomes less negative. If it reaches **threshold**, about −55 mV, (2) *voltage-gated sodium channels* fly open, Na^+ rushes in and the voltage shoots up to about +30 mV: **depolarization**. (3) Within a millisecond the sodium channels close and lock (inactivate), and slower *voltage-gated potassium channels* open; K^+ flows out and the voltage falls: **repolarization**. (4) The potassium channels are slow to close, so the voltage briefly dips below rest, to about −80 mV: **hyperpolarization**. (5) The pump

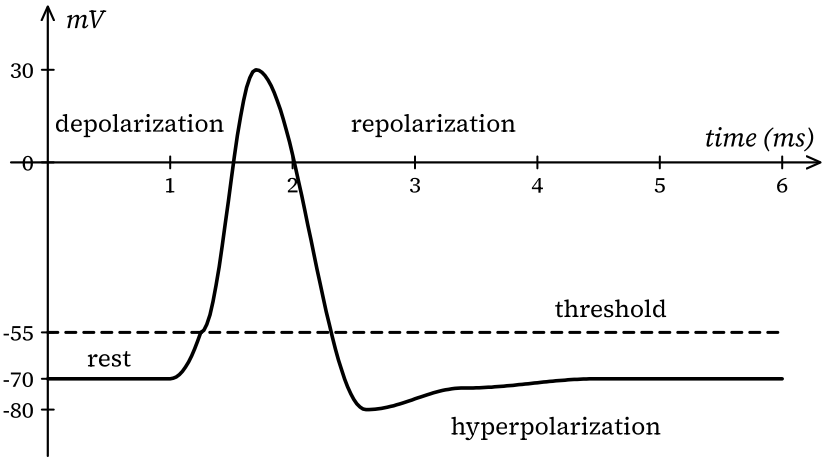
and leak channels restore the resting state. The whole event takes about 2 to 4 milliseconds. It is **all-or-none**: a stimulus that reaches threshold gives a full-size action potential, and a bigger stimulus gives more action potentials per second, not bigger ones. During the **absolute refractory period** the locked sodium channels cannot reopen, so the impulse can only travel forward, away from where it has just been.

Speed and myelin. Each patch of depolarized membrane triggers the patch next to it, so the action potential sweeps along the axon. In unmyelinated axons it moves only about 0.5 to 2 meters per second. **Myelin** insulates the axon, and sodium channels cluster at the gaps, the **nodes of Ranvier**; the current flows quickly inside the axon from node to node, and the action potential seems to jump (*saltatory conduction*), reaching up to about 120 m/s in large myelinated axons. Thicker axons also conduct faster. That is why the nerves to your muscles and the fibers that carry sharp pain are myelinated, while slow, dull, aching pain travels on thin unmyelinated fibers.

When it goes wrong. In **multiple sclerosis** the immune system attacks the myelin in the brain and spinal cord, leaving hardened scars (sclerosis) at many places. Where myelin is lost, current leaks out between nodes and the impulse slows or fails, so a person may have blurred vision, numbness, weakness or poor balance that come and go as lesions inflame and partly heal. The neurons themselves are not the first target: the insulation is. Several medicines now slow the attacks.



A myelinated motor neuron. Signals enter at the dendrites and cell body, start at the axon hillock and leave at the axon terminals.



One action potential. Sodium rushing in makes the rise; potassium flowing out makes the fall.

LAB

Domino Axons: Modeling Conduction and Myelin

You will model a nerve impulse with dominoes, compare “unmyelinated” and “myelinated” axons, and calculate speeds.

You will need

- About 60 dominoes (or index cards folded into tents), a meter stick, a stopwatch, a partner
- Several small books or blocks to represent myelin

Steps

1. Unmyelinated axon: stand 50 dominoes in a straight line 2 cm apart along the meter stick. Time the fall from the first domino to the last three times. Calculate the speed in meters per second.
2. Myelinated axon: over the same distance, replace runs of dominoes with “myelin” books laid flat, leaving gaps (nodes) with two or three dominoes. Arrange it so a falling domino at each node tips a ruler or book that quickly knocks over the next node. Time and calculate the speed again.
3. Refractory period: try to make the impulse run backward by tipping a domino in the middle of a fallen row. What happens?
4. All-or-none: push the first domino very gently and very hard. Does the last domino fall any harder?

Check your work

- ☐ Which model was faster? Which part of the real axon does each object represent?
- ☐ Where does the domino model fail? (Hint: can a real axon fire again a few milliseconds later?)
- ☐ How does the model show the all-or-none rule?

LAB NOTEBOOK

1. The labeled neuron and the action-potential graph, with the ion movement written on each phase.
2. Your domino data, speeds and a paragraph on the model’s strengths and limits.

KEY FORMULAS

$$t = \frac{d}{v} \qquad E_{ion} = 61.5 \log_{10} \frac{C_{out}}{C_{in}} \text{ mV}$$

From history. Cajal wanted to be an artist as a boy, and his father, a doctor, taught him anatomy by taking him to study bones in a cemetery. In 1850 Hermann von Helmholtz first measured the speed of a nerve impulse in a frog's leg, about 27 meters per second, much slower than many had assumed; before that some scientists thought nerve signals were too fast ever to be measured. Hodgkin and Huxley's work was interrupted for six years by the Second World War, when both worked on radar and other wartime research.

Practice habit. When you learn a sequence such as the action potential, draw it from memory as a graph and label each phase with the ion that is moving. Check against the book, and redraw until it is right twice in a row.

WORKED EXAMPLES

Example 1. Trace the timeline of the action potential in the core graph. At each time, give the voltage and what the ion channels are doing: 1.0 ms, 1.25 ms, 1.7 ms, 2.6 ms, 4.5 ms.

Show solution

1. 1.0 ms, −70 mV: at rest; the stimulus begins and the voltage starts to rise.
2. 1.25 ms, −55 mV: threshold; voltage-gated Na^+ channels open and Na^+ rushes in.
3. 1.7 ms, about +30 mV: peak; Na^+ channels inactivate, K^+ channels are opening.
4. 2.6 ms, about −80 mV: hyperpolarization; K^+ channels still open, K^+ still flowing out.
5. 4.5 ms, −70 mV: K^+ channels closed; pump and leak channels have restored rest.

Answer: Rest → threshold (Na^+ opens) → peak (Na^+ closes, K^+ opens) → hyperpolarized (K^+ slow to close) → rest, about 3.5 ms from stimulus to recovery

Example 2. A motor axon from the spinal cord to a foot muscle is 1.0 m long. How long does an impulse take if the axon is myelinated (100 m/s)? If it were unmyelinated (1 m/s)?

Show solution

1. $t = d/v = 1.0/100 = 0.010\ \text{s} = 10\ \text{ms}$
2. $t = 1.0/1 = 1.0\ \text{s}$

Answer: 10 ms myelinated versus a full second unmyelinated: 100 times slower, far too slow to catch yourself when you trip

Example 3. A neuron's absolute refractory period lasts 2 ms. What is the greatest number of action potentials it could fire per second?

Show solution

1. At most one action potential per refractory period.
2. $1/0.002\ \text{s} = 500$ per second

Answer: About 500 per second (real neurons usually fire far less often)

PRACTICE

CONCEPT CHECKS

1. Easy Which part of a neuron receives signals, and which part carries impulses away from the cell body?

   Show answer

   Dendrites receive; the axon carries impulses away.

2. Easy What is the resting membrane potential of a typical neuron, and which side is negative?

   Show answer

   About −70 mV; the inside is negative relative to the outside.

3. Medium Which ion rushes in during depolarization, and which flows out during repolarization?

   Show answer

   Sodium (Na^+) rushes in; potassium (K^+) flows out.

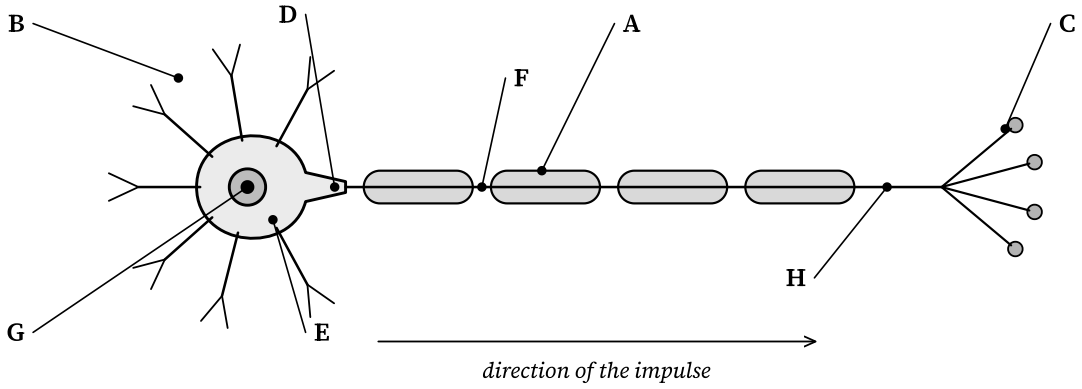
4. Medium What does “all-or-none” mean, and how does a neuron signal a stronger stimulus?

Show answer

If threshold is reached, the action potential is always full size; if not, there is none. A stronger stimulus makes the neuron fire more often (higher frequency), not bigger.

DIAGRAM AND DATA QUESTIONS

5. Medium Label the diagram of a neuron: name each part marked A to H.



Show answer

A, myelin sheath; B, dendrite; C, axon terminal; D, axon hillock; E, cell body; F, node of Ranvier; G, nucleus; H, axon.

6. Medium An impulse travels 0.6 m from the spinal cord to the hand in 10 ms. What is its speed? Is the axon likely myelinated?

Show answer

0.6 / 0.010 = 60 m/s. Yes: unmyelinated axons conduct only about 0.5–2 m/s.

7. Hard Dull, aching pain from a stubbed toe travels on thin unmyelinated fibers at about 2 m/s over 0.9 m. Sharp pain travels at about 20 m/s. How many milliseconds apart do the two arrive? Does that match your experience?

Show answer

Dull: 0.9/2 = 0.45 s = 450 ms. Sharp: 0.9/20 = 0.045 s = 45 ms. About 405 ms apart, which is why you feel a sharp pain first and the ache a moment later.

DISORDER AS A BROKEN MECHANISM

8. Medium In multiple sclerosis, myelin in the brain and spinal cord is destroyed. Explain why this slows or blocks nerve impulses even though the axons are still there.

Show answer

Myelin insulates the axon so current flows quickly inside from one node of Ranvier to the next, where sodium channels are clustered. Without myelin, current leaks out across the membrane, and the stretch between nodes has too few sodium channels to regenerate the action potential, so conduction slows or fails.

PREDICT THE EFFECT

9. Hard Predict the effect: a toxin (such as the one in puffer fish) blocks voltage-gated sodium channels. What happens to action potentials, and why could this be deadly?

Show answer

No sodium can rush in, so the membrane cannot depolarize and no action potentials fire. Nerves to muscles, including the breathing muscles, stop working, causing paralysis.

10. Challenge The Nernst equation at body temperature gives an ion's equilibrium voltage as $E = 61.5 \log_{10}(C_{out}/C_{in})$ mV. With K^+ at 5 mM outside and 140 mM inside, and Na^+ at 145 mM outside and 15 mM inside, find each. Why is the resting potential (−70 mV) close to one of them?

Show answer

$E(K^+) = 61.5 \log(5/140) \approx -89$ mV; $E(Na^+) = 61.5 \log(145/15) \approx +61$ mV. At rest the membrane is far more permeable to K^+ than to Na^+, so the resting potential lies near $E(K^+)$, pulled a little toward $E(Na^+)$ by the small sodium leak.

COMMON MISTAKES

- Saying the pump makes the action potential; ion channels make it, and the pump maintains the gradients over time.
- Thinking a stronger stimulus makes a taller action potential; it makes more of them per second.
- Saying sodium flows out during repolarization; potassium flows out.

- Picturing the impulse as electrons flowing down the axon like a wire; it is a wave of ion channels opening along the membrane.
- Forgetting that hyperpolarization overshoots below rest before recovering.

Make it a game · Human Action Potential. Family members stand in a line as patches of membrane, arms down (resting). When the person beside you raises their arms (depolarizes), raise yours, then lower them and turn your back for a count of three (refractory) before facing front again. Send waves from either end and watch why they cannot go backward. Then let one "myelin" person skip three places to show saltatory conduction.

Scripture. "I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well." (Psalm 139:14, KJV)

Billions of neurons fire in perfect timing every second, each impulse built from ion channels a few billionths of a meter across. Marvelous are His works.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

5.2 The Synapse: Loewi's Dream Experiment (1921)

Mark up this lesson

OBJECTIVES

- Describe the structure of a chemical synapse and the steps of synaptic transmission.
- Explain excitatory and inhibitory postsynaptic potentials and how a neuron adds them up (summation).
- Name major neurotransmitters and explain how some drugs and diseases act at synapses.

> **Warm-up.** Sit in a circle holding hands. One person squeezes the next person's hand, and the squeeze is passed around the circle. Time five trips around and find the time per person. Each "handoff" is like a synapse. What slows the signal down at each one?

WATCH

The Nervous System, Part 3 - Synapses!: Crash Course Anatomy & Physiology #10

CrashCourse · 10:57

https://www.youtube.com/watch?v=VitFvNvRIIY

> **WHEN TO WATCH**
> After the steps of transmission. Watch for excitatory and inhibitory signals and summation.

BACKUP VIDEO

Synapses - GCSE Biology

Launchpad Learning · 2:00

https://www.youtube.com/watch?v=_euaw86yEYM

A two-minute review after the core ideas.

KEY TERMS

synapse

The junction where a neuron passes its signal to another neuron, a muscle fiber or a gland cell.

synaptic vesicle

A tiny membrane sac in the axon terminal filled with neurotransmitter molecules.

synaptic cleft

The narrow gap, about 20 nanometers wide, between the presynaptic and postsynaptic membranes.

neurotransmitter

A chemical messenger released into the cleft that binds receptors on the next cell (acetylcholine, dopamine, serotonin, GABA, glutamate and others).

EPSP and IPSP

Excitatory and inhibitory postsynaptic potentials: small voltage changes that make the next neuron more or less likely to fire.

summation

Adding up many postsynaptic potentials, from many synapses at once (spatial) or one synapse firing rapidly (temporal), to reach threshold.

CORE IDEAS

The story. In 1897 the English physiologist Charles Sherrington named the meeting point between neurons the *synapse*, from Greek words meaning "to clasp together." But how did a signal cross? Some thought electrically, some chemically. The Austrian pharmacologist Otto Loewi had wondered about it for years when, on the night before Easter Sunday 1921, he dreamed of an experiment, woke and scribbled notes he could not read in the morning. The next night the dream returned; this time he went straight to his laboratory in Graz and did it. He and the English scientist Henry Dale shared the 1936 Nobel Prize.

How they figured it out. Loewi took two beating frog hearts, each in its own small bath of salt solution. He stimulated the vagus nerve of the first heart, which slowed its beat. Then he moved some of the fluid from around the first heart to the second heart, which had no nerve stimulation, and the second heart slowed too. The nerve must have released a chemical into the fluid; Loewi called it *Vagusstoff* ("vagus substance"). Dale's work showed it was acetylcholine. A simple, clean experiment with a control settled a question that argument could not.

Structure of a chemical synapse. The axon terminal of the *presynaptic* neuron holds hundreds of **synaptic vesicles** full of neurotransmitter, and many mitochondria to supply energy. Across a **synaptic cleft** only about 20 nanometers wide lies the *postsynaptic* membrane of the next cell, studded with **receptor** proteins. (A few synapses in the body are electrical: cells are joined by tiny channels called gap junctions, as in heart muscle, and the current passes directly. Most are chemical.)

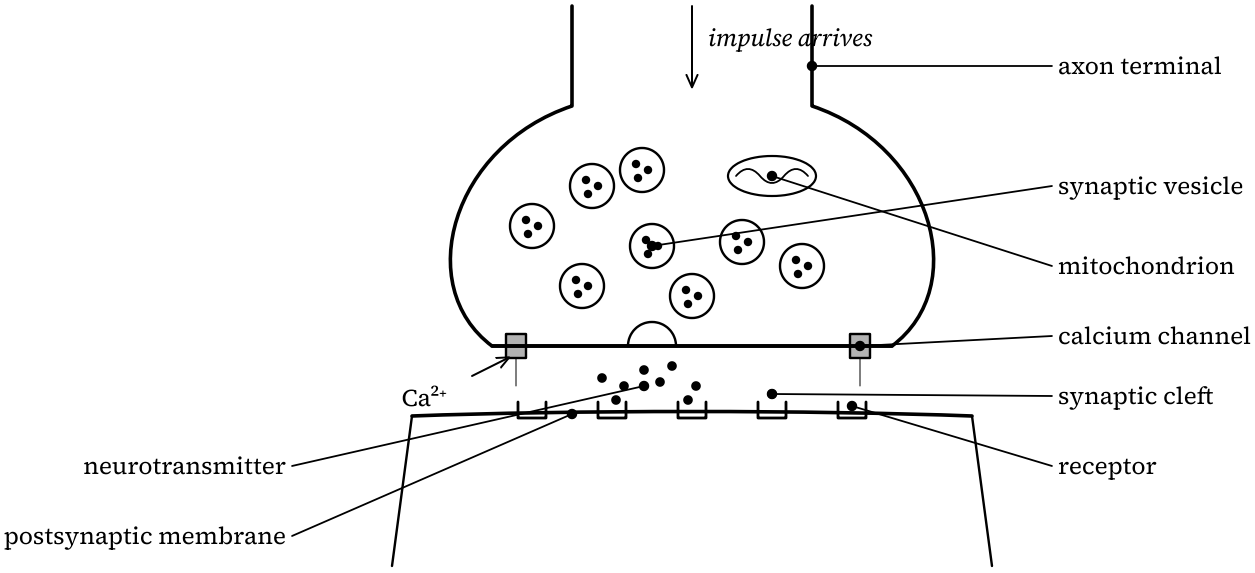
Transmission, step by step. (1) An action potential reaches the axon terminal. (2) Voltage-gated **calcium channels** open and Ca^{2+} flows in. (3) Calcium makes vesicles fuse with the membrane and release neurotransmitter into the cleft (exocytosis). (4) Neurotransmitter diffuses across and binds receptors, which open ion channels in the postsynaptic membrane. (5) The signal is ended quickly: the neurotransmitter is broken down by an enzyme (acetylcholinesterase destroys ACh), pumped back into the terminal for reuse (reuptake), or diffuses away. These steps add a *synaptic delay* of about half a millisecond, so a chain with many synapses is slower than one long axon. Because only the presynaptic side releases transmitter and only the postsynaptic side has receptors, signals cross in one direction.

Adding up signals. One synapse rarely makes the next neuron fire. If the transmitter opens sodium channels, the postsynaptic membrane depolarizes a few millivolts: an **excitatory postsynaptic potential (EPSP)**. If it opens chloride or potassium channels, the membrane becomes more negative: an **inhibitory postsynaptic potential (IPSP)**. A single neuron may receive thousands of synapses; at the axon hillock it adds all the EPSPs and IPSPs together. Many synapses firing at once give *spatial summation*; one synapse firing rapidly gives *temporal summation*. If the total reaches threshold, the neuron fires. In this way each neuron is a tiny decision-maker. Important transmitters include **acetylcholine** (muscles, memory, the parasympathetic system), **norepinephrine** (alertness, the sympathetic system), **dopamine** (movement and reward), **serotonin** (mood, sleep, appetite), **glutamate** (the main excitatory transmitter of the brain) and **GABA** (the main inhibitory one).

When it goes wrong. In **Parkinson's disease**, neurons in a small region of the midbrain called the substantia nigra slowly die. They send dopamine to deep brain regions that help start and smooth movement. With too little dopamine at those synapses, the circuits that release movement are held back: the person develops a resting tremor, stiffness, slowness and a shuffling walk. Dopamine itself cannot cross from the blood into the brain, so doctors give levodopa, a molecule that can

cross and that surviving neurons turn into dopamine. The disease shows how one missing transmitter at one set of synapses can change the whole body.

Where it is used and try it. Many medicines and poisons act at synapses. Caffeine blocks receptors for adenosine, a chemical that builds up while you are awake and makes you feel tired. Nicotine mimics acetylcholine at some receptors, which is part of why it is so addictive. Some nerve agents and insecticides block acetylcholinesterase, so ACh piles up and muscles cannot relax. Anesthesiologists use drugs that block ACh receptors to relax muscles during surgery. In the lab you will measure the delay that synapses add to a chain of people.



A chemical synapse. The electrical signal becomes a chemical one to cross the cleft, then electrical again on the other side.

LAB

The Human Synapse Chain

You will measure how much time synapses add to a signal by comparing a chain of people with a single person's reaction time.

You will need

- As many family members or friends as possible (at least 4), a stopwatch, a 30 cm ruler, a calculator

Steps

1. Measure each person's reaction time with the falling-ruler test: catch the ruler five times, convert each distance with $t = \sqrt{2d/g}$ and average.
2. Stand in a line with eyes closed, each person's hand on the next person's shoulder. The leader starts the stopwatch and squeezes; each person squeezes the next as soon as they feel it; the last person says "now" and the leader stops the watch. Do five trials.
3. Divide the average chain time by the number of handoffs to get the time per person. Compare with the ruler reaction time.
4. Repeat the chain with hands squeezing hands instead of shoulders (a shorter nerve path from hand to brain and back).

Check your work

- ☐ How does the time per person compare with a single reaction time? Did practice shorten it?
- ☐ Each person's "handoff" includes many synapses in the brain. Why does a chain with more synapses take longer?
- ☐ Why might the hand-to-hand version be faster than shoulder to shoulder?

LAB NOTEBOOK

1. A labeled drawing of a synapse with the five steps of transmission numbered on it.
2. Your reaction-time and chain data with calculations.

From history. Loewi was arrested in 1938 when Germany took over Austria and was allowed to leave only after he handed over his Nobel Prize money. He later taught for many years at New York University and spent his summers at the marine biology laboratory at Woods Hole, Massachusetts. In 1934 a young physician in London, Mary Walker, reasoned that myasthenia gravis looked like poisoning by curare, which blocks ACh receptors, and tried physostigmine, a drug that slows acetylcholinesterase. Within about half an hour her patient's drooping eyelids and weak muscles had improved.

Practice habit. For every new step in a process, ask "What would happen if this step were blocked?" and write a one-sentence answer. Predicting failures is the best test of understanding.

WORKED EXAMPLES

Example 1. A neuron rests at −70 mV and fires at −55 mV. Each EPSP adds 5 mV and each IPSP subtracts 5 mV, and they add together. How many EPSPs must arrive together to fire the neuron? How many if one IPSP arrives at the same time?

Show solution

1. Needed change: $-55 - (-70) = 15$ mV
2. $15/5 = 3$ EPSPs
3. With one IPSP: $(15 + 5)/5 = 4$ EPSPs

Answer: 3 EPSPs; 4 if one IPSP arrives at the same time

Example 2. Estimate the time for a knee-jerk reflex. The impulse travels 0.9 m from the knee to the spinal cord and 0.9 m back at 70 m/s, with one synapse (0.5 ms) in the cord.

Show solution

1. Travel: $1.8/70 = 0.0257$ s $= 25.7$ ms
2. Add the synapse: $25.7 + 0.5 = 26.2$ ms

Answer: About 26 ms, several times faster than a 150–250 ms reaction time that runs through the brain

Example 3. Trace what happens at a neuromuscular junction if acetylcholinesterase is blocked.

Show solution

1. ACh is released normally and binds receptors.
2. It is not broken down, so it stays in the cleft and keeps binding.
3. The muscle fiber stays stimulated and cannot relax properly; with time the receptors stop responding.

Answer: Twitching, then cramps and weakness; this is how some nerve agents and insecticides poison

PRACTICE

CONCEPT CHECKS

1. Easy What ion enters the axon terminal and triggers the release of neurotransmitter?

   Show answer

   Calcium (Ca^{2+}).

2. Easy Name three ways the action of a neurotransmitter is ended.

   Show answer

   It is broken down by an enzyme, taken back into the presynaptic terminal (reuptake), or diffuses away.

3. Medium Why can a chemical synapse pass signals in only one direction?

   Show answer

   Only the presynaptic terminal has vesicles of neurotransmitter, and only the postsynaptic membrane has the receptors.

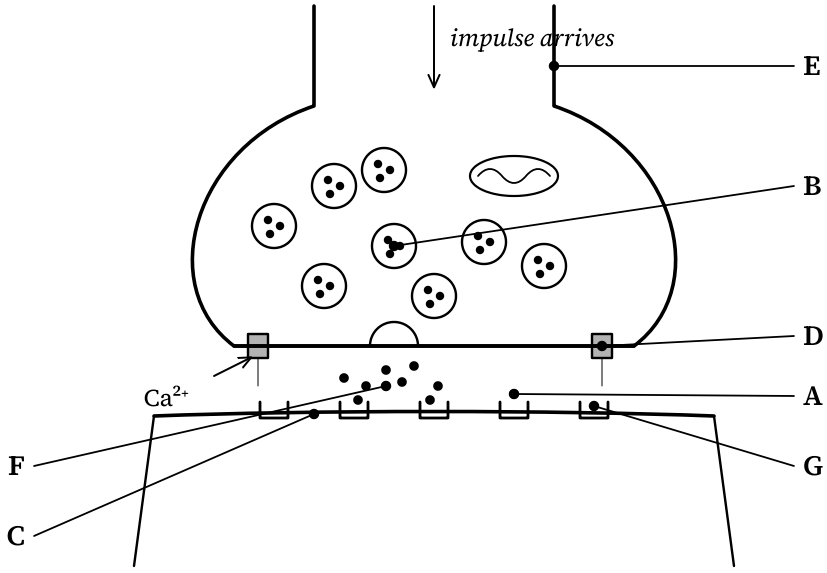
4. Medium What is the difference between spatial and temporal summation?

   Show answer

   Spatial: EPSPs from many synapses arriving at the same time add up.
   Temporal: EPSPs from one synapse firing rapidly add up before each one fades.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of a synapse: name each part marked A to G.



Show answer

A, synaptic cleft; B, synaptic vesicle; C, postsynaptic membrane; D, calcium channel; E, axon terminal; F, neurotransmitter; G, receptor.

6. **Medium** A neuron at −70 mV has a threshold of −55 mV. EPSPs here are 3 mV each. How many must arrive together to make it fire?

Show answer

15 / 3 = 5 EPSPs.

7. **Hard** Loewi's experiment needed the second heart to be unstimulated. Explain why that control was essential.

Show answer

If the second heart's nerve had been stimulated too, its slowing could have come from its own nerve. Because only the fluid was transferred, the slowing proved that a chemical released by the first heart's nerve carried the signal.

DISORDER AS A BROKEN MECHANISM

8. Medium In Parkinson's disease, dopamine-releasing neurons in the substantia nigra die. Explain how this produces slowness and tremor, and why doctors give levodopa instead of dopamine.

Show answer

With little dopamine reaching the deep brain circuits that start and smooth movement, those circuits hold movement back, causing slowness, stiffness and a resting tremor. Dopamine in the blood cannot cross the blood–brain barrier, but levodopa can, and surviving neurons convert it into dopamine.

PREDICT THE EFFECT

9. Hard Predict the effect: botulinum toxin stops vesicles from releasing acetylcholine at neuromuscular junctions. What happens to the muscles?

Show answer

No ACh is released, so the muscle fibers receive no signal: the muscles go limp (flaccid paralysis). In tiny doses doctors use this to relax muscle spasms.

10. Challenge Caffeine blocks adenosine receptors. Adenosine builds up in the brain the longer you are awake and acts mostly as an inhibitory signal. Explain why caffeine makes you feel alert and why heavy, regular use can lead to tiredness when it is stopped.

Show answer

By blocking adenosine receptors, caffeine removes an inhibitory brake, so neurons are more active and you feel alert. With regular use the brain adds more adenosine receptors; when caffeine stops, the extra receptors catch the adenosine, and the person feels unusually tired and may have headaches until the brain readjusts.

COMMON MISTAKES

- Saying the action potential jumps across the cleft; at a chemical synapse a chemical carries the signal across.
- Thinking one EPSP makes the next neuron fire; it usually takes many added together.
- Mixing up EPSP (toward threshold) and IPSP (away from threshold).
- Forgetting that neurotransmitter must be removed; otherwise the signal would never stop.

Make it a game · Synapse Card Sort. Write the steps of transmission on cards (impulse arrives, Ca^{2+} enters, vesicles fuse, transmitter crosses, binds receptor, ion channels open, transmitter removed). Shuffle. The student sorts them against a timer, then names one drug or disease that acts at any card. Beat your best time each round.

Scripture. “And the eye cannot say unto the hand, I have no need of thee: nor again the head to the feet, I have no need of you.” (1 Corinthians 12:21, KJV)

No neuron works alone. Every signal depends on the cell before it and the one after, just as every member of the church depends on the others.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

5.3 The Brain and Spinal Cord: Broca (1861) and Penfield's Maps

Mark up this lesson

OBJECTIVES

- Locate the major parts of the brain (cerebrum and its lobes, diencephalon, brainstem, cerebellum) and state the main jobs of each.
- Describe how the brain and spinal cord are protected (bone, meninges, cerebrospinal fluid, blood–brain barrier) and the structure of the spinal cord.
- Trace a reflex arc, name the 12 cranial nerves, and explain a stroke as a broken mechanism.

> **Warm-up.** Read the colors, not the words, as fast as you can: write the words RED, BLUE and GREEN in mismatched colored pencils (RED written in blue, and so on), ten words in all, and time yourself. Then time yourself on a list where the colors match the words. Why is the mismatched list slower?

WATCH

Central Nervous System: Crash Course Anatomy & Physiology #11

CrashCourse · 10:08

https://www.youtube.com/watch?v=q8NtmDrb_qo

> **WHEN TO WATCH**
> After the parts of the brain. Watch for the lobes and the brainstem.

BACKUP VIDEO

Brain Structure - GCSE Biology

Launchpad Learning · 2:23

https://www.youtube.com/watch?v=yJzMmIVq66g

A short review of the cerebrum, cerebellum and medulla.

KEY TERMS

cerebrum

The largest part of the brain, two hemispheres with a folded outer cortex of gray matter, responsible for thought, language, memory, sensation and voluntary movement.

cerebellum

The "little brain" at the back that coordinates movement, balance and posture.

hypothalamus

A small region below the thalamus that controls body temperature, hunger, thirst and the pituitary gland.

reflex arc

The pathway of a reflex: receptor, sensory neuron, integration in the spinal cord, motor neuron, effector.

lobes

The frontal (planning, speech, movement), parietal (touch and body position), temporal (hearing, memory) and occipital (vision) regions of each hemisphere.

brainstem

The midbrain, pons and medulla oblongata, which connect the brain to the spinal cord and control breathing, heart rate and other automatic functions.

meninges and cerebrospinal fluid

The three membranes (dura mater, arachnoid, pia mater) around the brain and cord, and the clear fluid that cushions them.

CORE IDEAS

The story. In April 1861 a patient named Louis Leborgne died in a Paris hospital. For twenty years he had understood speech and could gesture sensibly, but he could say only one syllable, "tan." The surgeon Paul Broca examined his brain and found damage in one small area of the left frontal lobe. Over the next few years Broca collected more cases and concluded that this region (now Broca's area) is needed to produce speech. In the twentieth century the American-born Canadian neurosurgeon Wilder Penfield, operating on patients with severe epilepsy at the Montreal Neurological Institute, gently stimulated the exposed surface of the brain

while the patients were awake and could tell him what they felt. He mapped the strips of cortex that control movement and receive touch for each part of the body.

How they figured it out. Broca's method was to link a lost function to a damaged place, then check the link in other patients: a careful use of comparison. Penfield's method was experimental: the brain itself feels no pain, so with local anesthetic in the scalp he could touch a point of cortex with a weak current and record what happened, a twitch of the thumb, a tingle in the lip. He found that the hands, lips and tongue take up far more cortex than the trunk, because they need finer control and richer feeling. Late in life, in *The Mystery of the Mind* (1975), Penfield wrote that after all his study the mind could not be fully explained by the action of the brain alone.

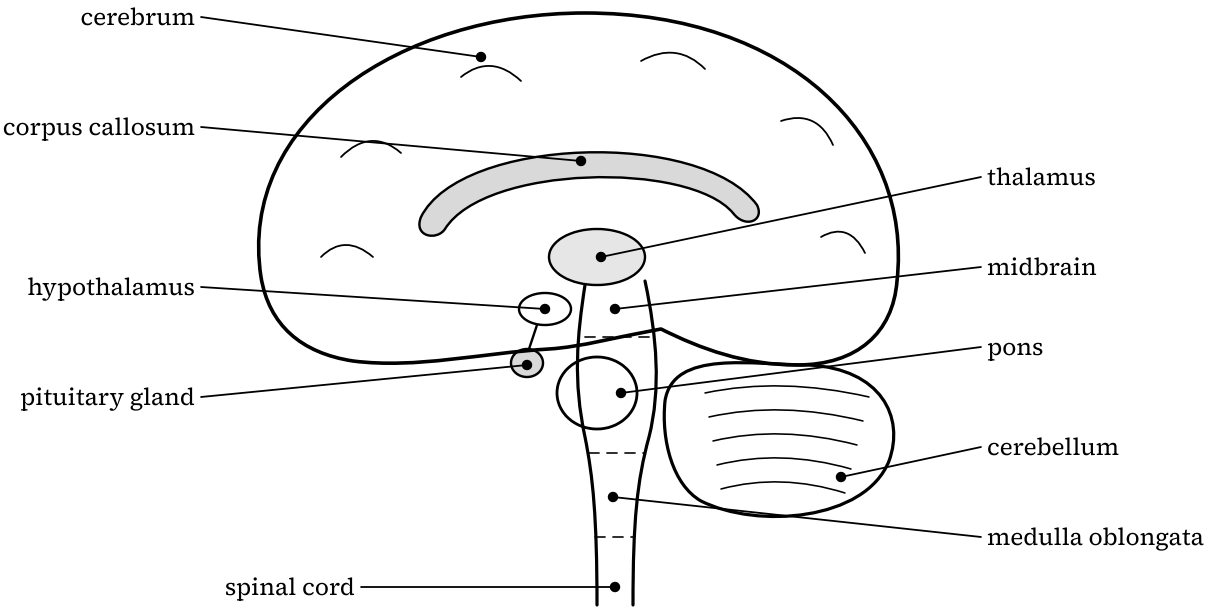
The cerebrum. The **cerebrum** has two hemispheres joined by a thick band of fibers, the **corpus callosum**. Its surface, the *cerebral cortex*, is gray matter (cell bodies) folded into ridges (gyri) and grooves (sulci); beneath it lies white matter (myelinated axons). Each hemisphere has four lobes. The **frontal lobe** plans, decides and controls voluntary movement; its back edge, the primary motor cortex, sends commands to the muscles, and in most people Broca's area for speech is on the left. The **parietal lobe** receives touch, pain and body position in the primary somatosensory cortex. The **temporal lobe** handles hearing, language understanding and memory. The **occipital lobe** handles vision. Each hemisphere controls and feels the opposite side of the body, because most motor and sensory pathways cross over.

The rest of the brain. Beneath the cerebrum, the **thalamus** is the relay station that sorts incoming sensations (except smell) and sends them to the right part of the cortex. Below it the small **hypothalamus** keeps homeostasis: body temperature, hunger, thirst, sleep and the control of the pituitary gland (Unit 6). The **brainstem** has three parts: the *midbrain* (eye movements and reflexes to sights and sounds), the *pons* (a bridge of fibers that also helps set the breathing rhythm) and the *medulla oblongata* (heart rate, blood pressure, breathing, swallowing, coughing and vomiting). Damage to the medulla is often fatal. The **cerebellum** at the back compares what the body is doing with what was intended and smooths movement, balance and posture; a person with cerebellar damage moves jerkily and walks as if dizzy.

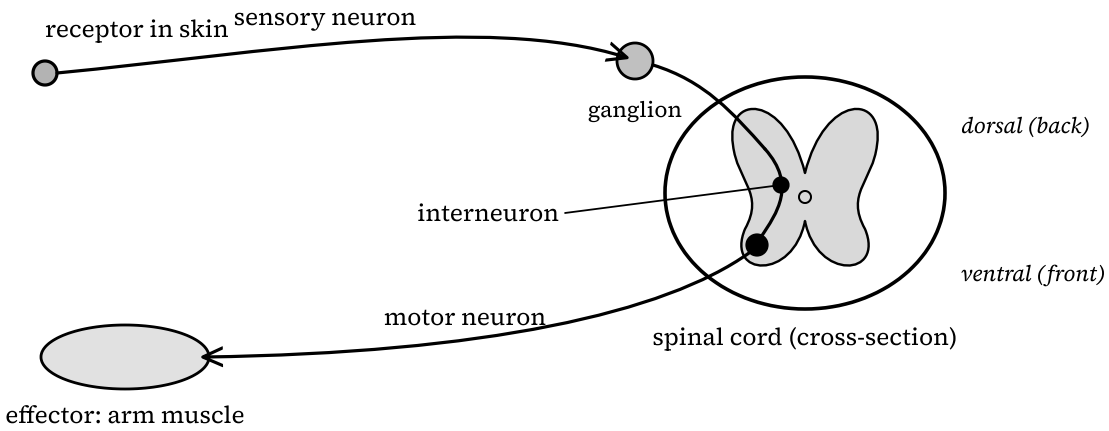
Protection and the spinal cord. The brain is guarded by the skull, three **meninges** (tough dura mater, web-like arachnoid, delicate pia mater), about 150 mL of **cerebrospinal fluid** (made at about 500 mL a day and constantly drained), and the **blood–brain barrier**, tight capillary walls that keep many substances in the blood out of the brain. The **spinal cord** runs from the medulla down the vertebral canal to about the first or second lumbar vertebra. In cross-section it has a butterfly of gray matter (dorsal horns receive sensory input; ventral horns hold motor neurons) surrounded by white matter tracts running up and down. Thirty-one pairs of **spinal nerves** leave it (8 cervical, 12 thoracic, 5 lumbar, 5 sacral, 1 coccygeal), and twelve pairs of **cranial nerves** leave the brain: olfactory (I), optic (II), oculomotor (III), trochlear (IV), trigeminal (V), abducens (VI), facial (VII), vestibulocochlear (VIII), glossopharyngeal (IX), vagus (X), accessory (XI) and hypoglossal (XII).

Reflexes. A **reflex** is a fast, automatic response. In a **reflex arc**, a receptor detects a stimulus, a sensory neuron carries the signal into the dorsal side of the spinal cord, the signal is processed (by one or more interneurons, or directly onto a motor neuron), and a motor neuron carries a command out to the effector, a muscle or gland. In the knee-jerk (patellar) reflex, the sensory neuron synapses directly on the motor neuron to the quadriceps: one synapse. Pulling your hand from a hot pan uses interneurons and also relaxes the opposing muscle. The brain learns about it a moment later. Doctors test reflexes because an absent or exaggerated reflex points to a problem at a particular level of the nerves or cord.

When it goes wrong. A **stroke** happens when blood flow to part of the brain is cut off, usually by a clot blocking an artery (ischemic stroke), or when a vessel bursts (hemorrhagic stroke). Neurons use oxygen fast and store almost none, so without blood they begin to die within minutes. The symptoms match the map: a stroke in the left frontal lobe may weaken the right arm and face and take away speech, as with Broca's patient. The signs are summed up as **BE FAST**: Balance loss, Eyes (vision loss), Face drooping, Arm weakness, Speech trouble, Time to call 911. Clot-dissolving medicine and clot-removal procedures work only if the patient arrives quickly.



The brain cut down the middle, front to the left. The brainstem keeps you alive; the cerebrum lets you think and act; the cerebellum makes movement smooth.



A withdrawal reflex arc: receptor, sensory neuron, interneuron, motor neuron, effector. The signal also travels up to the brain, which feels the pain a moment later.

> **Safety first.** Tap the knee gently with the side of the hand or a soft rubber hammer, never hard. Use only the ruler test for reaction time; do not startle people near stairs or hot surfaces.

LAB

Reflex Versus Reaction: Timing the Brain

You will compare a spinal reflex with reactions that must pass through the brain, and test how extra thinking slows a response.

You will need

- A 30 cm ruler, a partner, a calculator
- Colored pencils and index cards for a color-word test, a stopwatch
- A chair high enough for the legs to dangle

Steps

1. Knee-jerk: sit with legs dangling. Your partner taps just below the kneecap. Observe the kick. Repeat while you hook your fingers together and pull hard (this distraction often makes the reflex stronger). Record what you see.
2. Simple reaction: catch a dropped ruler ten times and convert each distance to time. Average.
3. Choice reaction: your partner calls “left” or “right” as the ruler drops, and you must catch with that hand only. Average ten trials.
4. Color-word test: time yourself naming the ink colors of a matching list and a mismatched list of 20 color words. Record both times.

Check your work

- ☐ Why can’t you measure the knee-jerk time with a ruler, and why is it so much faster than a reaction?
- ☐ How much did a choice add to your reaction time? Which brain regions had to do extra work?
- ☐ Which lobe reads the words, and why does reading interfere with naming the color?

LAB NOTEBOOK

1. The labeled midline brain with one job written beside each part.
2. The reflex arc diagram with the five parts numbered, and your timing data.

From history. Leborgne's brain, with the damaged area Broca described, is still kept in a scientific collection in Paris, and modern scans of it have confirmed and extended Broca's findings. Penfield founded the Montreal Neurological Institute in 1934 and insisted that surgeons and research scientists work in the same building, so questions from the operating room could go straight to the laboratory.

Practice habit. Use your sketchbook diagram as a map: each time you learn a new function, write it on the right region. Review by covering the labels and naming every region aloud.

Career connection. Emergency medical technicians (EMTs) and paramedics are often the first to see a stroke or a head or spinal injury. They check pupils, speech, strength and the BE FAST signs, and they protect the spine during transport. An EMT course takes a few months and ends with a certification exam; many EMTs go on to become paramedics, nurses or physician assistants. Some programs accept students at 18, and a few high schools offer the course to seniors.

WORKED EXAMPLES

Example 1. A man suddenly cannot move his right arm, his face droops on the right, and he cannot get words out though he understands everything said to him. Which hemisphere and lobe are most likely affected? Why?

Show solution

1. Right-sided weakness: motor pathways cross, so the left hemisphere.
2. Weakness of arm and face: the primary motor cortex, at the back of the frontal lobe.
3. Understands but cannot speak: Broca's area, in the left frontal lobe.

Answer: The left frontal lobe, likely a stroke; call 911 at once

Example 2. Count the spinal nerves: 8 cervical, 12 thoracic, 5 lumbar, 5 sacral and 1 coccygeal pairs. How many pairs, and how many nerves in all? Add the cranial nerves to find the total number of nerves leaving the brain and cord.

Show solution

1. $8 + 12 + 5 + 5 + 1 = 31$ pairs, so 62 spinal nerves.
2. 12 pairs of cranial nerves: 24 nerves.
3. $62 + 24 = 86$

Answer: 31 pairs (62) spinal nerves, plus 24 cranial nerves: 86 nerves in all

Example 3. The brain is about 1.4 kg in a 70 kg adult. What percent of body mass is it? It uses about 20% of the body's resting energy, roughly 320 of 1,600 kcal a day. What does this comparison show?

Show solution

1. $1.4/70 = 0.02 = 2\%$
2. $320/1600 = 0.20 = 20\%$

Answer: 2% of the mass uses 20% of the resting energy, ten times its share, which is why the brain cannot survive more than a few minutes without blood

PRACTICE

CONCEPT CHECKS

1. Easy Which part of the brain coordinates balance and smooth movement?

   Show answer

   The cerebellum.

2. Easy Name the four lobes of the cerebrum and one main job of each.

   Show answer

   Frontal: planning and voluntary movement (and speech); parietal: touch and body position; temporal: hearing and memory; occipital: vision.

3. **Medium** Which part of the brainstem controls heart rate and breathing, and why is injury there so dangerous?

Show answer

The medulla oblongata; it runs the automatic functions needed to stay alive, so damage can stop breathing or the heartbeat.

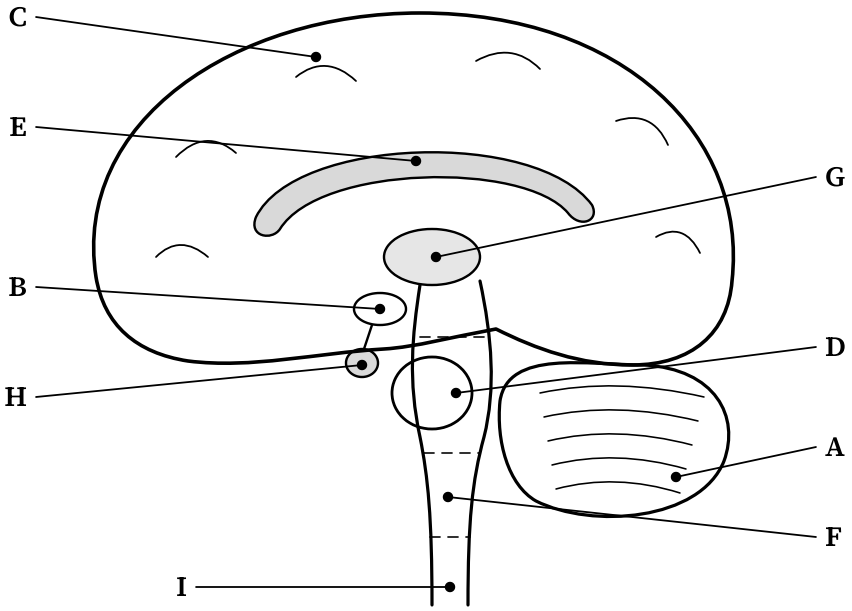
4. **Medium** List the five parts of a reflex arc in order.

Show answer

Receptor, sensory neuron, integration center (interneuron or synapse in the spinal cord), motor neuron, effector.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of the brain: name each part marked A to I.



Show answer

A, cerebellum; B, hypothalamus; C, cerebrum; D, pons; E, corpus callosum; F, medulla oblongata; G, thalamus; H, pituitary gland; I, spinal cord.

6. **Medium** A ruler falls 0.20 m before a student catches it. What is the reaction time? ($t = \sqrt{2d/g}$, g = 9.8 m/s²)

Show answer

t = √(2 × 0.20 / 9.8) ≈ 0.20 s.

7. Hard A patient can feel a pinprick on her left hand but cannot move her left hand. Which hemisphere and which strip of cortex is most likely damaged?

Show answer

The right hemisphere (pathways cross), in the primary motor cortex of the frontal lobe; the sensory strip in the parietal lobe is working.

DISORDER AS A BROKEN MECHANISM

8. Medium Explain why an ischemic stroke causes symptoms within minutes, and why the symptoms differ from one patient to another.

Show answer

A clot cuts off blood to a region of brain. Neurons use oxygen and glucose quickly and store almost none, so they stop working within minutes and begin to die. The symptoms depend on which region lost blood: motor cortex (weakness), Broca's area (speech), occipital lobe (vision) and so on.

PREDICT THE EFFECT

9. Hard Predict the effect: a diving accident crushes the spinal cord at the level of the lower neck. What functions are likely lost, and why are the arms partly spared while the legs are not?

Show answer

Nerves that leave the cord below the injury lose their connection to the brain, so the legs (and much of the trunk, bladder and bowel control) are paralyzed and lose feeling. The upper arm nerves leave the cord above or at the lower neck, so some arm and shoulder function may remain. Injuries higher in the neck can also stop breathing because the diaphragm's nerve leaves at C3–C5.

10. Challenge Penfield found that the hands and lips have much larger areas of motor and sensory cortex than the back. Explain why this makes sense, and how you could test the sensory part of it at home.

Show answer

Hands and lips need fine control and detailed feeling (writing, speaking, eating), so they have many more receptors and motor units, which need more cortex. Test with a two-point touch test: the smallest spacing at which two points feel like two is much smaller on the fingertips and lips than on the back.

COMMON MISTAKES

- Thinking the left brain controls the left side; most pathways cross, so each hemisphere controls the opposite side.
- Confusing the cerebrum (thinking) with the cerebellum (coordination).
- Saying reflexes go through the brain first; the spinal cord handles them, and the brain is told afterward.
- Believing you use only 10% of your brain; scans show activity throughout the brain over a day.
- Mixing up gray matter (cell bodies) and white matter (myelinated axons).

Make it a game · Brain Region Charades. The parent names an action (catching a ball, remembering a phone number, feeling a cold drink, reading a sign, breathing while asleep, standing on one foot, getting thirsty). The student points to the region on the core figure or on their own head and names it. Three correct in a row earns the right to make up the next action.

Scripture. "And be not conformed to this world: but be ye transformed by the renewing of your mind, that ye may prove what is that good, and acceptable, and perfect, will of God." (Romans 12:2, KJV)

The brain is changed by what we practice and think on. Paul calls believers to have their minds renewed by God.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

5.4 The Senses: Helmholtz's Ophthalmoscope (1851)

Mark up this lesson

OBJECTIVES

- Describe the structure of the eye and trace light from the cornea to the retina and the optic nerve.
- Explain how the ear turns sound into nerve signals and how the inner ear senses balance.
- Describe taste, smell and touch receptors, and calculate the position of the blind spot and the power of the eye's focusing.

> **Warm-up.** Close your left eye and stare at a spot on the wall with your right eye. Hold a pencil eraser at arm's length beside the spot and slowly move it outward to the right. Does it ever vanish? Write what you notice.

WATCH

Vision: Crash Course Anatomy & Physiology #18

CrashCourse · 9:39

https://www.youtube.com/watch?v=o0DYP-u1rNM

> **WHEN TO WATCH**
> After the parts of the eye. Watch for rods, cones and the path to the brain.

BACKUP VIDEO

GCSE Biology - How the Eye Works (Part 1) - Structure of the Eye & Iris Reflex

Cognito · 5:09

https://www.youtube.com/watch?v=9SGAicn9rXY

With the structure of the eye and the pupil reflex.

KEY TERMS

cornea and lens

The clear front of the eye, which does most of the focusing, and the flexible lens behind the pupil, which fine-tunes it.

accommodation

Changing the lens's shape to focus on near or far objects; the ciliary muscle contracts for near vision.

retina, rods and cones

The light-sensitive layer at the back of the eye; about 120 million rods see in dim light, about 6 million cones see color and detail.

fovea and optic disc

The small pit of tightly packed cones for sharpest vision, and the spot where the optic nerve leaves, which has no receptors (the blind spot).

cochlea

The snail-shaped, fluid-filled part of the inner ear whose hair cells turn sound vibrations into nerve signals.

vestibular system

The semicircular canals (head rotation) and the vestibule (gravity and straight-line motion) of the inner ear, which sense balance.

chemoreceptors

Receptors that respond to chemicals: taste buds for sweet, sour, salty, bitter and umami, and the olfactory receptors of smell.

CORE IDEAS

The story. In 1851 the German physicist and physician Hermann von Helmholtz built a simple instrument out of a few glass plates and a lens that let him look through a patient's pupil and see, for the first time in a living person, the retina, its blood vessels and the optic disc. The ophthalmoscope changed eye medicine overnight; diseases that had been guesses could now be seen. Helmholtz also measured how the lens changes shape to focus, developed Thomas Young's idea (1802) that color vision uses three kinds of receptors, and wrote a great handbook on the physics of sight and hearing.

How they figured it out. The retina had always been dark because the observer's own head blocks the light needed to see it. Helmholtz's insight was to send light into the eye along the same line the observer looks: light reflected off the glass plates into the patient's eye, and the observer looked through the plates and caught the light returning from the retina. Young's three-color idea came from reasoning about how all colors can be mixed from three lights; Helmholtz tested it with color-matching experiments, and in the twentieth century the three kinds of cones were found directly.

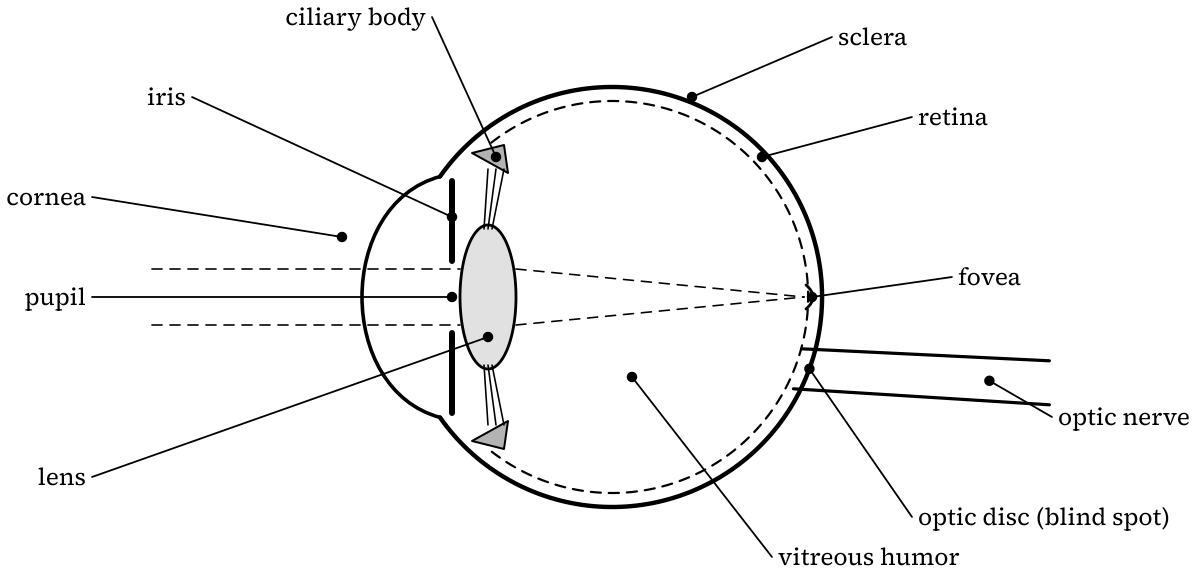
The eye. The eyeball has three layers: the tough white **sclera** (clear in front as the **cornea**), a middle layer rich in blood vessels that includes the **iris** and the **ciliary body**, and the inner **retina**. Light passes through the cornea, the watery aqueous humor, the **pupil** (the opening in the iris, which narrows in bright light), the **lens** and the jelly-like vitreous humor to the retina. The cornea does about two-thirds of the focusing; the lens fine-tunes it by **accommodation**: for near objects the ciliary muscle contracts, the ligaments holding the lens slacken and the lens rounds up. The image on the retina is upside down; the brain interprets it. In the retina, **rods** work in dim light and see only shades of gray, and three kinds of **cones** (sensitive to red, green and blue light) give color and detail, packed most densely in the **fovea**. Signals leave through the **optic nerve** at the **optic disc**, which has no receptors: the **blind spot**, about 15° to the side of where you are looking. Each eye's blind spot is covered by the other eye, and the brain fills in the gap.

Hearing and balance. Sound waves enter the outer ear canal and vibrate the **eardrum**. Three tiny bones of the middle ear, the malleus (hammer), incus (anvil) and stapes (stirrup), pass the vibration to the oval window of the inner ear, increasing its pressure about twentyfold so it can move fluid. In the **cochlea**, the vibration travels along a membrane lined with **hair cells**; high pitches move the part near the base, low pitches the part near the tip. When the hairs bend, the cells release neurotransmitter onto the auditory nerve. Young people hear from about 20 to 20,000 vibrations per second (hertz). Balance is sensed by the **vestibular system**: three semicircular canals at right angles detect head rotation as their fluid lags behind, and two small chambers with tiny crystals on their hair cells detect gravity and straight-line acceleration. The auditory tube links the middle ear to the throat and equalizes pressure when your ears "pop."

Taste, smell and touch. Taste buds on the tongue have receptor cells for five basic tastes: sweet, sour, salty, bitter and umami (savory). Most of what we call flavor is really smell: odor molecules from food rise to the olfactory receptors high in the nose, of which humans have roughly 400 different kinds, and their nerve fibers go straight to the brain without passing through the thalamus. The skin has separate receptors for light touch, pressure, vibration, stretch, heat, cold and pain. They are crowded on the fingertips and lips and sparse on the back, which is why you can tell two points apart much more easily on a fingertip.

When it goes wrong. A **cataract** is a clouding of the lens, most often with age: the lens proteins clump, so light is scattered and vision becomes blurry and glaring, as if through frosted glass. Surgeons remove the cloudy lens and put in a clear plastic one, one of the most common operations in the world. In **nearsightedness (myopia)** the eyeball is a little too long, so distant objects focus in front of the retina; a diverging lens corrects it. In **farsightedness** the eye is too short, and with age the lens stiffens so near focus fails (presbyopia), which is why many adults over 45 need reading glasses. Long exposure to loud sound kills cochlear hair cells, which do not grow back, so hearing protection matters.

Where it is used and try it. Optometrists measure focusing power in *diopters* (1 divided by the focal length in meters). Audiologists test hearing with tones at different pitches and fit hearing aids and cochlear implants, which stimulate the auditory nerve directly. In the lab you will map your blind spot, find your near point and test two-point touch on different parts of your skin.



Light is focused by the cornea and lens onto the retina. Where the optic nerve leaves there are no rods or cones: the blind spot.

> **Safety first.** Never look at the sun or shine a light directly into anyone's eyes. Use toothpick tips gently and never near the face or eyes. Keep sound tests at normal speaking volume.

LAB

Senses Lab: Blind Spot, Near Point and Two-Point Touch

You will measure where your blind spot is, how close you can focus, and how densely touch receptors are packed on your skin.

You will need

- An index card, a marker, a meter stick or tape measure, a calculator
- Two toothpicks or a bent paper clip and a ruler
- A partner

Steps

1. Blind spot: draw a small cross and, 8 cm to its right, a dot on the card. Close your left eye, stare at the cross with your right eye and move the card slowly toward you from arm's length. Have your partner measure the distance from your eye to the card when the dot vanishes. Calculate the angle with $\tan\theta = 8/d$.
2. Near point: with one eye closed, bring a page of small print toward your eye until it just begins to blur. Measure the distance. Ask an adult over 45 to try it too.
3. Two-point touch: with your eyes closed, your partner touches your skin with one or two toothpick points, randomly, at spacings of 2, 5, 10, 20 and 40 mm. Find the smallest spacing at which you correctly feel two points on the fingertip, palm, forearm, back of the neck and calf.
4. Taste and smell: hold your nose and taste a flavored jelly bean or a piece of fruit with your eyes closed. Try to name the flavor. Then let go of your nose.

Check your work

- ☐ What angle did you find for your blind spot? How close is it to 15°?
- ☐ Whose near point was farther, yours or the adult's? Why?
- ☐ Rank the body sites by two-point distance. How does this match Penfield's maps from Lesson 5.3?
- ☐ What changed when you let go of your nose?

LAB NOTEBOOK

1. The labeled eye with the path of light drawn in.
2. Your blind-spot calculation, near-point data and a two-point touch bar graph.

KEY FORMULAS

$$P = \frac{1}{f}\ (\text{diopters, } f \text{ in m}) \qquad \tan\theta = \frac{x}{d}$$

From history. Helmholtz began as an army surgeon because his family could not afford a university education otherwise; the Prussian army paid for his medical training in return for years of service. In 1862, eleven years after the ophthalmoscope, the Dutch eye doctor Herman Snellen published his letter chart, and "20/20 vision" comes from it: what you can read at 20 feet, a typical eye can read at 20 feet.

Practice habit. When you study a sense organ, trace the path out loud in order, from the outside world to the brain, naming every structure. If you skip one, start again.

Career connection. Optometrists examine eyes, prescribe glasses and contact lenses, and look for diseases such as glaucoma and cataracts with descendants of Helmholtz's ophthalmoscope. In the United States they earn a four-year Doctor of Optometry degree after college. Opticians, who fit and make glasses, train in shorter programs; audiologists, who test hearing and fit hearing aids, earn a doctorate in audiology.

WORKED EXAMPLES

Example 1. The blind spot is about 15° to the side of where you look. If you hold a card 30 cm from your eye, how far from the cross should the dot be to vanish?

Show solution

1. $\tan 15^\circ = x/30$
2. $x = 30\tan 15^\circ = 30(0.268) = 8.0$ cm

Answer: About 8 cm, which is why the card in the lab uses 8 cm

Example 2. Lens power in diopters is $P = 1/f$ with f in meters. The whole relaxed eye focuses parallel light about 17 mm behind its optical center. What is its power? To focus on a page 25 cm away, how many diopters must accommodation add?

Show solution

1. $P = 1/0.017 \approx 59$ D
2. Extra power for an object at 0.25 m: $1/0.25 = 4$ D

Answer: About 59 diopters relaxed; the lens must add about 4 diopters to read at 25 cm

Example 3. A 50-year-old's near point is 1.0 m. How many diopters of accommodation does he have left, and what reading glasses would let him read at 25 cm?

Show solution

1. Remaining accommodation: $1/1.0 = 1$ D
2. Needed for 25 cm: 4 D
3. Glasses must add $4 - 1 = 3$ D

Answer: About 1 diopter left; +3 diopter reading glasses

PRACTICE

CONCEPT CHECKS

1. Easy Which structure of the eye does most of the focusing: the cornea or the lens?

   Show answer

   The cornea, about two-thirds; the lens fine-tunes.

2. Easy What is the difference between rods and cones?

   Show answer

   Rods work in dim light and see shades of gray; cones need brighter light and see color and fine detail.

3. **Medium** Trace a sound wave from the air to the auditory nerve.

Show answer

Ear canal → eardrum → malleus, incus, stapes → oval window → fluid of the cochlea → hair cells bend → neurotransmitter onto the auditory nerve.

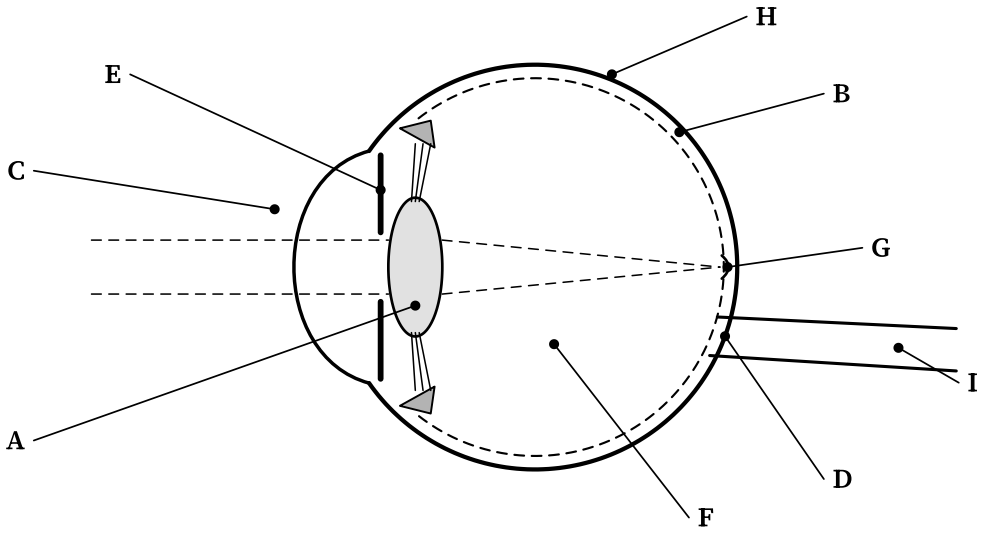
4. **Medium** Why does food taste bland when you have a stuffy nose?

Show answer

Much of flavor is smell; with the nose blocked, odor molecules cannot reach the olfactory receptors, leaving only the five basic tastes.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of the eye: name each part marked A to I.



Show answer

A, lens; B, retina; C, cornea; D, optic disc (blind spot); E, iris; F, vitreous humor; G, fovea; H, sclera; I, optic nerve.

6. **Medium** In the blind-spot test the dot vanishes when the card is 25 cm away and the dot is 7 cm from the cross. What angle is that?

Show answer

$\tan\theta = 7/25$, $\theta \approx 15.6°$.

7. Hard A student's near point is 10 cm. How many diopters of accommodation does she have? Why do young children's eyes focus so close?

Show answer

1/0.10 = 10 D. Young lenses are soft and elastic, so they round up a great deal when the ciliary muscle contracts; the lens stiffens with age.

DISORDER AS A BROKEN MECHANISM

8. Medium Explain why a cataract blurs vision even though the retina and optic nerve are healthy, and why replacing the lens restores sight.

Show answer

In a cataract the proteins of the lens clump and cloud it, so light is scattered instead of being focused sharply on the retina. The receptors and nerve still work; once the cloudy lens is replaced with a clear artificial one, a sharp image reaches the retina again.

PREDICT THE EFFECT

9. Hard Predict the effect: an ear infection fills the middle ear with fluid. Which kind of hearing is reduced, and why?

Show answer

Fluid damps the movement of the eardrum and the three small bones, so less vibration reaches the cochlea; sounds seem muffled (a conductive hearing loss), even though the hair cells and nerve are fine.

10. Challenge Why do you not notice your blind spot in everyday life, even with one eye closed?

Show answer

With both eyes open, each eye's blind spot falls on a part of the scene the other eye sees. With one eye closed, the brain fills in the gap using the surrounding pattern, and the eyes constantly move, so no part of the scene stays in the blind spot.

COMMON MISTAKES

- Thinking the lens does all the focusing; the cornea does most of it.
- Saying the eye sees a right-side-up image; the retinal image is upside down and the brain interprets it.

- Calling the cochlea an organ of balance; the cochlea hears, and the semicircular canals and vestibule sense balance.
- Believing there is a “tongue map” with one taste per region; all five tastes are sensed all over the tongue.

Make it a game · Blindfold Sense Detective. Blindfold the student. The family presents six mystery items to be identified by one sense only: smell (orange peel, cinnamon), touch (a coin, a feather), hearing (keys shaken, paper crumpled). For each correct answer the student must also name the receptor or organ that did the work (olfactory receptors, touch receptors, cochlea). Switch roles and compare scores.

Scripture. “He that planted the ear, shall he not hear? he that formed the eye, shall he not see?” (Psalm 94:9, KJV)

The Creator of the eye and ear sees and hears perfectly. Helmholtz could finally look into the eye; God sees into the heart.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

5.5 The Autonomic Nervous System and the Neuro Check: Cannon's "Fight or Flight" (1915)

Mark up this lesson

OBJECTIVES

- Compare the somatic and autonomic nervous systems and the sympathetic and parasympathetic divisions (origin, ganglia, neurotransmitters, effects).
- Predict the effects of each division on the heart, lungs, eyes, digestion and other organs.
- Perform a basic neurological check safely (pupils, eye movements, face, strength, coordination, balance, reflexes) and record it in clinical form.

> **Warm-up.** Sit quietly for 2 minutes and count your pulse for 30 seconds. Then have someone surprise you with a sudden loud clap (no one with a heart condition should do this) and count again at once. What changed, and how quickly did it return to normal? You did not decide to make it change. What did?

WATCH

Autonomic Nervous System: Crash Course Anatomy & Physiology #13

CrashCourse · 8:49

https://www.youtube.com/watch?v=71pCilo8k4M

> **WHEN TO WATCH**
> After the two divisions. Watch for where each division leaves the spinal cord and what each does.

BACKUP VIDEO

The Autonomic Nervous System: Sympathetic and Parasympathetic Divisions

Professor Dave Explains · 6:38

https://www.youtube.com/watch?v=DPWEhl7gbu4

With the comparison table.

KEY TERMS

somatic nervous system

The part of the peripheral nervous system under voluntary control: one motor neuron from the CNS to each skeletal muscle, releasing acetylcholine.

autonomic nervous system

The involuntary motor system to the heart, smooth muscle and glands, using a chain of two neurons with a ganglion between them.

sympathetic division

The "fight or flight" division, leaving the thoracic and lumbar spinal cord; its postganglionic neurons mostly release norepinephrine.

parasympathetic division

The "rest and digest" division, leaving the brainstem (cranial nerves, especially the vagus) and the sacral cord; it releases acetylcholine at its targets.

ganglion

A cluster of neuron cell bodies outside the brain and spinal cord.

neuro check

A quick, repeatable neurological assessment: level of consciousness, pupils, eye movements, face, speech, strength, coordination, sensation and reflexes.

Glasgow Coma Scale

A 3-to-15-point score of eye opening (1–4), verbal response (1–5) and motor response (1–6) used to track consciousness.

CORE IDEAS

The story. The Harvard physiologist Walter Bradford Cannon spent years watching what happens inside animals and people under stress. In 1915 he published *Bodily Changes in Pain, Hunger, Fear and Rage*, describing how the sympathetic nerves and adrenaline from the adrenal glands prepare the body for an emergency: what he called the "fight or flight" response. In 1926 he coined the word *homeostasis* for the body's ability to keep its inner conditions steady, and in *The Wisdom of the Body* (1932) he showed that the autonomic nervous system is one of its main tools.

How they figured it out. Cannon first noticed, using early X-rays to watch digestion in cats, that the stomach stopped churning whenever the animal was frightened. He measured blood sugar, heart rate and blood clotting before and after stress, and found they all changed in ways that would help in a struggle. To separate the effects of the nerves from those of adrenaline, he studied animals in which one or the other had been removed, and found that each could partly do the job of the other. His approach was to ask what a response is *for*, then test whether the measurements fit that purpose.

Somatic versus autonomic. The **somatic** motor system controls skeletal muscle: one motor neuron runs from the brainstem or spinal cord all the way to the muscle and releases acetylcholine, and you can control it at will. The **autonomic** system controls cardiac muscle, smooth muscle (in vessels, airways, the gut, the iris) and glands, mostly without conscious control. It uses *two* neurons in a row: a **preganglionic neuron** with its cell body in the brainstem or cord, and a **postganglionic neuron** with its cell body in a **ganglion** outside the CNS. The hypothalamus and brainstem are its command centers.

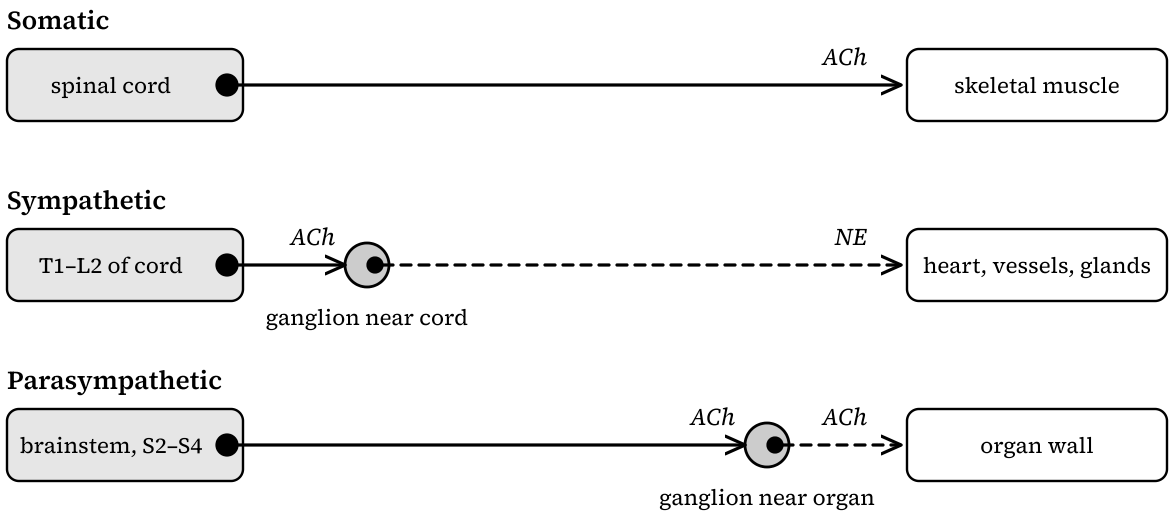
Two divisions. The **sympathetic division** leaves the cord from the thoracic and upper lumbar segments (T1–L2). Its preganglionic neurons are short and end in a chain of ganglia beside the spine; its postganglionic neurons are long and mostly release **norepinephrine** (sweat glands are an exception, using ACh). It also stimulates the adrenal medulla to pour epinephrine into the blood, spreading the effect everywhere. The **parasympathetic division** leaves the brainstem in four cranial nerves (III, VII, IX and X; the vagus nerve carries most of it) and the sacral cord (S2–S4). Its preganglionic neurons are long and end in ganglia in or near the target organ; its short postganglionic neurons release **acetylcholine**. Most organs receive both, and the balance between them sets the organ's activity, like a car's accelerator and brake.

What each division does. In "fight or flight" the sympathetic division speeds and strengthens the heartbeat, raises blood pressure, widens the airways, dilates the pupils, sends blood to the skeletal muscles and away from the gut and skin, releases glucose from the liver, and slows digestion. In "rest and digest" the parasympathetic division slows the heart, narrows the pupils and airways, increases saliva, stomach and intestinal activity, and helps empty the bladder. At rest the heart is mostly under parasympathetic (vagal) control: its pacemaker on its own would beat about 100

times a minute, but the vagus slows it to the familiar 60 to 80. Prayer, slow breathing and a calm evening routine shift the balance toward the parasympathetic side.

When it goes wrong. In ordinary **fainting (vasovagal syncope)**, often triggered by the sight of blood, pain, standing still a long time in heat, or fear, the autonomic reflexes overshoot: a surge of parasympathetic (vagal) activity slows the heart while sympathetic tone to the blood vessels suddenly drops, so they widen. Blood pressure falls, too little blood reaches the brain, and the person collapses. Lying flat brings blood back to the brain and the person wakes within a minute or so. It shows that the two divisions must stay balanced; it is a normal reflex working too hard, not a damaged nerve. Fainting with chest pain, during exercise, or without a clear trigger needs a doctor.

The clinical skills lab: a neuro check. Nurses, EMTs and doctors use a short, repeatable **neuro check** to find problems in the nervous system and to see whether a patient is getting better or worse. It checks: *level of consciousness* (alert and oriented to person, place, time and situation; the **Glasgow Coma Scale** for serious injuries); *pupils* (equal, round, reactive to light and accommodation, written PERRLA, testing cranial nerves II and III); *eye movements* (following a finger in an H pattern: nerves III, IV, VI); *face* (smile, raise eyebrows, puff cheeks: VII); *shoulder shrug* (XI) and *tongue* out straight (XII); *strength* (equal grip; holding the arms out with the eyes closed to watch for one drifting down); *coordination* (finger to nose, heel down shin: cerebellum); *balance* (Romberg test: feet together, eyes closed); *sensation*; and *reflexes*. In the lab you will practice it on a healthy partner and record it. This is practice, not diagnosis: any sudden change in a real person is an emergency.



solid: preganglionic (or somatic) neuron · dashed: postganglionic neuron

One neuron for somatic control; two for autonomic. Sympathetic: short then long, ending in NE. Parasympathetic: long then short, ending in ACh.

> **Safety first.** This lab is practice on a healthy volunteer, never a diagnosis. Shine a penlight into each eye for only a second or two, from the side. During the Romberg test a spotter stands close behind with hands ready, away from furniture and stairs. Skip the startle test for anyone with a heart condition. If a real person shows sudden weakness, facial droop, slurred speech, confusion or unequal pupils after a head injury, call 911.

LAB

Clinical Skills Lab: A Basic Neuro Check

You will learn the steps of a nurse's or EMT's neuro check, practice them on a healthy partner and record the results in a clinical table.

You will need

- A small penlight or phone flashlight, a cotton ball, a pen to look at, a rubber reflex hammer or the side of your hand
- A watch with a second hand, a printed checklist and pencil, a partner, a spotter

Steps

1. Vital signs and consciousness: count your partner's pulse and breathing for 30 seconds each and double. Ask four orientation questions: name, where you are, the date, why you are here. Record "alert and oriented ×4" if all are right.
2. Pupils (II, III): in dim light, look at the size and shape of both pupils. Shine the light from the side into one eye for a second: both pupils should narrow. Then have your partner look from a far wall to a pen 15 cm away: the pupils narrow for near focus. Record PERRLA if all is normal.
3. Eye movements and face (III, IV, VI, VII): hold a pen 40 cm away and move it slowly in an H pattern; the eyes should follow smoothly together. Ask your partner to raise the eyebrows, close the eyes tightly, smile and puff the cheeks; look for symmetry. Shrug the shoulders against your hands (XI) and stick out the tongue (XII).
4. Strength and drift: compare grip strength in both hands. Ask your partner to hold both arms straight out, palms up, eyes closed, for 20 seconds; watch whether one arm drifts down or turns inward.
5. Coordination and balance (cerebellum): finger-to-nose (touch your finger, then their own nose, back and forth, eyes open) and heel-to-shin. Romberg: feet together, arms at sides, eyes open for 20 seconds, then eyes closed for 20 seconds, with a spotter close behind.

6. Sensation and reflexes: with eyes closed, your partner says “now” when you touch each hand and foot lightly with the cotton ball. Test the knee-jerk reflex on both sides, gently. Then fill in the record table and write a one-line summary, the way a nurse would chart it.

Check your work

- ☐ Which steps tested cranial nerves, which tested the cerebellum, and which tested the motor pathways?
- ☐ Why is every test done on both sides and compared?
- ☐ Why do nurses repeat the same neuro check every hour for a patient with a head injury instead of doing it once?
- ☐ Which autonomic effects did you notice in your partner (pupil size, pulse) during the lab?

LAB NOTEBOOK

1. A two-column table of sympathetic and parasympathetic effects on eight organs.
2. Your completed neuro-check record and a one-line chart summary.

From history. Cannon was one of the first to use X-rays in physiology, beginning in 1896 as a medical student, only months after Röntgen’s discovery. The Glasgow Coma Scale was published in 1974 by the neurosurgeons Graham Teasdale and Bryan Jennett of Glasgow, Scotland, to give nurses and doctors a common language for describing consciousness; it is now used around the world.

Practice habit. Practice the neuro check in the same order every time, saying each step and its cranial nerve aloud. Clinicians rely on a fixed order so nothing is skipped under pressure.

WORKED EXAMPLES

Example 1. Trace what each division does when a student is chased by a dog, then sits down to supper an hour later: heart rate, pupils, airways, digestion, blood glucose.

Show solution

1. Chase: sympathetic. Heart rate up, pupils dilate, airways widen, digestion slows, liver releases glucose; adrenal medulla adds epinephrine.
2. Supper: parasympathetic. Heart rate down, pupils narrow, airways back to normal, saliva and stomach and intestinal activity increase, insulin helps store glucose (Lesson 6.4).

Answer: Fight or flight, then rest and digest: the two divisions act like an accelerator and a brake on the same organs

Example 2. A patient opens his eyes only when spoken to (3), speaks in confused sentences (4) and obeys commands (6). What is his Glasgow Coma Scale score? An hour later: eyes open only to pain (2), only moaning sounds (2), pulls away from pain (4). What is the new score, and what does the change mean?

Show solution

1. First: $3 + 4 + 6 = 13$
2. Later: $2 + 2 + 4 = 8$

Answer: 13, then 8: his consciousness is falling, an emergency that needs the doctor at once. A score of 8 or less is classed as a severe brain injury.

Example 3. A resting pulse is 18 beats in 15 seconds. After a sudden fright it is 28 beats in 15 seconds. Find both rates per minute and the percent increase.

Show solution

1. $18 \times 4 = 72$ per minute; $28 \times 4 = 112$ per minute
2. $(112 - 72)/72 \approx 0.56$

Answer: 72 and 112 beats per minute: a 56% increase from a sympathetic surge

PRACTICE

CONCEPT CHECKS

1. **Easy** Which division of the autonomic nervous system is “fight or flight,” and which is “rest and digest”?

   Show answer

   Sympathetic is fight or flight; parasympathetic is rest and digest.

2. **Easy** What neurotransmitter do most sympathetic postganglionic neurons release? Parasympathetic postganglionic neurons?

   Show answer

   Sympathetic: norepinephrine. Parasympathetic: acetylcholine.

3. **Medium** State the effect of each division on (a) the pupils, (b) the airways, (c) the stomach and intestines.

   Show answer

   Sympathetic: (a) dilate, (b) widen, (c) slow down. Parasympathetic: (a) narrow, (b) narrow, (c) speed up.

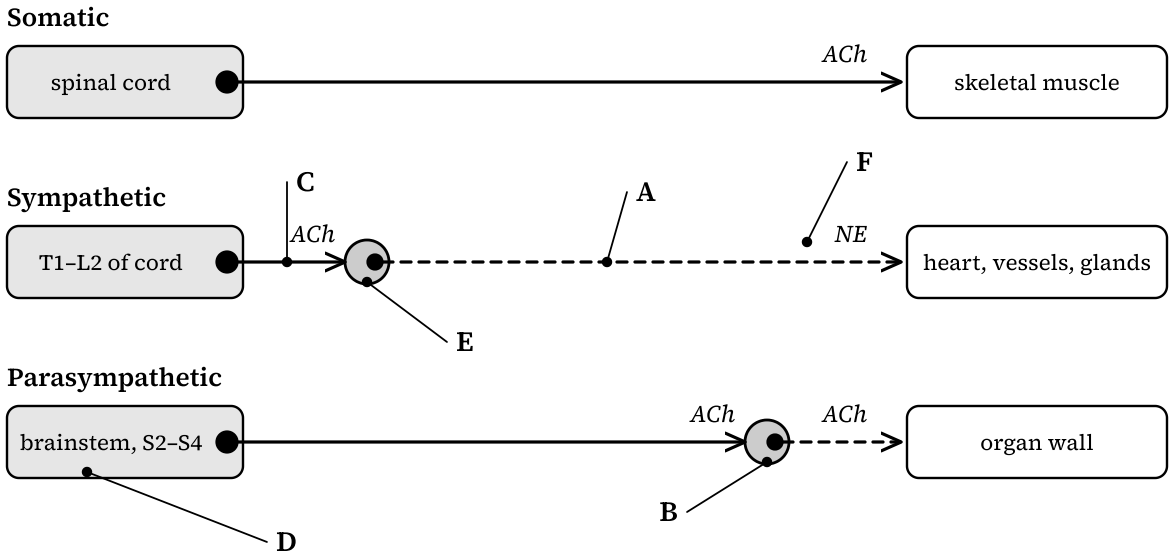
4. **Medium** Which cranial nerve carries most of the parasympathetic output, and which organs does it reach?

   Show answer

   The vagus nerve (X); it reaches the heart, lungs and most of the digestive tract.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of motor pathways: name each structure or event marked A to F.



solid: preganglionic (or somatic) neuron · dashed: postganglionic neuron

Show answer

A, postganglionic neuron; B, parasympathetic ganglion; C, preganglionic neuron (sympathetic); D, brainstem or sacral spinal cord; E, sympathetic ganglion; F, norepinephrine (NE) released here.

6. **Medium** During a neuro check a patient opens his eyes spontaneously (4), is oriented and talks normally (5) and obeys commands (6). What is his Glasgow Coma Scale score?

Show answer

4 + 5 + 6 = 15, the highest possible score (normal).

7. **Hard** In the arm-drift test, a patient's left arm slowly drifts down and turns palm-in with her eyes closed. Which side of the brain might be affected, and which pathway?

Show answer

The right hemisphere, because the motor pathways cross; a subtle weakness in the motor pathway (motor cortex or the tract from it) to the left arm.

DISORDER AS A BROKEN MECHANISM

8. Medium A student faints at the sight of blood. Explain the autonomic mechanism, and why lying down fixes it.

Show answer

A strong vagal (parasympathetic) surge slows the heart while sympathetic tone to the blood vessels drops, so they widen. Blood pressure falls and too little blood reaches the brain. Lying flat removes the need to pump blood uphill to the brain, so blood flow returns and she wakes.

PREDICT THE EFFECT

9. Hard Predict the effect: a drug blocks acetylcholine receptors on the heart (but not on skeletal muscle). What happens to the resting heart rate, and why?

Show answer

The heart rate rises toward the pacemaker's own rate of about 100 per minute, because the vagus nerve's slowing (parasympathetic, using ACh) is blocked.

10. Challenge In the Romberg test a person stands steadily with eyes open but sways and nearly falls when the eyes close. What three sources of information does balance use, and what does this result suggest?

Show answer

Balance uses vision, the inner ear's vestibular system and position sense (proprioception) from muscles and joints, sent up the spinal cord. Steady with eyes open but not closed means vision was making up for a problem in position sense or the vestibular system; with the eyes closed the remaining senses are not enough.

COMMON MISTAKES

- Thinking the sympathetic division is always "on" in a crisis and off otherwise; both divisions are active all the time, and their balance shifts.
- Saying the parasympathetic system slows everything; it speeds up digestion.
- Forgetting that the autonomic pathway has two neurons and a ganglion; the somatic pathway has one.
- Writing PERRLA when a pupil was not actually tested for accommodation; record only what you checked.
- Treating the lab neuro check as a diagnosis; it is practice, and real sudden changes are emergencies.

Make it a game · Accelerator or Brake?. The parent names an effect (pupils dilate, more saliva, heart slows, airways widen, bladder empties, liver releases glucose, digestion speeds up, sweating). The student stamps the floor for sympathetic (accelerator) or touches the floor gently for parasympathetic (brake), then names the neurotransmitter. Keep score and race against a 60-second timer.

Scripture. "Be careful for nothing; but in every thing by prayer and supplication with thanksgiving let your requests be made known unto God. And the peace of God, which passeth all understanding, shall keep your hearts and minds through Christ Jesus." (Philippians 4:6–7, KJV)

The body was made with an alarm for real danger. Paul shows a better way than living in constant alarm: bring every care to God in prayer.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

UNIT 5

The Nervous System

The nervous system is the body's fast communication network. This unit follows five discoveries: Cajal's drawings of separate neurons (1888) and Hodgkin and Huxley's explanation of the action potential (1952), Otto Loewi's two frog hearts (1921), Broca's speech area (1861) and Penfield's maps of the cortex, Helmholtz's ophthalmoscope (1851), and Walter Cannon's "fight or flight" (1915).

Students trace the action potential millisecond by millisecond, add up synaptic signals, locate the parts of the brain and the cranial nerves, calculate the blind spot and the eye's focusing power, and compare the two divisions of the autonomic system. The unit ends with a clinical-skills lab: a basic neuro check of pupils, eye movements, face, strength, coordination, balance and reflexes, practiced safely on a healthy partner. Labs use dominoes, a ruler, index cards, toothpicks and a penlight.

PREREQUISITES

- Unit 1, especially Lesson 1.3 (homeostasis and feedback)
- Unit 2, especially Lessons 2.2 (membrane transport) and 2.4 (nervous tissue)
- Unit 4, especially Lesson 4.2 (the neuromuscular junction)
- Logarithms for the Nernst equation (optional challenge problems)

MASTERY CHECKLIST

- ☐ I can label a neuron and trace the action potential through each phase, naming the ions and channels.
- ☐ I can describe synaptic transmission step by step and explain summation of EPSPs and IPSPs.
- ☐ I can locate the major parts of the brain, state their jobs, and trace a reflex arc.
- ☐ I can trace light through the eye and sound through the ear, and calculate the blind-spot angle and diopters.
- ☐ I can compare the sympathetic and parasympathetic divisions and predict their effects on organs.
- ☐ I can perform and record a basic neuro check safely, and explain a nervous-system disorder as a broken mechanism.

LESSONS IN THIS UNIT

5.1 Neurons and the Action Potential: Cajal (1888) and Hodgkin and Huxley (1952)
4 sessions of 45 minutes

5.2 The Synapse: Loewi's Dream Experiment (1921) — 4 sessions of 45 minutes

5.3 The Brain and Spinal Cord: Broca (1861) and Penfield's Maps
4 sessions of 45 minutes

5.4 The Senses: Helmholtz's Ophthalmoscope (1851) — 4 sessions of 45 minutes

5.5 The Autonomic Nervous System and the Neuro Check: Cannon's "Fight or Flight" (1915)

4 sessions of 45 minutes, plus the clinical-skills lab

Unit 5 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **8 pts** **Lesson 5.1**
   Describe the action potential in order: what happens to the voltage and which channels open or close at threshold, at the peak, and during hyperpolarization.

2. **7 pts** **Lesson 5.1**
   An impulse travels along a 1.2 m axon at 60 m/s. How long does it take, in milliseconds? Why would an unmyelinated axon of the same length be much slower?

3. **6 pts** **Lesson 5.1**
   Explain why an action potential cannot travel backward along an axon.

4. **8 pts** **Lesson 5.2**
   List the steps of chemical transmission at a synapse, from the arrival of the action potential to the end of the signal.

5. **7 pts** **Lesson 5.2**
   A neuron rests at −70 mV and fires at −55 mV. At one moment it receives 6 EPSPs of 4 mV each and 2 IPSPs of 3 mV each. Does it fire? Show the sum.

6. **7 pts** **Lesson 5.3**
   Give the main job of: (a) the medulla oblongata, (b) the cerebellum, (c) the hypothalamus, (d) the occipital lobe.

7. **7 pts** **Lesson 5.3**

   Draw or describe the reflex arc for pulling a hand away from a hot pan, naming all five parts.

8. **7 pts** **Lesson 5.4**

   Trace light from outside the eye to the brain, naming each structure.

9. **7 pts** **Lesson 5.4**

   A person holds the blind-spot card 35 cm from the eye. Using a blind-spot angle of 15°, how far from the cross must the dot be to disappear?

10. **8 pts** **Lesson 5.5**

    Compare the sympathetic and parasympathetic divisions: where each leaves the CNS, where the ganglia are, the neurotransmitter at the target, and two effects of each.

11. **6 pts** **Lesson 5.5**

    Clinical skills: A patient's GCS is eye opening 3, verbal 4, motor 5. What is the score? Which cranial nerves are tested when you check that both pupils narrow in light?

DISORDERS AND SHORT ESSAY

12. **10 pts** **Lesson 5.1**

    Choose two of multiple sclerosis, Parkinson's disease, stroke and cataract. For each, name the structure that fails, explain the mechanism, and connect it to the symptoms.

13. **12 pts** **Lesson 5.3**

    Short essay: Cajal, Hodgkin and Huxley, Loewi, Broca and Penfield each discovered something about the nervous system that no one could see directly. Choose two. For each, describe the question, the method and what it showed. What do their methods have in common?

ANSWER KEY

1. Threshold (about −55 mV): voltage-gated Na^+ channels open and Na^+ rushes in, depolarizing to about +30 mV. Peak: Na^+ channels inactivate and voltage-gated K^+ channels open; K^+ flows out and the membrane repolarizes. Hyperpolarization: K^+ channels are slow to close, so the voltage dips to about −80 mV before the pump and leak channels restore −70 mV.
2. 1.2/60 = 0.020 s = 20 ms. Without myelin the action potential must be regenerated at every patch of membrane instead of jumping from node to node, so it travels only about 0.5–2 m/s.
3. The patch of membrane just behind the impulse is in its absolute refractory period: its sodium channels are inactivated and cannot reopen, so only the membrane ahead can fire.
4. Action potential reaches the terminal → voltage-gated Ca^{2+} channels open, Ca^{2+} enters → vesicles fuse and release neurotransmitter → it diffuses across the cleft → binds receptors, opening ion channels → EPSP or IPSP in the next cell → transmitter removed by enzyme breakdown, reuptake or diffusion.
5. Net change = 6 × 4 − 2 × 3 = 24 − 6 = +18 mV, so the membrane reaches −52 mV, above the −55 mV threshold: it fires.
6. (a) heart rate, breathing, blood pressure and other automatic functions; (b) coordination, balance and smooth movement; (c) homeostasis (temperature, hunger, thirst) and control of the pituitary; (d) vision.
7. Receptor (pain and heat receptors in the skin) → sensory neuron into the dorsal spinal cord → interneuron in the gray matter → motor neuron out through the ventral root → effector (the arm's flexor muscles), which pulls the hand away. The brain feels it a moment later.
8. Cornea → aqueous humor → pupil (in the iris) → lens → vitreous humor → retina (rods and cones) → optic nerve (leaving at the optic disc) → brain (occipital lobe).
9. x = 35 × tan 15° ≈ 35 × 0.268 ≈ 9.4 cm.
10. Sympathetic: T1–L2 of the cord; ganglia in a chain near the spine; norepinephrine; e.g. heart speeds up, pupils dilate, airways widen, digestion slows. Parasympathetic: brainstem (cranial nerves III, VII, IX, X) and S2–S4; ganglia in or near the organ; acetylcholine; e.g. heart slows, pupils narrow, digestion speeds up, saliva increases.

11. 3 + 4 + 5 = 12. The optic nerve (II) carries the light signal in, and the oculomotor nerve (III) narrows the pupils.
12. Look for: MS (myelin destroyed, current leaks between nodes, slowed or blocked conduction, changing numbness, weakness or vision problems); Parkinson's (dopamine neurons of the substantia nigra die, too little dopamine at deep brain synapses, tremor, stiffness, slowness; levodopa crosses the blood–brain barrier); stroke (blood supply cut off, neurons die in minutes, symptoms match the region, BE FAST); cataract (lens proteins clump, light scattered, blurry glaring vision, lens replacement).
13. Look for accurate summaries (Cajal: silver stain and drawings, separate neurons; Hodgkin and Huxley: squid giant axon and voltage clamp, sodium and potassium currents, equations; Loewi: two frog hearts, transferred fluid, chemical transmission; Broca: linking lost speech to damage in the left frontal lobe; Penfield: stimulating the cortex of awake patients to map motor and sensory areas) and a thoughtful conclusion about careful observation, controls and measurement.

UNIT 6

The Endocrine System

The endocrine system signals by broadcasting hormones in the blood: slower than nerves, but reaching every cell and lasting much longer. This unit follows four discoveries: Bayliss and Starling's secretin (1902), the first hormone; Geoffrey Harris's portal vessels and the isolation of the first hypothalamic releasing hormone (1969); David Marine's iodine trial in Akron schoolgirls (1917–1922) and Edward Kendall's crystals of thyroxine (1914); and Banting and Best's insulin (1921–1922), which turned diabetes from a death sentence into a manageable disease.

Students compare the two ways hormones act on cells, trace feedback loops step by step (thyroid, water balance, calcium and glucose), calculate half-lives, percent reabsorption, the iodine content of thyroxine and average glucose from A1C, and explain endocrine diseases as broken links in a loop. Labs use index-card receptors, a two-day water log, a cold-water stress test and glucose test strips on foods.

PREREQUISITES

- Unit 1, especially Lesson 1.3 (homeostasis and feedback loops)
- Unit 5, especially Lesson 5.5 (the autonomic nervous system)
- Chemistry: molar mass and solutions
- Biology 2.1–2.2 (carbohydrates and proteins)

MASTERY CHECKLIST

- ☐ I can compare the endocrine and nervous systems and explain how water-soluble and lipid-soluble hormones act on target cells.
- ☐ I can describe how the hypothalamus controls both lobes of the pituitary and trace the thyroid and ADH feedback loops.
- ☐ I can explain how the thyroid, parathyroids and adrenal glands work, including calcium control and the stress response.
- ☐ I can trace the insulin–glucagon feedback loop and compare type 1 and type 2 diabetes.
- ☐ I can interpret hormone lab results (high or low) by asking which link in the loop is broken.
- ☐ I can tell the stories of Bayliss and Starling, Harris, Kendall and Banting and Best.

LESSONS IN THIS UNIT

6.1 Hormones and Receptors: Bayliss and Starling's Secretin (1902)
4 sessions of 45 minutes

6.2 The Hypothalamus and Pituitary: Cushing, Harris and the Master Control
4 sessions of 45 minutes

6.3 Thyroid, Parathyroids and Adrenals: Iodine, Goiter and Kendall's Hormones
4 sessions of 45 minutes

6.4 Insulin and Diabetes: Banting and Best (1921) 4 sessions of 45 minutes

Unit 6 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **7 pts** **Lesson 6.1**

   Explain how a water-soluble hormone and a lipid-soluble hormone each change a target cell. Give one example of each.

2. **6 pts** **Lesson 6.1**

   A hormone's half-life is 8 minutes. If release stops, what percent remains after 24 minutes?

3. **7 pts** **Lesson 6.2**

   Name the two lobes of the pituitary, how the hypothalamus controls each, and two hormones released by each.

4. **9 pts** **Lesson 6.2**

   Trace the hypothalamus–pituitary–thyroid loop for a person whose T4 is too high, naming each hormone and saying whether it rises or falls.

5. **7 pts** **Lesson 6.2**

   The kidneys filter 180 L a day. On a hot day a worker makes only 0.9 L of urine. What percent of the filtrate was reabsorbed, and what was his ADH level probably doing?

6. **7 pts** **Lesson 6.3**

   List the effects of PTH that raise blood calcium, and name the hormone that opposes it and where it is made.

7. **7 pts** **Lesson 6.3**

   Compare the adrenal cortex and adrenal medulla: tissue type, hormones, and what controls each.

8. **6 pts** **Lesson 6.3**

   Thyroxine ($C_{15}H_{11}I_4NO_4$) has a molar mass of about 777 g/mol. What mass of iodine is in 1.00 mg of thyroxine? (Iodine is 126.9 g/mol.)

9. **9 pts** **Lesson 6.4**

   Trace the glucose feedback loop after a large meal, naming the sensor, the hormone, its targets and their responses, and how the loop turns off.

10. **7 pts** **Lesson 6.4**

    A patient's fasting glucose is 132 mg/dL and her A1C is 6.8%. (a) Convert the glucose to mmol/L. (b) Find her estimated average glucose from the A1C. (c) Do these meet the diagnostic criteria for diabetes?

11. **6 pts** **Lesson 6.4**

    List four signs of hypoglycemia and the first-aid "rule of 15."

DISORDERS AND SHORT ESSAY

12. **10 pts** **Lesson 6.4**

    Choose two of type 1 diabetes, type 2 diabetes, iodine-deficiency goiter, Graves' disease, and gigantism. For each, name the broken link in the hormone loop and explain how it produces the main signs.

13. **12 pts** **Lesson 6.4**

    Short essay: Bayliss and Starling cut the nerves before testing; Marine compared treated and untreated schoolgirls; Banting and Best measured each dog's blood sugar before and after the extract. What does each method have in common? Choose two and explain how their design made the conclusion convincing.

ANSWER KEY

1. Water-soluble (insulin, epinephrine, ADH): binds a receptor on the cell surface, which makes a second messenger such as cAMP inside the cell that activates existing enzymes, quickly. Lipid-soluble (cortisol, aldosterone, thyroid hormone): crosses the membrane, binds a receptor inside the cell, and the pair binds DNA to switch genes on or off, so new proteins are made, slowly but lastingly.
2. 24/8 = 3 half-lives; $(1/2)^3 = 1/8 = 12.5\%$.
3. Posterior: controlled by nerves (neurosecretory axons from the hypothalamus), releases ADH and oxytocin. Anterior: controlled by releasing and inhibiting hormones carried by the hypophyseal portal veins, releases two of GH, TSH, ACTH, prolactin, FSH, LH.
4. High T4 and T3 give strong negative feedback on the hypothalamus and pituitary → TRH falls → TSH falls → the thyroid is stimulated less and releases less T4 and T3 → levels fall toward normal, and feedback eases.
5. (180 − 0.9)/180 = 99.5%. ADH was high, because sweating concentrated his blood and the kidneys were told to return as much water as possible.
6. PTH: osteoclasts release calcium from bone; kidneys keep calcium; kidneys activate vitamin D, increasing absorption from the gut. Calcitonin opposes it, made by the C cells of the thyroid.
7. Cortex: gland tissue making steroids (aldosterone, controlled mainly by the renin–angiotensin system and potassium; cortisol, controlled by ACTH; small amounts of androgens). Medulla: modified sympathetic nervous tissue releasing epinephrine and norepinephrine, controlled by sympathetic nerves.
8. Iodine fraction = 4 × 126.9 / 777 ≈ 0.653; 1.00 mg × 0.653 ≈ 0.653 mg of iodine.
9. Glucose rises → beta cells in the islets sense it → release insulin → muscle and fat cells take up glucose; liver and muscle store glycogen; fat cells store fat; liver stops releasing glucose → blood glucose falls toward normal → beta cells sense the fall and release less insulin (negative feedback).
10. (a) 132/18 ≈ 7.3 mmol/L. (b) 28.7 × 6.8 − 46.7 ≈ 148.5 mg/dL. (c) Yes: fasting glucose ≥ 126 mg/dL and A1C ≥ 6.5% (a doctor confirms with repeat testing).
11. Shakiness, sweating, fast heartbeat, hunger, confusion or irritability. Give about 15 g of fast sugar (juice, regular soda, glucose tablets) if the person can swallow, recheck in 15 minutes, repeat if still low; call emergency help if the person cannot swallow or does not improve.

12. Look for: type 1 (beta cells destroyed, no insulin, high glucose, thirst, weight loss, ketoacidosis); type 2 (insulin resistance plus tiring beta cells, slowly rising glucose); goiter (no iodine, low T4, weak feedback, high TSH, gland enlarges); Graves' (antibodies stimulate TSH receptors, high T4, low TSH, fast heart, weight loss); gigantism (GH tumor ignores feedback, long bones grow while plates are open).
13. Look for: each removed or controlled other explanations (nerves cut; an untreated comparison group; each animal as its own before-and-after comparison), measured a clear outcome, and repeated the result; a thoughtful conclusion about controls, honest measurement and why their discoveries were trusted.

6.1 Hormones and Receptors: Bayliss and Starling's Secretin (1902)

Mark up this lesson

OBJECTIVES

- Compare the endocrine and nervous systems as ways the body sends signals.
- Classify hormones as water-soluble (peptides, proteins, most amines) or lipid-soluble (steroids, thyroid hormones) and explain how each acts on its target cells.
- Explain what controls hormone release, why only target cells respond, and how half-life and feedback set a hormone's level.

> **Warm-up.** A message can be sent by phone call to one person or by a notice in the town newspaper that everyone receives but only some act on. List two advantages of each. Which is more like a nerve, and which is more like a hormone?

WATCH

Endocrine System, Part 1 - Glands & Hormones: Crash Course Anatomy & Physiology #23

CrashCourse · 10:25

https://www.youtube.com/watch?v=eWHH9je2zG4

> **WHEN TO WATCH**
> After the two kinds of hormones. Watch for how each kind reaches its receptor.

BACKUP VIDEO

Endocrine System

Amoeba Sisters · 9:23

https://www.youtube.com/watch?v=emvHaBiRY8Q

Before the lesson, as a tour of the major glands.

KEY TERMS

hormone

A chemical messenger made by an endocrine gland or cell, carried by the blood, that changes the activity of target cells elsewhere.

endocrine and exocrine glands

Endocrine glands release hormones into the blood; exocrine glands release secretions through ducts (sweat, saliva, digestive enzymes).

target cell

A cell with receptors for a particular hormone; only target cells respond.

water-soluble hormone

A peptide, protein or most amine hormones (insulin, ADH, epinephrine); binds a receptor on the cell surface and works through a second messenger.

lipid-soluble hormone

A steroid (cortisol, aldosterone) or thyroid hormone; crosses the membrane, binds a receptor inside the cell and changes which genes are read.

second messenger

A molecule inside the cell, such as cyclic AMP, that carries the hormone's signal from a surface receptor and amplifies it.

half-life

The time for the amount of a hormone in the blood to fall by half; minutes for insulin, about a week for thyroxine.

CORE IDEAS

The story. In January 1902, in a laboratory at University College London, the physiologists William Bayliss and Ernest Starling asked a simple question: when acid food leaves the stomach and enters the small intestine, how does the pancreas know to pour out its digestive juice? The leading view, from Ivan Pavlov's famous work, was that nerves carried the message. Bayliss and Starling cut every nerve to a loop of a dog's intestine, leaving only its blood vessels, and put weak acid in the loop. The pancreas still secreted. In 1905 Starling gave such chemical messengers a name: *hormones*, from a Greek word meaning "to set in motion."

How they figured it out. With the nerves cut, the message had to travel by blood. To prove it, they scraped the lining of the intestine, ground it with acid, filtered it and

injected the extract into a vein. Within a minute or two the pancreas began to secrete. Extracts from other tissues did nothing. They named the substance *secretin*. The experiment shows the logic of a good test: remove the pathway you suspect (the nerves), see if the effect survives, then supply the other pathway (the blood) by itself and see if it causes the effect.

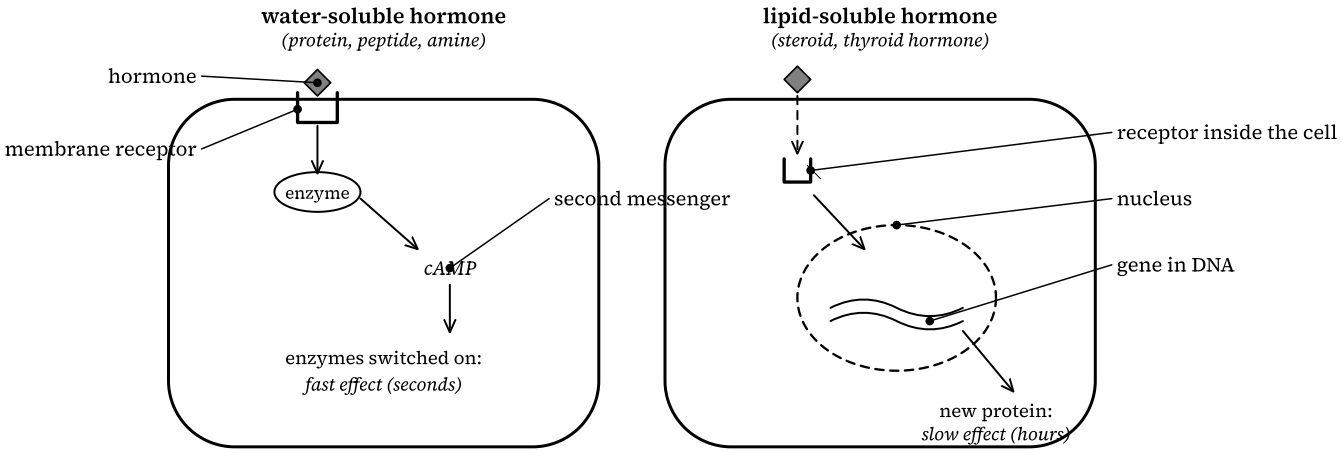
Two signaling systems. The nervous system sends fast, precise signals along wires to particular cells; its effects begin in milliseconds and end quickly. The **endocrine system** broadcasts hormones into the blood, which reaches every cell; its effects begin in seconds to hours and can last days. The major endocrine glands are the hypothalamus and pituitary (Lesson 6.2), the pineal gland, the thyroid and parathyroids, the thymus, the adrenal glands (6.3), the pancreatic islets (6.4) and the gonads; the heart, kidneys, stomach, intestines and fat tissue also release hormones. Only **target cells** with the right receptor respond, so one hormone in the blood can reach every cell but change only a few kinds. Cells can add receptors when a hormone is scarce (up-regulation) or remove them when it is plentiful (down-regulation).

Two kinds of hormones, two ways of acting. Water-soluble hormones, the peptides and proteins (insulin, ADH, growth hormone) and the amine epinephrine, dissolve in plasma but cannot cross the fatty cell membrane. They bind receptors on the cell surface, which switch on an enzyme that makes a **second messenger** such as cyclic AMP inside the cell; that activates enzymes already present. Because each step multiplies the signal, a few hormone molecules can change thousands of enzyme molecules within seconds. **Lipid-soluble hormones**, the steroids made from cholesterol (cortisol, aldosterone and the sex hormones) and the thyroid hormones, travel in the blood mostly bound to carrier proteins. They slip through the membrane and bind receptors inside the cell; the hormone–receptor pair attaches to DNA and switches genes on or off, so the cell makes new proteins. Their effects are slower, taking hours, but last longer.

What controls release. A gland releases its hormone in response to one of three signals. A *humoral* stimulus is a change in the blood itself: high blood glucose triggers insulin; low blood calcium triggers parathyroid hormone. A *neural* stimulus is a nerve signal: sympathetic nerves make the adrenal medulla release epinephrine. A *hormonal* stimulus is another hormone: TSH from the pituitary makes the thyroid release its hormones. Most of these systems are controlled by **negative feedback**

(Lesson 1.3): the hormone's effect removes the stimulus, so release slows. A hormone's level also depends on how fast it is removed by the liver and kidneys, measured by its **half-life**: insulin's is only about 5 minutes, so its level can change quickly, while thyroxine's is about a week.

When it goes wrong. A hormone can fail at any point: too much made, too little made, or a target that cannot respond. In **nephrogenic diabetes insipidus**, the brain makes plenty of antidiuretic hormone (ADH), but the receptors on the kidney's collecting-duct cells do not respond to it. The kidneys cannot pull water back into the blood, so the person makes large amounts of dilute urine and is always thirsty. Giving more ADH does not help, because the problem is the receptor, not the hormone. Comparing this with central diabetes insipidus (Lesson 6.2), where too little ADH is made and giving ADH does help, shows why doctors must find which link in the chain is broken.



Water-soluble hormones knock at the door (surface receptors and second messengers); lipid-soluble hormones walk in and change which genes are read.

LAB

Lock-and-Key Hormone Model and a Signal Race

You will model why only target cells respond to a hormone, and compare the speed and reach of nerve and hormone signals.

You will need

- Index cards, scissors, markers, tape
- A bowl of water, food coloring, a dropper, a stopwatch, a partner

Steps

1. Cut ten index-card “cells.” Cut a notch shaped like a triangle, square or circle into the edge of each (the receptors). Make three “hormones” of matching shapes. Scatter the cells on a table, “broadcast” one hormone by passing it over every cell, and count which cells it fits. Record the targets for each hormone.
2. Make two cells with two different receptor shapes. Explain how one cell can respond to two hormones.
3. Signal race: in a still bowl of water, put one drop of food coloring at one side and time how long it takes for color to reach the far side (diffusion and mixing, like a hormone spreading). Compare with the 0.01 seconds an impulse needs to travel the same distance along a nerve at 100 m/s.
4. Write a half-life table: start with 1,000 hormone molecules and halve the number every 5 minutes for 30 minutes. Graph it.

Check your work

- ☐ Why does a hormone in the blood not affect every cell?
- ☐ Which signal was faster, and which reached more of the bowl? Which would you choose to start a sprint, and which to grow taller?
- ☐ How long until fewer than 20 of the 1,000 molecules remained?

LAB NOTEBOOK

1. The two hormone mechanisms drawn and labeled side by side.
2. A table comparing the nervous and endocrine systems (speed, reach, duration, messenger, pathway).

KEY FORMULAS

$$\text{fraction left} = \left(\tfrac{1}{2}\right)^{t/t_{1/2}}$$

From history. Starling is also remembered for "Starling's law of the heart" (a heart that is filled more pumps more strongly) and for his work on how fluid moves between capillaries and tissues. Bayliss and Starling were brothers-in-law: Bayliss married Starling's sister Gertrude. Secretin was the first hormone to be discovered; insulin, discovered nineteen years later, is the subject of Lesson 6.4.

Practice habit. For every hormone you learn, fill in the same five boxes: gland, stimulus for release, target, effect, and what turns it off.

WORKED EXAMPLES

Example 1. A hormone has a half-life of 10 minutes. If its release stops, what fraction remains in the blood after 30 minutes?

Show solution

1. 30 minutes is $30/10 = 3$ half-lives.
2. $(1/2)^3 = 1/8$

Answer: 1/8 (12.5%) remains

Example 2. Model amplification: one epinephrine molecule activates a receptor that switches on 10 enzyme molecules; each makes 100 cyclic AMP molecules; each cAMP (through further steps) leads to 1,000 glucose molecules released by a liver cell. How many glucose molecules does one hormone molecule release?

Show solution

1. $1 \times 10 \times 100 \times 1000 = 10^6$

Answer: About a million: a model of why tiny hormone concentrations have big effects (real numbers vary)

Example 3. Trace a simple humoral feedback loop: what happens, step by step, when you eat a salty meal and the sodium concentration of your blood rises?

Show solution

1. Sensor: osmoreceptors in the hypothalamus detect the more concentrated blood.
2. Control center: the hypothalamus makes you thirsty and the posterior pituitary releases more ADH.
3. Effectors: you drink; the kidneys reabsorb more water and make less, more concentrated urine.
4. Result: the blood is diluted back toward normal, the stimulus fades, and ADH release falls (negative feedback).

Answer: Stimulus → sensor → control center → effector → response that removes the stimulus

PRACTICE

CONCEPT CHECKS

1. Easy What is the difference between an endocrine gland and an exocrine gland? Give an example of each.

   Show answer

   Endocrine glands release hormones into the blood (thyroid, adrenal glands); exocrine glands release secretions through ducts (sweat glands, salivary glands).

2. Easy Name three ways the endocrine system differs from the nervous system.

   Show answer

   Hormones travel in the blood (not along nerves), reach the whole body (not specific cells), act more slowly (seconds to hours) and last longer.

3. Medium Why can cortisol enter a cell but insulin cannot?

   Show answer

   Cortisol is a steroid, lipid-soluble, so it passes through the fatty membrane. Insulin is a protein, water-soluble and large, so it binds a receptor on the surface.

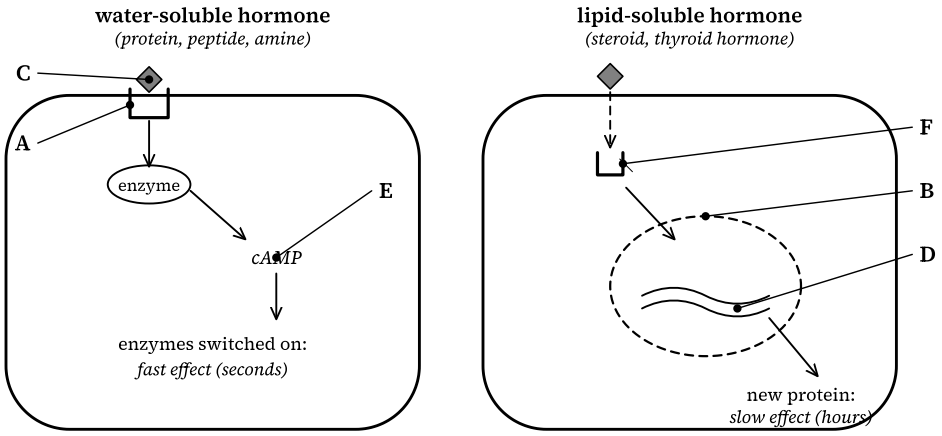
4. **Medium** Classify each stimulus for hormone release as humoral, neural or hormonal: (a) TSH makes the thyroid release T4; (b) high blood glucose triggers insulin; (c) sympathetic nerves make the adrenal medulla release epinephrine.

Show answer

(a) hormonal, (b) humoral, (c) neural.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram of hormone action: name each item marked A to F.



Show answer

A, membrane receptor; B, nucleus; C, hormone; D, gene in DNA; E, second messenger (cyclic AMP); F, receptor inside the cell.

6. **Medium** Insulin's half-life is about 5 minutes. If the pancreas stopped releasing it, what fraction would remain after 20 minutes?

Show answer

20/5 = 4 half-lives; $(1/2)^4 = 1/16$, about 6%.

7. **Hard** Thyroxine's half-life is about 7 days. A person stops taking a thyroxine pill. About what fraction of the pill's thyroxine would remain after 4 weeks? Why do doctors wait several weeks before rechecking a dose change?

Show answer

28/7 = 4 half-lives, $(1/2)^4 = 1/16$ remains. Because thyroxine changes so slowly, it takes several weeks for the level to settle at its new steady value.

DISORDER AS A BROKEN MECHANISM

8. Medium A child makes large amounts of dilute urine and is always thirsty. Her blood ADH is high, and an ADH injection does not help. Which link in the hormone chain is broken, and why does the injection fail?

Show answer

The kidney's target cells: their ADH receptors (or the steps right after them) do not respond, so water is not reabsorbed (nephrogenic diabetes insipidus). The hormone is already present, so giving more cannot fix a broken receptor.

PREDICT THE EFFECT

9. Hard Predict the effect: a cell is exposed to a very high level of a hormone for weeks. What might happen to its receptors, and how would that change its response?

Show answer

It may down-regulate, removing receptors from its surface, so it responds less to the same hormone level (one part of how insulin resistance develops).

10. Challenge Bayliss and Starling cut the nerves to the intestine before testing. Then they injected an extract into the blood. Explain why both steps were needed to show that the message was chemical.

Show answer

Cutting the nerves ruled out a nervous signal: if the pancreas still responded, something else carried the message. Injecting the extract into a vein showed that a substance from the intestinal lining, carried by blood alone, was enough to cause the response. Together they showed the messenger was a chemical in the blood.

COMMON MISTAKES

- Thinking a hormone affects every cell it reaches; only cells with its receptor respond.
- Saying all hormones enter the cell; water-soluble hormones act at the surface.
- Confusing endocrine (into blood) and exocrine (through ducts) glands; the pancreas is both.
- Assuming more hormone always means more effect; receptors can be lost or broken.

Make it a game · Lock and Key Relay. Make cards for ten hormones and ten target organs. Lay the organ cards face up across the room. The student draws a hormone card, runs it to the correct target and says whether the hormone is water-soluble or lipid-soluble. A wrong target or class means back to the start. Time the whole deck, then try to beat it.

Scripture. “To every thing there is a season, and a time to every purpose under the heaven:” (Ecclesiastes 3:1, KJV)

Hormones work by timing: released at the right moment, acting for the right length of time, then cleared away. The body keeps seasons too.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

6.2 The Hypothalamus and Pituitary: Cushing, Harris and the Master Control

Mark up this lesson

OBJECTIVES

- Describe how the hypothalamus controls the posterior pituitary (by nerves) and the anterior pituitary (by releasing hormones through portal veins).
- Name the pituitary hormones and their targets, and trace the hypothalamus–pituitary–thyroid feedback loop.
- Explain how ADH controls water balance, and explain gigantism and diabetes insipidus as broken mechanisms.

> **Warm-up.** Drink nothing for an hour, then note the color of your urine. Drink two full glasses of water and check again an hour later. What changed? Which organ decided, and what told it?

WATCH

Endocrine System, Part 2 - Hormone Cascades: Crash Course Anatomy & Physiology #24

CrashCourse · 9:34

https://www.youtube.com/watch?v=SCV_m91mN-Q

> **WHEN TO WATCH**
> After the portal veins. Watch for the hypothalamus–pituitary–thyroid cascade and feedback.

BACKUP VIDEO

2-Minute Neuroscience: Hypothalamus & Pituitary Gland

Neuroscientifically Challenged · 2:01

https://www.youtube.com/watch?v=TVhm2rBGhB0

A two-minute review after the anatomy.

KEY TERMS

hypothalamus

The brain region that links the nervous and endocrine systems; it senses the blood and controls the pituitary.

anterior pituitary

The front lobe, made of gland tissue; it makes GH, TSH, ACTH, prolactin, FSH and LH when signaled by hypothalamic releasing hormones.

tropic hormone

A hormone whose target is another endocrine gland, such as TSH (thyroid) and ACTH (adrenal cortex).

growth hormone (GH)

An anterior pituitary hormone that promotes growth of bone and muscle, largely through IGF-1 made by the liver, and raises blood glucose.

posterior pituitary

The back lobe, made of nerve tissue; it releases ADH and oxytocin made by hypothalamic neurons.

hypophyseal portal system

Blood vessels that carry releasing hormones directly from the hypothalamus to the anterior pituitary.

antidiuretic hormone (ADH)

Also called vasopressin; makes the kidneys return more water to the blood, so less urine is made.

CORE IDEAS

The story. The pituitary, a gland the size of a pea hanging under the brain, was long thought to drain mucus into the nose. The American neurosurgeon Harvey Cushing operated on hundreds of pituitary tumors in the early 1900s and showed how too much or too little of its hormones changes the whole body; in 1932 he described the disease of excess adrenal stimulation that bears his name. But what controlled the pituitary? In the late 1940s and 1950s the English physiologist Geoffrey Harris proposed that the hypothalamus sends chemical signals down a small set of blood vessels to the pituitary. In 1969 the teams of Roger Guillemin and Andrew Schally, working separately, finally isolated the first of these signals, thyrotropin-releasing hormone (TRH), and shared the 1977 Nobel Prize.

How they figured it out. Harris noticed that the anterior pituitary has almost no nerves from the brain, yet the brain clearly controls it. He showed that blood in the portal vessels of the stalk flows downward, from the hypothalamus to the pituitary. When he cut the stalk and let it heal with the vessels blocked, the pituitary failed; when the vessels regrew, it recovered. When he transplanted a pituitary to a distant place in the body, it stopped working normally; placed back under the hypothalamus, it recovered. The releasing hormones themselves were so scarce that Guillemin's and Schally's teams processed hundreds of thousands of hypothalami from sheep and pigs, collected from meatpacking plants, to purify about a milligram of TRH.

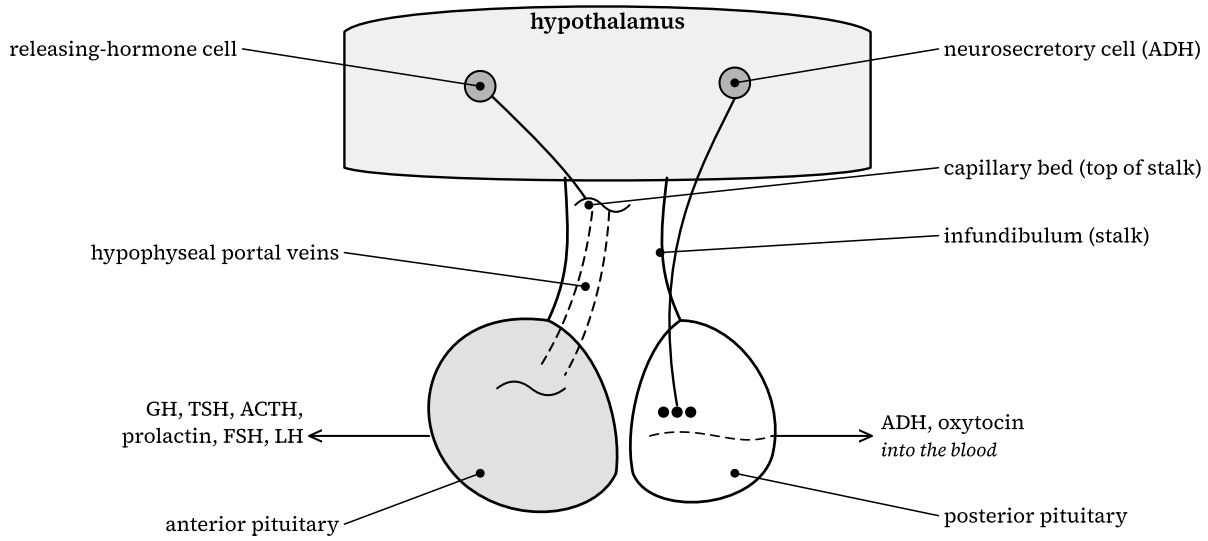
Two lobes, two control systems. The **posterior pituitary** is really an extension of the brain. Neurosecretory cells in the hypothalamus make **antidiuretic hormone (ADH)** and **oxytocin**, send them down their axons through the stalk (infundibulum), and release them into the blood when the neurons fire. The **anterior pituitary** is true gland tissue. Other hypothalamic neurons release *releasing* and *inhibiting* hormones into capillaries at the top of the stalk; the **hypophyseal portal veins** carry them straight down to a second capillary bed in the anterior pituitary, so these hormones reach their target at high concentration without being diluted in the whole bloodstream.

The anterior pituitary's hormones. Six main hormones, four of them *tropic* (they act on other glands): **TSH** (thyroid-stimulating hormone) tells the thyroid to make T4 and T3; **ACTH** (adrenocorticotropic hormone) tells the adrenal cortex to make cortisol; **FSH** and **LH** regulate the gonads. **Growth hormone (GH)** makes the liver release IGF-1, which drives the growth of bone and muscle; GH also raises blood glucose and helps burn fat, and it is released mostly in deep sleep. **Prolactin** stimulates milk production. Each is controlled by its own hypothalamic hormone: TRH raises TSH, CRH raises ACTH, GHRH raises GH while somatostatin lowers it, and dopamine holds prolactin down.

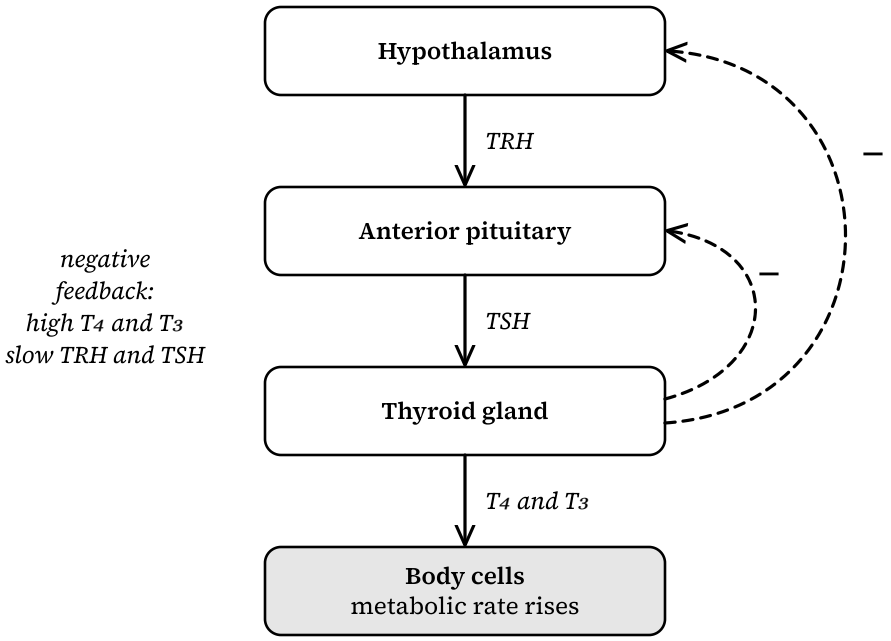
Feedback loops traced. In the **hypothalamus–pituitary–thyroid axis**, the hypothalamus releases TRH, which makes the anterior pituitary release TSH, which makes the thyroid release T4 and T3, which raise the metabolic rate of body cells. When T4 and T3 rise, they act back on both the pituitary and the hypothalamus to cut TRH and TSH: **negative feedback**, like a thermostat. In water balance, osmoreceptors in the hypothalamus sense when the blood becomes too

concentrated (after sweating or salty food); the posterior pituitary releases more ADH; the kidneys insert water channels in their collecting ducts and return more water to the blood; urine becomes small in volume and dark. When the blood is diluted again, ADH falls and urine becomes plentiful and pale. The kidneys filter about 180 liters of fluid a day and return all but 1 to 2 liters to the blood.

When it goes wrong. A benign tumor of the GH-making cells releases growth hormone without regard to feedback. If it begins in childhood, before the growth plates close, the long bones keep growing: **gigantism**. Robert Wadlow of Alton, Illinois, reached 8 feet 11.1 inches (272 cm) before his death in 1940 at age 22, the tallest person reliably measured. If the excess begins in adulthood, after the plates have closed, bones cannot lengthen, but the hands, feet, jaw and brow thicken: **acromegaly**. In **central diabetes insipidus**, damage to the hypothalamus or posterior pituitary leaves too little ADH, and the person makes large volumes of dilute urine; here, unlike the kidney form in Lesson 6.1, a synthetic ADH medicine works. Surgeons now reach the pituitary through the nose, the route Cushing pioneered.



Nerves control the posterior pituitary; portal blood vessels carry releasing hormones to the anterior pituitary.



A three-step hormone cascade with negative feedback from the final hormone to both control centers.

> **Safety first.** Never drink large amounts of water quickly: more than about a liter in an hour can upset the body's salt balance. Keep any extra drink to one ordinary glass, skip the experiment if a doctor has limited your fluids or you have a kidney or heart condition, and stop if you feel unwell.

LAB

Water-Balance Log: Watching ADH Work

You will record your fluid intake and urine for two days and use the results to see ADH's feedback loop in action.

You will need

- A measuring cup, a notebook, a urine color chart (or the scale in the steps)
- A kitchen scale (optional), a thermometer for outdoor temperature

Steps

1. For two days, record every drink (time and volume) and every trip to the bathroom (time, and color on a 1–8 scale from pale straw to dark amber). Note exercise and outdoor temperature.
2. On the second day, do 20 minutes of exercise that makes you sweat (with water available) and note any changes afterward.
3. Weigh yourself before and after the exercise if you have a scale; each kilogram lost is about a liter of sweat.
4. Graph urine color against time for both days, and mark when you drank, ate salty food and exercised.

Check your work

- ☐ When was your urine darkest? What was your ADH level probably doing then, and why?
- ☐ Trace the feedback loop for one change you saw: stimulus, sensor, control center, hormone, effector, response.
- ☐ Why is pale but not colorless urine a reasonable goal?

LAB NOTEBOOK

1. The hypothalamus and pituitary drawn and labeled, with the hormones of each lobe listed beside it.
2. The HPT axis and the ADH loop drawn as feedback diagrams, plus your water-log graph.

From history. Cushing kept detailed drawings and photographs of his patients and a brain-tumor registry of more than two thousand cases. He also won the Pulitzer Prize in 1926 for his biography of his teacher, the physician William Osler. Guillemin and Schally were fierce rivals racing to purify the same molecules; they shared the 1977 Nobel Prize with Rosalyn Yalow, whose radioimmunoassay made it possible to measure tiny amounts of hormones in blood.

Practice habit. Draw every hormone system as a loop, never as a straight line: write the stimulus at the top, the hormone in the middle and the feedback arrow back to the start.

WORKED EXAMPLES

Example 1. Trace the HPT feedback loop for a person whose thyroid hormone level has fallen below normal. Say what each gland does next, and why the level returns to normal.

Show solution

1. Low T4 and T3 means less negative feedback on the hypothalamus and pituitary.
2. The hypothalamus releases more TRH; the anterior pituitary releases more TSH.
3. TSH stimulates the thyroid to make and release more T4 and T3.
4. As T4 and T3 rise back to normal, they feed back to cut TRH and TSH, and release settles.

Answer: Low T4 → more TRH → more TSH → more T4 → feedback cuts TRH and TSH: the loop corrects itself

Example 2. The kidneys filter 180 L of fluid a day. With normal ADH, about 1.5 L of urine is made. What percent of the filtered fluid is returned to the blood? With no ADH at all, urine might reach 12 L a day. What percent is returned then?

Show solution

1. Normal: $(180 - 1.5)/180 = 0.9917$
2. No ADH: $(180 - 12)/180 = 0.9333$

Answer: About 99.2% normally and 93.3% without ADH. A small change in percent makes an eightfold change in urine.

Example 3. A pituitary tumor makes extra GH. Predict the result in (a) a 10-year-old and (b) a 40-year-old.

Show solution

1. (a) The growth plates are still open cartilage, so long bones keep lengthening.
2. (b) The plates have turned to bone, so bones can only thicken; soft tissues and bones of the hands, feet, jaw and brow enlarge.

Answer: (a) gigantism, unusual height; (b) acromegaly, thickened hands, feet and facial bones

PRACTICE

CONCEPT CHECKS

1. Easy Which two hormones are released by the posterior pituitary, and where are they made?

   Show answer

   ADH and oxytocin; they are made by neurons in the hypothalamus.

2. Easy What is a tropic hormone? Name two from the anterior pituitary.

   Show answer

   A hormone whose target is another endocrine gland: TSH (thyroid), ACTH (adrenal cortex), FSH and LH (gonads).

3. **Medium** Why does the anterior pituitary need a portal system of blood vessels rather than nerves from the hypothalamus?

Show answer

It is gland tissue, not nerve tissue; the hypothalamus controls it with releasing hormones, and the portal veins carry them straight to it in high concentration without diluting them in the whole circulation.

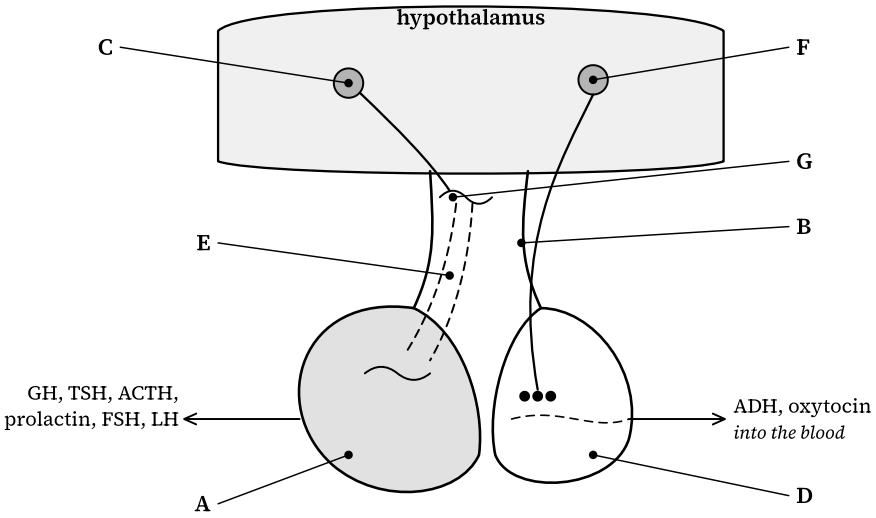
4. **Medium** What does ADH do in the kidney, and what happens to urine when ADH is high?

Show answer

It makes the collecting ducts insert water channels and return more water to the blood; urine becomes small in volume and concentrated (dark).

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram: name each structure marked A to G.



Show answer

A, anterior pituitary; B, infundibulum (stalk); C, releasing-hormone cell in the hypothalamus; D, posterior pituitary; E, hypophyseal portal veins; F, neurosecretory cell making ADH; G, capillary bed at the top of the stalk.

6. **Medium** If the kidneys filter 180 L a day and make 1.8 L of urine, what percent of the filtrate is reabsorbed?

Show answer

(180 − 1.8)/180 = 99%.

7. Hard A blood test shows high TSH and low T4. Is the problem more likely in the pituitary or in the thyroid? Explain with the feedback loop.

Show answer

In the thyroid. Low T4 removes the negative feedback, so a healthy pituitary releases more TSH; the thyroid is not responding. If the pituitary were the problem, TSH would be low too.

DISORDER AS A BROKEN MECHANISM

8. Medium Explain why a GH-secreting pituitary tumor causes gigantism in a child but acromegaly in an adult.

Show answer

The tumor releases GH without regard to feedback. In a child the growth plates are still cartilage, so extra GH (through IGF-1) makes the long bones keep lengthening. In an adult the plates have turned to bone, so the bones can only thicken, and the hands, feet, jaw and brow enlarge instead.

PREDICT THE EFFECT

9. Hard Predict the effect: alcohol suppresses ADH release. What happens to urine output and the body's water after drinking alcohol, and why?

Show answer

With less ADH, the kidneys return less water to the blood, so more dilute urine is made and the body loses water, causing dehydration and thirst later.

10. Challenge A person takes high doses of thyroid hormone pills for months. Predict the levels of TRH and TSH and the size and activity of their own thyroid gland. Explain.

Show answer

The extra hormone gives strong negative feedback, so TRH and TSH fall very low. With little TSH, the person's own thyroid is barely stimulated, so it makes little hormone and may shrink.

COMMON MISTAKES

- Saying the posterior pituitary makes ADH; it stores and releases ADH made in the hypothalamus.
- Calling the pituitary the "master gland" without noting that the hypothalamus controls it.

- Forgetting that the final hormone in a cascade feeds back on both the hypothalamus and the pituitary.
- Thinking high ADH means more urine; ADH is antidiuretic, so it means less urine.

Make it a game · Cascade Chain. Three players stand in a line as hypothalamus, pituitary and target gland, each with a card for its hormone (TRH, TSH, T4; or CRH, ACTH, cortisol). The parent calls “level low” or “level high.” Players must pass (or hold back) their cards down the line correctly, and the target gland must say what its hormone does to the body. Rotate roles and add the ADH loop.

Scripture. “Let all things be done decently and in order.” (1 Corinthians 14:40, KJV)

The hypothalamus and pituitary keep order in the body: each signal in its turn, each gland checked by feedback.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

6.3 Thyroid, Parathyroids and Adrenals: Iodine, Goiter and Kendall's Hormones

Mark up this lesson

OBJECTIVES

- Describe how the thyroid makes T4 and T3 from iodine and what they do, and explain goiter as a broken feedback loop.
- Trace the control of blood calcium by parathyroid hormone and calcitonin.
- Describe the adrenal cortex (aldosterone, cortisol) and adrenal medulla (epinephrine), and compare the short-term and long-term stress responses.

> **Warm-up.** Look at a container of table salt in your kitchen. Does it say "iodized"? Look for the words "This salt supplies iodide, a necessary nutrient." Why would anyone add iodine to salt?

WATCH

GCSE Biology - Endocrine System & Hormones

Cognito · 5:04

https://www.youtube.com/watch?v=BvpPCn1rwsw

> **WHEN TO WATCH**
> After the thyroid section. Watch for thyroxine's negative feedback and adrenaline.

BACKUP VIDEO

Adrenaline - GCSE Biology

Launchpad Learning · 2:17

https://www.youtube.com/watch?v=MvCxSQCwQfo

With the adrenal medulla.

KEY TERMS

thyroid hormones (T4 and T3)

Thyroxine (four iodine atoms) and triiodothyronine (three), which raise the metabolic rate and are needed for growth and brain development.

goiter

An enlarged thyroid gland, most often from too little iodine in the diet.

parathyroid hormone (PTH)

Hormone of the four small parathyroid glands that raises blood calcium by acting on bone, kidneys and (through vitamin D) the intestine.

calcitonin

Hormone from the thyroid's C cells that lowers blood calcium by slowing the cells that break down bone.

aldosterone

A hormone of the adrenal cortex that makes the kidneys keep sodium (and water) and excrete potassium.

cortisol

The adrenal cortex's main stress hormone: raises blood glucose, breaks down protein, reduces inflammation, and follows a daily rhythm.

epinephrine

Adrenaline, the adrenal medulla's hormone, which reinforces the sympathetic "fight or flight" response.

CORE IDEAS

The story. A century ago, in the region around the Great Lakes and in mountain valleys around the world, swollen necks from goiter were common, and some children grew up stunted and slow because their mothers had lacked iodine. Between 1917 and 1922 the physician David Marine and the school official O. P. Kimball gave small doses of iodine to schoolgirls in Akron, Ohio, and compared them with girls who did not take it. Far fewer of the treated girls developed goiters. In 1924 Michigan began selling iodized salt, and the practice spread across the country. Meanwhile, on Christmas Day 1914, the chemist Edward Kendall at the Mayo Clinic had isolated crystals of the thyroid hormone thyroxine; he later helped isolate cortisone from the adrenal glands and shared the 1950 Nobel Prize with Philip Hench and Tadeus Reichstein.

How they figured it out. Marine had shown earlier that goitrous thyroids in dogs and in trout at a fish hatchery shrank when iodine was added to their food or water. The Akron study was a field trial: one group received the treatment and a comparison group did not, and both were examined over several years. Kendall worked backward from the gland: he extracted tons of animal thyroid tissue, tracked which fraction had the biological effect, and kept purifying until he had crystals. Iodine made up most of their weight, which explained why the gland needs it.

The thyroid gland. The butterfly-shaped thyroid lies in front of the trachea, below the larynx. It is made of hollow spheres called follicles filled with a protein gel (colloid). Follicle cells trap iodide from the blood and attach it to the protein, then cut off the finished hormones: **thyroxine (T4)**, with four iodine atoms, and the more active **triiodothyronine (T3)**, with three. Most T4 is converted to T3 in the tissues. Thyroid hormones are lipid-soluble and act on genes in nearly every cell: they raise the metabolic rate and heat production, speed the heart, and are essential for normal growth and brain development in children. Their release is controlled by TSH in the feedback loop of Lesson 6.2. Scattered between the follicles, **C cells** make calcitonin.

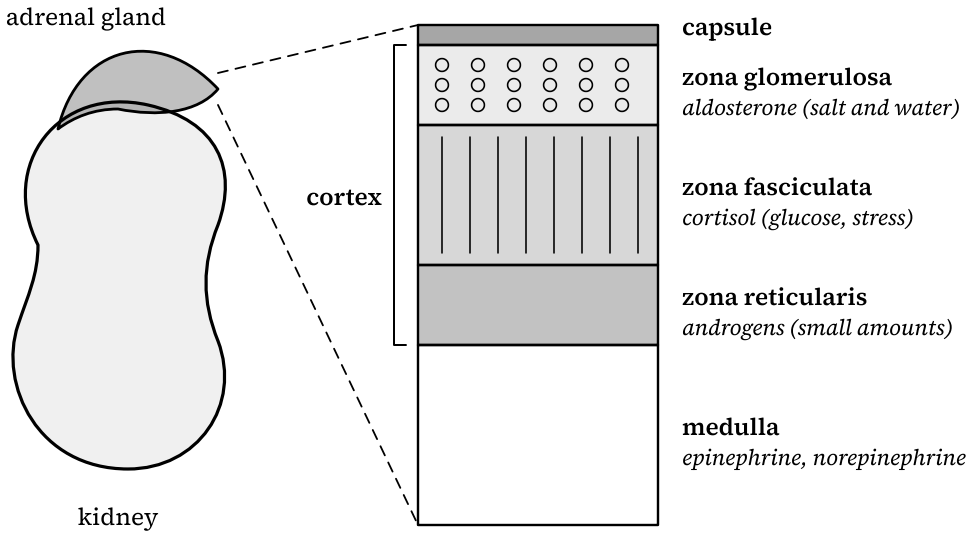
Calcium control. Blood calcium must stay in a narrow range, about 8.5 to 10.5 mg/dL in typical lab results, because nerves, muscles, the heart and blood clotting all depend on it. Four tiny **parathyroid glands** on the back of the thyroid sense calcium directly. When it falls, they release **parathyroid hormone (PTH)**, which (1) stimulates osteoclasts to release calcium from bone, (2) makes the kidneys keep calcium and excrete phosphate, and (3) makes the kidneys activate vitamin D, which increases calcium absorption from food. When calcium rises, PTH falls, and **calcitonin** from the thyroid's C cells slows osteoclasts. PTH is far more important day to day; calcitonin matters most in children's growing bones.

The adrenal glands. An adrenal gland sits on top of each kidney and is really two glands in one. The outer **adrenal cortex** makes steroid hormones in three zones: **aldosterone** (outer zone) makes the kidneys keep sodium and water and excrete potassium, helping set blood pressure; **cortisol** (middle zone, controlled by ACTH) raises blood glucose by making the liver build glucose from amino acids, damps inflammation and immune responses, and rises each morning before you wake; small amounts of androgens come from the inner zone. The inner **adrenal medulla** is modified sympathetic nervous tissue that releases **epinephrine** and some

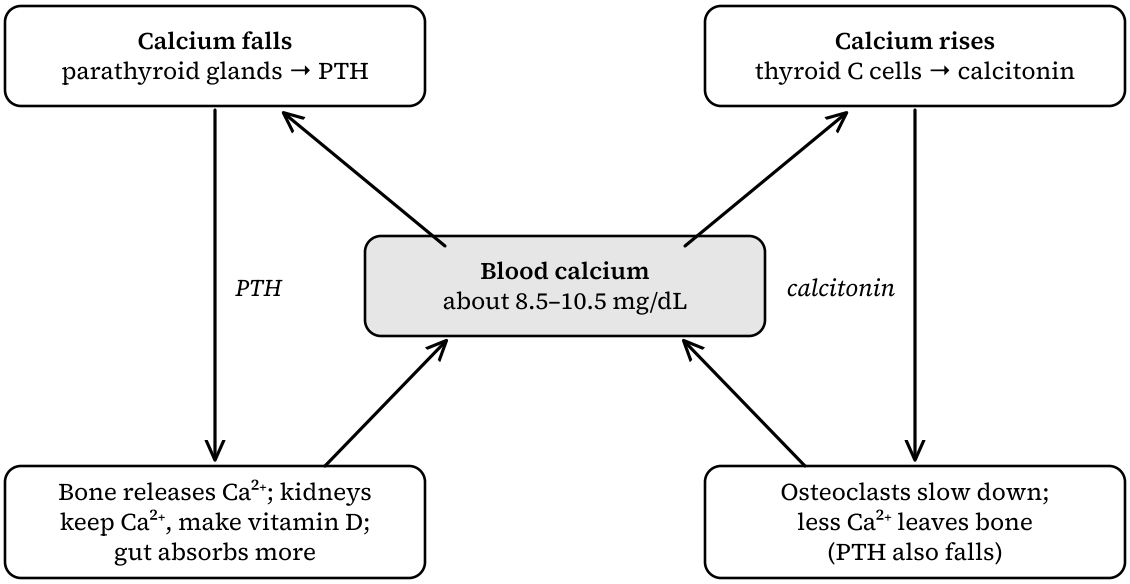
norepinephrine within seconds of a sympathetic signal. In a sudden emergency, epinephrine gives seconds-to-minutes help: faster heart, wider airways, more glucose. In stress that lasts for days or weeks, cortisol keeps fuel available but, if it stays high, it slows healing and weakens immune defenses.

When it goes wrong. In iodine deficiency, the broken link is the raw material. Without iodine the thyroid cannot make enough T4 and T3. Low thyroid hormone gives weak negative feedback, so the hypothalamus and pituitary keep raising TRH and TSH; TSH also makes thyroid cells grow, so the gland swells into a **goiter**, working harder and harder at a job it cannot finish. The person may be tired, cold and sluggish (hypothyroidism). Iodized salt fixed this for most of the world. Other thyroid diseases break different links: in **Graves' disease** antibodies imitate TSH and overdrive the gland (hyperthyroidism, with a fast heart, weight loss and heat intolerance); in Hashimoto's thyroiditis the immune system slowly destroys it. In **Addison's disease** the adrenal cortex is destroyed and too little cortisol and aldosterone are made, causing weakness, low blood pressure and salt craving.

Where it is used and try it. TSH is one of the most frequently ordered blood tests in medicine; newborns in the United States are screened for low thyroid hormone in the first days of life, because early treatment prevents lasting harm to the brain. Cortisone-like drugs treat asthma, arthritis and allergies. Epinephrine auto-injectors save people with severe allergic reactions. In the lab you will measure a short-term stress response and survey the iodine labeling in your kitchen.



The adrenal gland is two glands in one: a steroid-making cortex and a medulla that is part of the sympathetic nervous system.



Two opposing hormones hold blood calcium steady. PTH does most of the daily work.

> **Safety first.** The cold-water test is for healthy students only: skip it if you have a heart condition, high blood pressure, Raynaud's or any problem with cold. Use cool tap water with ice (not colder than an ice-water bath), keep your hand in for no more than 60 seconds, and stop at once if it hurts badly. Do not taste anything in the kitchen survey.

LAB

A Short-Term Stress Response and an Iodine Survey

You will measure how fast the sympathetic system and adrenal medulla respond to a mild stress, and survey where iodine enters your family's diet.

You will need

- A bowl of ice water, a towel, a stopwatch, a partner
- A home blood-pressure cuff (optional), a notebook
- Salt containers and food labels from your kitchen

Steps

1. Sit quietly for 5 minutes. Your partner measures your pulse (and blood pressure, if you have a cuff) twice and averages.
2. Put one hand in the ice water up to the wrist for 60 seconds (or less if it becomes very uncomfortable). Your partner measures your pulse during the last 15 seconds.
3. Take the hand out, dry it, and measure the pulse every minute for 5 minutes. Graph pulse against time.
4. Iodine survey: list every salt and food container in the kitchen that mentions iodine or iodide (table salt, sea salt, seasoned salt, dairy, seafood, eggs, bread). Note which salts are iodized and which are not.

Check your work

- ☐ How much did your pulse rise, and how quickly did it return? Which hormones and nerves were responsible?
- ☐ Why does the pulse fall back within minutes after the cold, while cortisol from long-term stress stays up much longer?
- ☐ Are all the salts in your kitchen iodized? Why might someone who uses only non-iodized salt need iodine from other foods?

LAB NOTEBOOK

1. The adrenal gland with each layer and its hormone, and the calcium feedback chart.
2. Your stress-response graph and iodine survey table.

From history. Before thyroxine was purified, patients whose thyroid glands failed were treated with dried animal thyroid; the English chemist Charles Harington worked out thyroxine's structure in 1926 and made it in the laboratory the next year. Philip Hench's first patient to receive cortisone, a woman crippled by rheumatoid arthritis, walked out of the hospital within days in 1948, one of the most dramatic moments in twentieth-century medicine. Thomas Addison of Guy's Hospital, London, described adrenal failure in 1855.

Practice habit. When a question gives a lab result (high TSH, low calcium), always ask two questions: what is the body's feedback trying to do, and which link must be broken for the result to look this way?

Career connection. Medical laboratory scientists run the blood tests that diagnose thyroid, adrenal and many other diseases: TSH, T4, calcium, cortisol and hundreds more. They usually earn a bachelor's degree in medical laboratory science and pass a national certification exam; medical laboratory technicians train in two-year programs. Their careful, accurate measurements stand behind a large share of the decisions doctors make.

WORKED EXAMPLES

Example 1. Thyroxine is $C_{15}H_{11}I_4NO_4$. Using atomic masses C 12.011, H 1.008, I 126.904, N 14.007 and O 15.999, find its molar mass and the percent of its mass that is iodine.

Show solution

1. $15(12.011) + 11(1.008) + 4(126.904) + 14.007 + 4(15.999) = 776.87$ g/mol
2. Iodine: $4(126.904) = 507.62$
3. $507.62 / 776.87 = 0.653$

Answer: 776.87 g/mol; about 65% iodine by mass, which is why a lack of iodine stops thyroid hormone production

Example 2. Trace the feedback loop in iodine deficiency and explain why the thyroid enlarges.

Show solution

1. No iodine → the thyroid cannot finish making T4 and T3 → blood levels fall.
2. Weak negative feedback → hypothalamus releases more TRH → pituitary releases more TSH.
3. TSH stimulates thyroid cells to work and to grow → more cells, more colloid, a larger gland.
4. But without iodine T4 stays low, so TSH stays high and the gland keeps growing.

Answer: A goiter: the loop keeps pressing the accelerator because the product never arrives

Example 3. Trace what happens when blood calcium falls slightly, for example after a week of eating little calcium.

Show solution

1. Sensor: the parathyroid cells detect low calcium.
2. Hormone: PTH rises.
3. Effectors: osteoclasts release calcium from bone; kidneys keep calcium and activate vitamin D; the intestine absorbs more calcium from any food eaten.
4. Result: blood calcium rises to normal and PTH falls (negative feedback).

Answer: PTH restores blood calcium, borrowing from the bones if the diet is short, which is why long-term low calcium weakens bones

PRACTICE

CONCEPT CHECKS

1. Easy What element must be in the diet for the thyroid to make its hormones, and how many atoms are in T4 and T3?

   Show answer

   Iodine; T4 has four iodine atoms and T3 has three.

2. **Easy** Name the hormone of the adrenal medulla and two of the adrenal cortex.

Show answer

Medulla: epinephrine (and norepinephrine). Cortex: cortisol and aldosterone (also small amounts of androgens).

3. **Medium** List three ways PTH raises blood calcium.

Show answer

It releases calcium from bone (via osteoclasts), makes the kidneys keep calcium, and makes the kidneys activate vitamin D, which increases calcium absorption from the intestine.

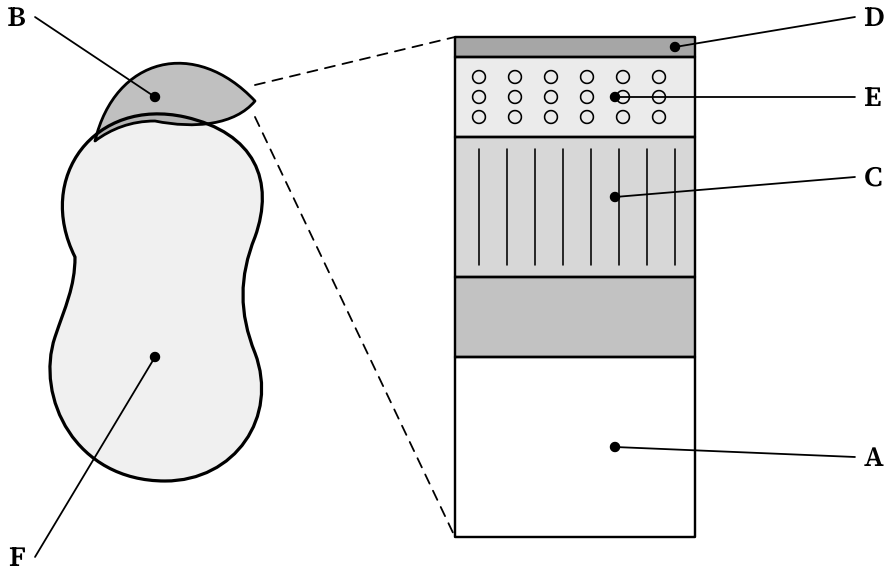
4. **Medium** Compare the short-term (epinephrine) and long-term (cortisol) stress responses: speed, main effects and what happens if each stays high for weeks.

Show answer

Epinephrine acts in seconds, raising heart rate, opening airways and releasing glucose, and fades in minutes. Cortisol acts over hours to days, keeping glucose available and damping inflammation; if it stays high for weeks it slows healing, weakens immune defenses and breaks down muscle.

DIAGRAM AND DATA QUESTIONS

5. **Medium** Label the diagram: name each structure marked A to F.



Show answer

A, adrenal medulla; B, adrenal gland; C, adrenal cortex (zona fasciculata, which makes cortisol); D, capsule; E, zona glomerulosa (makes aldosterone); F, kidney.

6. **Medium** Triiodothyronine (T3) is $C_{15}H_{12}I_3NO_4$. Find its molar mass and the percent iodine by mass (C 12.011, H 1.008, I 126.904, N 14.007, O 15.999).

Show answer

15(12.011) + 12(1.008) + 3(126.904) + 14.007 + 4(15.999) = 650.98 g/mol; iodine 380.71/650.98 ≈ 58.5%.

7. **Hard** A suppose-problem: a salt contains 45 micrograms of iodine per gram. How many grams would supply the 150 micrograms a day adults need? Why do doctors not recommend getting all of it from salt?

Show answer

150/45 ≈ 3.3 g of salt a day. Iodine also comes from dairy, eggs, seafood and bread, and too much salt raises blood pressure for many people, so salt should not be increased just for iodine.

DISORDER AS A BROKEN MECHANISM

8. Medium In Graves' disease, antibodies bind to and switch on the TSH receptors of the thyroid. Predict the levels of T4 and of TSH, and explain the patient's fast heart and weight loss.

Show answer

The antibodies stimulate the thyroid regardless of TSH, so T4 and T3 are high. The high T4 gives strong negative feedback, so the pituitary's own TSH is very low. Excess thyroid hormone raises the metabolic rate, speeding the heart and burning more fuel, so the patient loses weight and feels hot.

PREDICT THE EFFECT

9. Hard Predict the effect: during neck surgery, all four parathyroid glands are accidentally removed. What happens to blood calcium, and why might muscles twitch and cramp?

Show answer

Without PTH, blood calcium falls. Low calcium makes nerve and muscle membranes overexcitable, so they fire on their own, causing tingling, twitches and cramps (tetany); it can be dangerous and is treated with calcium and active vitamin D.

10. Challenge Doctors who give a patient cortisone-like drugs for months must stop them slowly, not suddenly. Use the feedback loop (CRH → ACTH → cortisol) to explain why.

Show answer

The drug gives strong negative feedback, so CRH and ACTH stay low for months and the person's own adrenal cortex, unstimulated, shrinks and makes little cortisol. Stopping suddenly would leave the body with almost no cortisol until the axis wakes up, which can cause dangerous weakness and low blood pressure; tapering gives the hypothalamus, pituitary and adrenals time to recover.

COMMON MISTAKES

- Saying calcitonin is the main calcium hormone; PTH does most of the daily work.
- Mixing up the adrenal cortex (steroids) and medulla (epinephrine).
- Thinking a goiter always means too much thyroid hormone; the most common cause worldwide is too little iodine, with too little hormone.

- Calling cortisol bad; it is essential for life, and harm comes from levels that stay too high or too low.

Make it a game · Which Gland Am I?. The parent gives clues one at a time ("I sit on the kidney." "My inner part is really nervous tissue." "I help you in a sudden scare."). The student guesses the gland and hormone after as few clues as possible: 3 points after one clue, 2 after two, 1 after three. Switch roles and let the student write clues for the thyroid, parathyroids and pituitary.

Scripture. "A merry heart doeth good like a medicine: but a broken spirit drieth the bones." (Proverbs 17:22, KJV)

Solomon saw that the state of the heart shows in the body. Long, unrelieved distress keeps cortisol high and wears the body down; joy and peace are good medicine.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

6.4 Insulin and Diabetes: Banting and Best (1921)

Mark up this lesson

OBJECTIVES

- Describe the endocrine pancreas (islets, beta and alpha cells) and trace the negative-feedback loop that controls blood glucose with insulin and glucagon.
- Tell how Banting, Best, Macleod and Collip discovered insulin, and why it was a turning point.
- Compare type 1 and type 2 diabetes as broken mechanisms, interpret glucose and A1C numbers, and recognize low blood sugar.

> **Warm-up.** Before a meal, estimate how many grams of carbohydrate you will eat (use labels). Your blood holds only about 4 or 5 grams of glucose in all. Where does the rest of the glucose from your meal go?

WATCH

GCSE Biology - Control of Blood Glucose Concentration

Cognito · 4:34

https://www.youtube.com/watch?v=OHrX3X3LGzI

> **WHEN TO WATCH**
> After the feedback loop. Watch for what insulin and glucagon do in the liver.

BACKUP VIDEO

Insulin - How insulin works, in 2mins!

Dr Matt & Dr Mike · 2:27

https://www.youtube.com/watch?v=Qya7rTEIfz8

With insulin's action on cells.

KEY TERMS

pancreatic islets

Small clusters of endocrine cells (islets of Langerhans), about 1 to 2% of the pancreas, scattered among the exocrine tissue that makes digestive enzymes.

glucagon

The alpha cells' hormone, released when blood glucose falls; it makes the liver break down glycogen and make new glucose.

type 2 diabetes

Cells respond poorly to insulin (insulin resistance) and the beta cells cannot keep up; about 90 to 95% of cases.

hypoglycemia

Blood glucose below about 70 mg/dL; it causes shakiness, sweating and confusion and is treated at once with fast sugar.

insulin

The beta cells' hormone, released when blood glucose rises; it helps muscle and fat cells take up glucose and makes the liver and muscles store it as glycogen.

type 1 diabetes

The immune system destroys the beta cells, so little or no insulin is made; insulin must be replaced.

hemoglobin A1C

The percent of hemoglobin with glucose attached; it reflects average blood glucose over the past two to three months.

CORE IDEAS

The story. Before 1922 a child with diabetes usually died within a year or two; the only treatment was a near-starvation diet that bought a little time. On the night of October 31, 1920, Frederick Banting, a young surgeon in London, Ontario, read an article about the pancreas and wrote a short note: tie off the pancreatic ducts of dogs, let the enzyme-making tissue waste away, and extract the islets that remain. In May 1921 the physiologist J. J. R. Macleod gave him laboratory space at the University of Toronto and a student assistant, Charles Best. That summer they kept dogs whose pancreas had been removed alive with their extract. The biochemist James Collip purified it, and on January 23, 1922, an improved extract brought the

blood sugar of 14-year-old Leonard Thompson down to near normal. He lived another thirteen years.

How they figured it out. Others had suspected the islets made a sugar-controlling substance, but their extracts were destroyed by the pancreas's own digestive enzymes. Banting's idea was to remove that problem first. The team removed the pancreas of dogs (which then developed diabetes), injected their extract, and measured blood and urine sugar before and after: a clear measure with each animal as its own comparison. When the first human trial in January 1922 gave only a small effect and a reaction at the injection site, Collip's better purification made the second trial work. In 1923 Banting and Macleod received the Nobel Prize; Banting shared his prize money with Best, and Macleod with Collip. Banting, Best and Collip sold the patent to the University of Toronto for one dollar each so insulin could be made widely and cheaply.

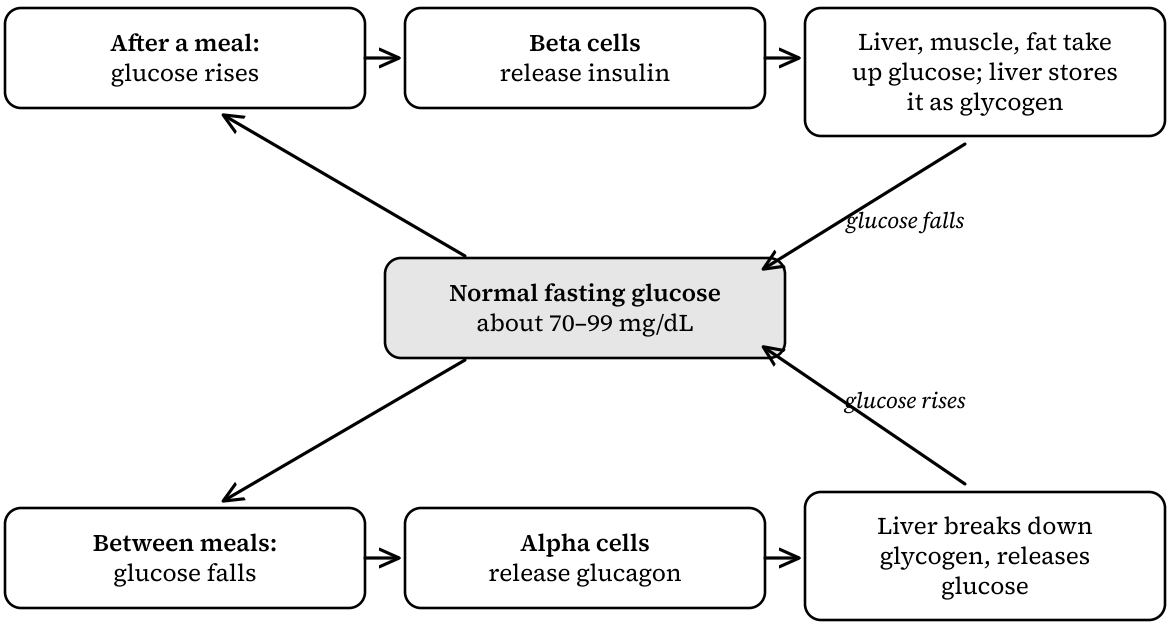
The endocrine pancreas. Most of the pancreas is exocrine tissue that sends digestive enzymes down a duct to the small intestine (Unit 9). Scattered through it are about a million tiny **pancreatic islets**, rich in capillaries. Most islet cells are **beta cells**, which make **insulin**; **alpha cells** make **glucagon**; delta cells make somatostatin, which damps both. Beta cells sense glucose directly: when more glucose enters them, they make more ATP, which sets off the release of insulin within minutes.

The glucose feedback loop, traced. Fasting blood glucose is normally about 70 to 99 mg/dL. *After a meal,* glucose from digested food enters the blood and rises. The beta cells detect it and release insulin. Insulin makes muscle and fat cells insert glucose transporters into their membranes and take up glucose; it makes the liver and muscles store glucose as *glycogen* and the fat cells store fat; and it tells the liver to stop releasing glucose. Blood glucose falls back toward normal, the stimulus fades, and insulin release slows. *Between meals* and overnight, glucose falls. The alpha cells release glucagon, which makes the liver break down glycogen and build new glucose from amino acids and other molecules; glucose rises back to normal, and glucagon falls. The brain needs glucose every minute, so this loop runs all day, a balance of two opposing hormones like those for calcium in Lesson 6.3.

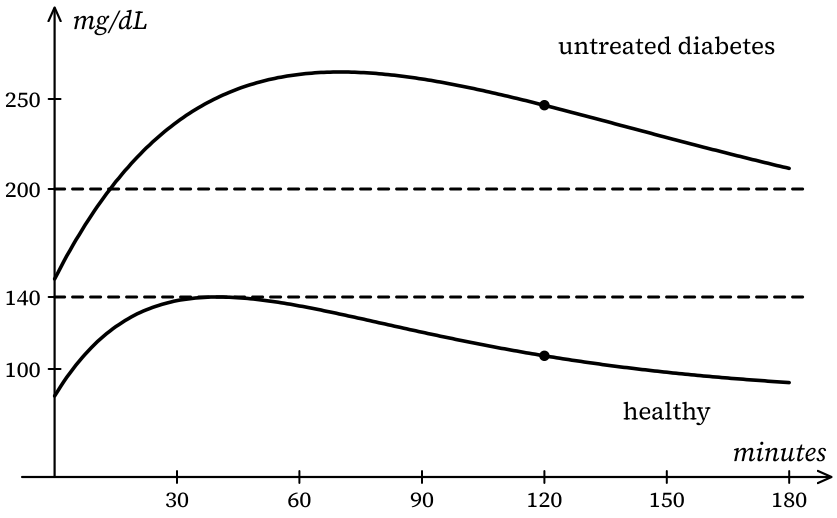
When it goes wrong. In **type 1 diabetes**, usually beginning in childhood or youth, the immune system destroys the beta cells. With no insulin, glucose cannot enter muscle and fat cells, and the liver keeps releasing more; blood glucose climbs,

glucose spills into the urine and pulls water with it (much urination and thirst), and the body, starving amid plenty, breaks down fat and muscle (weight loss). Fat breakdown makes acidic ketones, and without insulin they can build up into a life-threatening *diabetic ketoacidosis*. Insulin must be replaced by injections or a pump. In **type 2 diabetes**, usually beginning in adulthood but increasingly in teens, muscle, fat and liver cells respond poorly to insulin (*insulin resistance*), and over years the beta cells cannot make enough extra to overcome it. Its risk rises with inactivity, extra body fat and family history; regular exercise, wise eating and a healthy weight help prevent and treat it, with medicines and sometimes insulin. Both types, if poorly controlled for years, damage small blood vessels and nerves in the eyes, kidneys and feet. Doctors diagnose diabetes with a fasting glucose of 126 mg/dL or more, a two-hour glucose tolerance test of 200 or more, or an A1C of 6.5% or more.

Where it is used and try it. People with diabetes check their glucose with finger-stick meters or continuous sensors and count carbohydrates to match their insulin doses, following a plan from their doctor. Anyone can learn to recognize **hypoglycemia** (low blood sugar, below about 70 mg/dL), which can happen when too much insulin is given or a meal is missed: shakiness, sweating, a fast heartbeat, hunger, confusion. The "rule of 15" is to give about 15 grams of fast sugar (half a cup of juice or regular soda, or glucose tablets) and recheck in 15 minutes; a person who cannot swallow safely needs emergency help. In the lab you will use glucose test strips to find which foods contain free glucose.



Insulin lowers blood glucose; glucagon raises it. Each loop switches itself off as glucose returns to normal.



A glucose tolerance test (schematic). A two-hour value of 200 mg/dL or more is one of the criteria for diabetes; dots mark the two-hour readings.

> **Safety first.** Use the test strips only on food solutions in cups, never on yourself, and do not taste the samples. Wash hands after the lab. These strips are for this experiment and are not a medical test. Anyone with diabetes should follow their own doctor's plan for testing.

LAB

Which Foods Contain Glucose? A Test-Strip Lab

You will use glucose test strips (sold in pharmacies for urine testing) to find which foods contain free glucose, and discover that sweet does not always mean glucose.

You will need

- A small bottle of urine glucose test strips with a color chart (glucose oxidase type)
- Clear cups, measuring spoons, water, a marker for labels
- Samples: apple or grape juice, honey, table sugar, regular soda, diet soda, milk, a ripe banana, a sports drink, plain water

Steps

1. Dilute each liquid: 1 tablespoon of juice, soda, milk or honey in 9 tablespoons of water (1 to 10). Dissolve 1 teaspoon of table sugar in half a cup of water. Plain water is your negative control.
2. Dip a strip into each cup for the time stated on the bottle and compare the color with the chart. Record the result (negative, trace, or the level).
3. Mash a slice of ripe banana in 2 tablespoons of water and test the liquid. Test the sports drink (diluted 1 to 10) and the diet soda the same way.
4. Read the ingredient labels of every sample. Mark which list glucose (or dextrose, its other name) or high-fructose corn syrup, which list only sucrose, and which list a non-sugar sweetener. Compare with your strip results.

Check your work

- ☐ Which foods contained free glucose? Which gave a negative result even though they are sweet?
- ☐ Why did table sugar test negative even though it is sweet? (Hint: sucrose is glucose joined to fructose, and the strip's enzyme reacts only with free glucose.)
- ☐ Why did milk test negative? What sugar does milk contain?

- [ ] Why does the body need insulin even after a meal with no table sugar at all?

LAB NOTEBOOK

1. The glucose feedback loop drawn from memory, with both hormones and their targets.
2. Your test-strip results table and a sentence explaining each surprise.

KEY FORMULAS

$$\text{eAG (mg/dL)} = 28.7 \times \text{A1C} - 46.7 \qquad \text{mmol/L} = \frac{\text{mg/dL}}{18}$$

From history. Banting first wanted to be a minister, then studied medicine, served as a battlefield surgeon in the First World War and won the Military Cross for continuing to treat the wounded after being hit by shrapnel. When news of insulin spread in 1922, desperate parents brought dying children to Toronto, and a drug company, Eli Lilly, worked with the university to make it in large quantities. Within a few years children who would have died were growing up. Charles Best later became a leading medical researcher himself, and Banting was knighted in 1934.

Practice habit. When you trace a feedback loop, always finish with the sentence "...and so the stimulus fades and the hormone falls." If you cannot finish that sentence, the loop is not complete.

Career connection. Nurses, dietitians and pharmacists who specialize in diabetes can earn the Certified Diabetes Care and Education Specialist credential, after gaining experience teaching patients and passing a national exam. They teach newly diagnosed children and their families to count carbohydrates, check glucose, give insulin and recognize low blood sugar. Registered nurses train in two- to four-year programs and pass a national licensing exam.

WORKED EXAMPLES

Example 1. An adult has 5.0 L of blood (50 dL) with a glucose concentration of 90 mg/dL. How many grams of glucose are in the blood? Compare this with a meal containing 60 g of carbohydrate.

Show solution

1. $90\ \text{mg/dL} \times 50\ \text{dL} = 4500\ \text{mg} = 4.5\ \text{g}$
2. $60 / 4.5 \approx 13$

Answer: About 4.5 g, so one meal can deliver more than 13 times the glucose in the whole bloodstream; insulin must move it into storage quickly

Example 2. Trace the feedback loop for a student who skips breakfast and runs a cross-country race at 10 a.m. What happens to blood glucose, which hormone responds, and what does it do?

Show solution

1. Overnight and during the race, cells use glucose, so blood glucose falls.
2. Alpha cells sense it and release glucagon (insulin falls; epinephrine from the race helps too).
3. Glucagon makes the liver break down glycogen and make new glucose, and release it into the blood.
4. Glucose returns toward normal, and glucagon release slows. If liver glycogen runs low, the runner may feel weak and shaky.

Answer: Low glucose → glucagon → liver releases glucose → glucose back to normal (negative feedback)

Example 3. The estimated average glucose is $\text{eAG} = 28.7 \times \text{A1C} - 46.7$ (mg/dL). Find the eAG for A1C values of 6.5% and 9.0%. To convert mg/dL to mmol/L, divide by 18.

Show solution

1. $28.7(6.5) - 46.7 = 139.8$ mg/dL; $139.8/18 = 7.8$ mmol/L
2. $28.7(9.0) - 46.7 = 211.6$ mg/dL; $211.6/18 = 11.8$ mmol/L

Answer: About 140 mg/dL (7.8 mmol/L) at 6.5%, the diagnostic cutoff; about 212 mg/dL (11.8 mmol/L) at 9.0%, poorly controlled

PRACTICE

CONCEPT CHECKS

1. Easy Which cells make insulin, and which make glucagon?

   Show answer

   Beta cells make insulin; alpha cells make glucagon (both in the pancreatic islets).

2. Easy What is glycogen, and where is it stored?

   Show answer

   A branched chain of glucose molecules used for storage, mainly in the liver and skeletal muscles.

3. Medium Give three things insulin does that lower blood glucose.

   Show answer

   It makes muscle and fat cells take up glucose (inserting glucose transporters), makes the liver and muscle store glucose as glycogen, and tells the liver to stop releasing glucose.

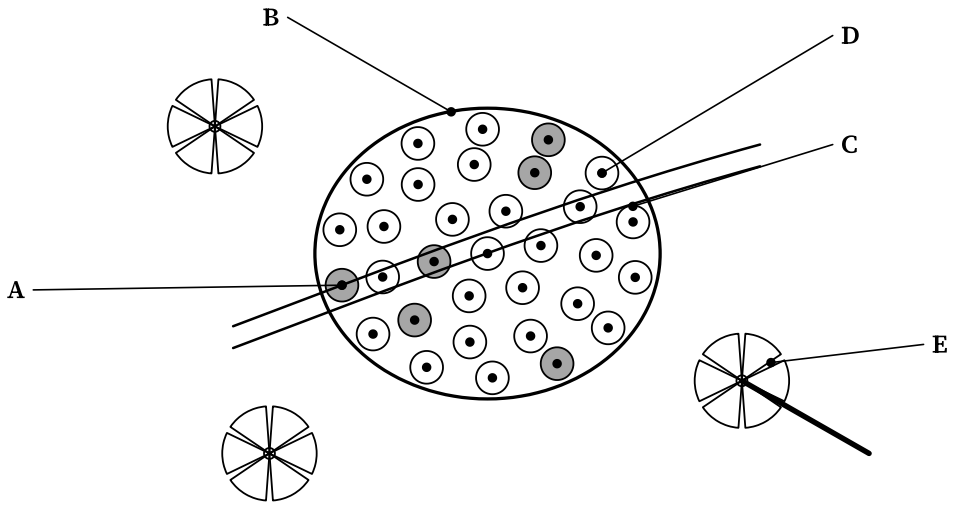
4. Medium Why did Banting want to tie off the pancreatic ducts before making an extract?

   Show answer

   So the enzyme-making exocrine tissue would waste away; earlier extracts had failed because the pancreas's digestive enzymes destroyed the insulin, which is a protein.

DIAGRAM AND DATA QUESTIONS

5. Medium Label the diagram of pancreatic tissue: name each structure marked A to E.



Show answer

A, alpha cell (makes glucagon); B, pancreatic islet; C, capillary; D, beta cell (makes insulin); E, acinar cells (exocrine, make digestive enzymes).

6. Medium Convert to mmol/L by dividing by 18: (a) 126 mg/dL, (b) 70 mg/dL, (c) 200 mg/dL.

Show answer

(a) 7.0 mmol/L, (b) 3.9 mmol/L, (c) 11.1 mmol/L.

7. Hard Using eAG = 28.7 × A1C − 46.7, find the average glucose for A1C 7.0% and 5.7%. What does each mean?

Show answer

7.0%: 28.7 × 7.0 − 46.7 ≈ 154 mg/dL, a common treatment goal for adults with diabetes. 5.7%: ≈ 117 mg/dL, the lower edge of the prediabetes range (5.7–6.4%).

DISORDER AS A BROKEN MECHANISM

8. Medium Compare type 1 and type 2 diabetes: for each, name the broken link in the glucose loop, and explain why both lead to high blood glucose.

Show answer

Type 1: the beta cells are destroyed by the immune system, so little or no insulin is made (the signal is missing). Type 2: the target cells in muscle, fat and liver respond poorly to insulin (insulin resistance), and over time the beta cells cannot make enough extra (the receiver is weak). Either way glucose is not taken up and stored, and the liver keeps releasing it, so blood glucose stays high.

PREDICT THE EFFECT

9. Hard Predict the effect: a person with type 1 diabetes takes his usual insulin dose but then skips lunch and plays basketball. What may happen, what are the signs, and what should a friend do?

Show answer

Blood glucose can fall too low (hypoglycemia), because insulin keeps moving glucose into cells and exercise uses more, with no food coming in. Signs: shakiness, sweating, fast heartbeat, hunger, confusion. If he can swallow, give about 15 g of fast sugar (juice, regular soda or glucose tablets), recheck in 15 minutes, and call for emergency help if he cannot swallow or does not improve.

10. Challenge In untreated type 1 diabetes, glucose appears in the urine and the person urinates often and is very thirsty. Explain the chain of cause and effect from missing insulin to thirst.

Show answer

Without insulin, blood glucose rises far above normal. The kidneys filter more glucose than their transporters can reabsorb (above roughly 180 mg/dL), so glucose stays in the urine. Glucose in the urine holds water with it by osmosis, so large volumes of urine are made; the body loses water, the blood becomes concentrated, and the hypothalamus triggers intense thirst.

COMMON MISTAKES

- Saying insulin “breaks down” sugar; it moves glucose into cells and storage.
- Thinking glucagon and glycogen are the same; glucagon is a hormone, glycogen is stored glucose.

- Believing type 2 diabetes is caused simply by eating sugar; it develops from insulin resistance with many causes, including inactivity, extra body fat and family history.
- Giving insulin to someone who is shaky and confused; low blood sugar needs sugar, and an unconscious person needs emergency help.
- Treating type 1 and type 2 as mild and severe versions of one disease; they break different links in the loop.

Make it a game · Glucose Thermostat. Put 20 beans in a bowl: that is "normal blood glucose." The parent calls events (a big pasta supper: add 10; a long hike: remove 6; overnight fast: remove 4; a glass of juice: add 5). After each, the student must say which hormone is released (insulin or glucagon), which organ responds, and move beans between the bowl and a "liver glycogen" cup to bring the bowl back to 20. Then play a round where the parent says "no insulin" and watch what happens.

Scripture. "Heal the sick, cleanse the lepers, raise the dead, cast out devils: freely ye have received, freely give." (Matthew 10:8, KJV)

Banting, Best and Collip sold the insulin patent for a dollar each so the gift could reach every sick child. Christ's command to His disciples is a pattern for using any gift: freely received, freely given.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

UNIT 6

The Endocrine System

The endocrine system signals by broadcasting hormones in the blood: slower than nerves, but reaching every cell and lasting much longer. This unit follows four discoveries: Bayliss and Starling's secretin (1902), the first hormone; Geoffrey Harris's portal vessels and the isolation of the first hypothalamic releasing hormone (1969); David Marine's iodine trial in Akron schoolgirls (1917–1922) and Edward Kendall's crystals of thyroxine (1914); and Banting and Best's insulin (1921–1922), which turned diabetes from a death sentence into a manageable disease.

Students compare the two ways hormones act on cells, trace feedback loops step by step (thyroid, water balance, calcium and glucose), calculate half-lives, percent reabsorption, the iodine content of thyroxine and average glucose from A1C, and explain endocrine diseases as broken links in a loop. Labs use index-card receptors, a two-day water log, a cold-water stress test and glucose test strips on foods.

PREREQUISITES

- Unit 1, especially Lesson 1.3 (homeostasis and feedback loops)
- Unit 5, especially Lesson 5.5 (the autonomic nervous system)
- Chemistry: molar mass and solutions
- Biology 2.1–2.2 (carbohydrates and proteins)

MASTERY CHECKLIST

- ☐ I can compare the endocrine and nervous systems and explain how water-soluble and lipid-soluble hormones act on target cells.
- ☐ I can describe how the hypothalamus controls both lobes of the pituitary and trace the thyroid and ADH feedback loops.
- ☐ I can explain how the thyroid, parathyroids and adrenal glands work, including calcium control and the stress response.
- ☐ I can trace the insulin–glucagon feedback loop and compare type 1 and type 2 diabetes.
- ☐ I can interpret hormone lab results (high or low) by asking which link in the loop is broken.
- ☐ I can tell the stories of Bayliss and Starling, Harris, Kendall and Banting and Best.

LESSONS IN THIS UNIT

6.1 Hormones and Receptors: Bayliss and Starling's Secretin (1902)
4 sessions of 45 minutes

6.2 The Hypothalamus and Pituitary: Cushing, Harris and the Master Control
4 sessions of 45 minutes

6.3 Thyroid, Parathyroids and Adrenals: Iodine, Goiter and Kendall's Hormones
4 sessions of 45 minutes

6.4 Insulin and Diabetes: Banting and Best (1921) 4 sessions of 45 minutes

Unit 6 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit and sensible significant figures. The test is worth 100 points.

1. **7 pts** **Lesson 6.1**

   Explain how a water-soluble hormone and a lipid-soluble hormone each change a target cell. Give one example of each.

2. **6 pts** **Lesson 6.1**

   A hormone's half-life is 8 minutes. If release stops, what percent remains after 24 minutes?

3. **7 pts** **Lesson 6.2**

   Name the two lobes of the pituitary, how the hypothalamus controls each, and two hormones released by each.

4. **9 pts** **Lesson 6.2**

   Trace the hypothalamus–pituitary–thyroid loop for a person whose T4 is too high, naming each hormone and saying whether it rises or falls.

5. **7 pts** **Lesson 6.2**

   The kidneys filter 180 L a day. On a hot day a worker makes only 0.9 L of urine. What percent of the filtrate was reabsorbed, and what was his ADH level probably doing?

6. **7 pts** **Lesson 6.3**

   List the effects of PTH that raise blood calcium, and name the hormone that opposes it and where it is made.

7. **7 pts** **Lesson 6.3**

   Compare the adrenal cortex and adrenal medulla: tissue type, hormones, and what controls each.

8. **6 pts** **Lesson 6.3**

   Thyroxine ($C_{15}H_{11}I_4NO_4$) has a molar mass of about 777 g/mol. What mass of iodine is in 1.00 mg of thyroxine? (Iodine is 126.9 g/mol.)

9. **9 pts** **Lesson 6.4**

   Trace the glucose feedback loop after a large meal, naming the sensor, the hormone, its targets and their responses, and how the loop turns off.

10. **7 pts** **Lesson 6.4**

    A patient's fasting glucose is 132 mg/dL and her A1C is 6.8%. (a) Convert the glucose to mmol/L. (b) Find her estimated average glucose from the A1C. (c) Do these meet the diagnostic criteria for diabetes?

11. **6 pts** **Lesson 6.4**

    List four signs of hypoglycemia and the first-aid "rule of 15."

DISORDERS AND SHORT ESSAY

12. **10 pts** **Lesson 6.4**

    Choose two of type 1 diabetes, type 2 diabetes, iodine-deficiency goiter, Graves' disease, and gigantism. For each, name the broken link in the hormone loop and explain how it produces the main signs.

13. **12 pts** **Lesson 6.4**

    Short essay: Bayliss and Starling cut the nerves before testing; Marine compared treated and untreated schoolgirls; Banting and Best measured each dog's blood sugar before and after the extract. What does each method have in common? Choose two and explain how their design made the conclusion convincing.

ANSWER KEY

1. Water-soluble (insulin, epinephrine, ADH): binds a receptor on the cell surface, which makes a second messenger such as cAMP inside the cell that activates existing enzymes, quickly. Lipid-soluble (cortisol, aldosterone, thyroid hormone): crosses the membrane, binds a receptor inside the cell, and the pair binds DNA to switch genes on or off, so new proteins are made, slowly but lastingly.
2. 24/8 = 3 half-lives; $(1/2)^3 = 1/8 = 12.5\%$.
3. Posterior: controlled by nerves (neurosecretory axons from the hypothalamus), releases ADH and oxytocin. Anterior: controlled by releasing and inhibiting hormones carried by the hypophyseal portal veins, releases two of GH, TSH, ACTH, prolactin, FSH, LH.
4. High T4 and T3 give strong negative feedback on the hypothalamus and pituitary → TRH falls → TSH falls → the thyroid is stimulated less and releases less T4 and T3 → levels fall toward normal, and feedback eases.
5. (180 − 0.9)/180 = 99.5%. ADH was high, because sweating concentrated his blood and the kidneys were told to return as much water as possible.
6. PTH: osteoclasts release calcium from bone; kidneys keep calcium; kidneys activate vitamin D, increasing absorption from the gut. Calcitonin opposes it, made by the C cells of the thyroid.
7. Cortex: gland tissue making steroids (aldosterone, controlled mainly by the renin–angiotensin system and potassium; cortisol, controlled by ACTH; small amounts of androgens). Medulla: modified sympathetic nervous tissue releasing epinephrine and norepinephrine, controlled by sympathetic nerves.
8. Iodine fraction = 4 × 126.9 / 777 ≈ 0.653; 1.00 mg × 0.653 ≈ 0.653 mg of iodine.
9. Glucose rises → beta cells in the islets sense it → release insulin → muscle and fat cells take up glucose; liver and muscle store glycogen; fat cells store fat; liver stops releasing glucose → blood glucose falls toward normal → beta cells sense the fall and release less insulin (negative feedback).
10. (a) 132/18 ≈ 7.3 mmol/L. (b) 28.7 × 6.8 − 46.7 ≈ 148.5 mg/dL. (c) Yes: fasting glucose ≥ 126 mg/dL and A1C ≥ 6.5% (a doctor confirms with repeat testing).
11. Shakiness, sweating, fast heartbeat, hunger, confusion or irritability. Give about 15 g of fast sugar (juice, regular soda, glucose tablets) if the person can swallow, recheck in 15 minutes, repeat if still low; call emergency help if the person cannot swallow or does not improve.

12. Look for: type 1 (beta cells destroyed, no insulin, high glucose, thirst, weight loss, ketoacidosis); type 2 (insulin resistance plus tiring beta cells, slowly rising glucose); goiter (no iodine, low T4, weak feedback, high TSH, gland enlarges); Graves' (antibodies stimulate TSH receptors, high T4, low TSH, fast heart, weight loss); gigantism (GH tumor ignores feedback, long bones grow while plates are open).
13. Look for: each removed or controlled other explanations (nerves cut; an untreated comparison group; each animal as its own before-and-after comparison), measured a clear outcome, and repeated the result; a thoughtful conclusion about controls, honest measurement and why their discoveries were trusted.

UNIT 7

Blood, Heart and Defense

This unit follows the blood: what it is made of and how it is matched for transfusion, the heart that pumps it and the electrical system that times every beat, the vessels and pressure that drive it into every tissue, and the defenses it carries. The history runs from Harvey's circulation (Biology 10.2) through Laennec's stethoscope (1816), Landsteiner's blood groups (1901), Einthoven's ECG (1903) and Korotkov's blood-pressure sounds (1905) to Metchnikoff's phagocytes and von Behring's antitoxin.

The unit has the course's main clinical-skills lab: measuring blood pressure with a home cuff (Lesson 7.3). It also uses a stethoscope or cardboard tube, a simulated blood-typing kit or a homemade substitute, food coloring and simple household materials. No real blood is handled. Lessons 7.4 and 7.5 build on bacteria, viruses and vaccines in Biology 8.1; the vaccine lesson is factual and leaves health decisions to each family and its doctor.

PREREQUISITES

- Unit 1 (homeostasis and feedback loops) and Unit 2 (cells and tissues)
- Biology 10.2 (Harvey and the path of blood through the heart)
- Biology 5.3 (inheritance of ABO blood types) and 8.1 (bacteria, viruses and vaccines)

MASTERY CHECKLIST

- ☐ I can describe the parts of blood, calculate a hematocrit, explain clotting, and decide which donor red cells are safe for any ABO and Rh type.
- ☐ I can trace blood through the heart, explain the heart sounds and the conduction system, read rate and intervals from an ECG, and calculate cardiac output and ejection fraction.
- ☐ I can compare the vessels, measure blood pressure correctly, calculate MAP and pulse pressure, classify readings and explain the baroreceptor reflex.
- ☐ I can explain how lymph forms and returns, what the lymphoid organs do, and how barriers, phagocytes, inflammation and fever defend the body.
- ☐ I can explain B cells, T cells, antibodies, primary and secondary responses, active and passive immunity, how vaccines work, and allergy and autoimmunity as misdirected defense.

LESSONS IN THIS UNIT

7.1 Blood and Blood Typing: Landsteiner's Three Groups (1901)

4 sessions of 45 minutes

7.2 The Heart and Its Electrical System: Laennec's Stethoscope (1816) and Einthoven's ECG (1903)

4 sessions of 45 minutes

7.3 Vessels and Blood Pressure: Hales's Glass Tube (1733) and Korotkov's Sounds (1905)

4 sessions of 45 minutes

7.4 The Lymphatic System and Innate Defense: Metchnikoff's Starfish (1882)

3 sessions of 45 minutes

7.5 Adaptive Immunity and Vaccines: Von Behring's Antitoxin (1890)

3 sessions of 45 minutes

Unit 7 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **6 pts** **Lesson 7.1**
   Name the three layers of a spun blood sample from top to bottom, and give the job of red cells, white cells and platelets.

2. **7 pts** **Lesson 7.1**
   A spun sample is 50 mm tall with 21 mm of red cells. Find the hematocrit and say whether it is normal for a man (42–52%).

3. **8 pts** **Lesson 7.1**
   A patient is type AB-negative. Which donor types of red cells are safe? Which donor types of plasma are safe?

4. **7 pts** **Lesson 7.2**
   Put these in order of the electrical signal: AV node, Purkinje fibers, SA node, bundle branches, bundle of His. Which one sets the heart rate?

5. **8 pts** **Lesson 7.2**
   A ventricle fills to 130 mL and empties to 60 mL; the heart rate is 72. Find stroke volume, ejection fraction and cardiac output.

6. **7 pts** **Lesson 7.2**

   On an ECG strip, R waves are 3 large boxes apart and the PR interval is 4 small boxes. Find the heart rate and PR interval. Is either abnormal?

7. **7 pts** **Lesson 7.3**

   A reading is 150/95 mmHg. Find the pulse pressure and MAP, and classify the reading.

8. **7 pts** **Lesson 7.3**

   Explain why halving an arteriole's radius has such a large effect on flow.

9. **8 pts** **Lesson 7.3**

   List four things a person must do for an accurate blood-pressure reading.

10. **6 pts** **Lesson 7.4**

    Blood capillaries filter 20 L/day and reabsorb 17 L/day. How much lymph forms, and what happens if the lymphatic vessels of a limb are blocked?

11. **7 pts** **Lesson 7.4**

    Describe the sequence of events in inflammation after a splinter carries bacteria into the skin.

12. **7 pts** **Lesson 7.5**

    Compare the primary and secondary immune responses in speed, size and main antibody class, and explain why they differ.

13. **7 pts** **Lesson 7.5**

    Explain how a toxoid vaccine for tetanus protects a person, and why it is classed as active immunity.

SHORT ESSAY

14. **8 pts** **Lesson 7.1–7.5**

    Choose one: (a) hemophilia, (b) heart block, (c) varicose veins, (d) anaphylaxis. Explain it as a broken mechanism: what the normal mechanism is, which part fails, and how the symptoms follow.

ANSWER KEY

1. Plasma (top), buffy coat of white cells and platelets, packed red cells. Red cells carry oxygen (hemoglobin); white cells fight infection; platelets begin clotting.
2. 42.0%, at the low end of normal
3. Red cells: AB−, A−, B−, O− (any ABO type, Rh-negative). Plasma: AB only, because only AB plasma lacks both anti-A and anti-B.
4. SA node, AV node, bundle of His, bundle branches, Purkinje fibers. The SA node sets the rate.
5. SV 70 mL; EF 54%; CO 5,040 mL/min ≈ 5.0 L/min
6. 100 beats per minute (300 ÷ 3), at the upper limit of normal resting rate; PR 0.16 s, normal.
7. Pulse pressure 55 mmHg; MAP ≈ 95 + 55/3 ≈ 113 mmHg; stage 2 high blood pressure.
8. Resistance varies as $1/r^4$, so halving the radius multiplies resistance by 16; at the same pressure, flow falls to 1/16.
9. Any four: sit with back supported and feet flat for 5 minutes; arm bare, supported at heart level; correct cuff size and position; no talking; no caffeine or exercise just before; average two or three readings a minute apart.
10. 3 L/day. Fluid builds up in the limb's tissues (lymphedema).
11. Damaged cells and mast cells release histamine; arterioles widen (redness, heat); capillaries leak fluid (swelling); pain nerves fire; neutrophils and then macrophages leave the capillaries and engulf the bacteria; clotting proteins wall off the area.
12. Primary: slower (peak about 1–2 weeks), smaller, first mostly IgM. Secondary: within a day or two, much larger, mostly IgG. Memory cells already exist in large numbers the second time.
13. An inactivated tetanus toxin cannot cause disease but has the same antigens; the person's own B cells make antibodies and memory cells against it, so a real toxin is neutralized quickly. The body made its own antibodies, so it is active (artificial) immunity.
14. Look for: a correct normal mechanism (clotting cascade; AV conduction; venous valves and muscle pump; IgE and mast cells), the specific failing part, and a clear chain from that failure to the symptoms.

7.1 Blood and Blood Typing: Landsteiner's Three Groups (1901)

Mark up this lesson

OBJECTIVES

- Describe the parts of blood (plasma, red cells, white cells, platelets) and calculate a hematocrit.
- Explain how hemoglobin carries oxygen, how red cells are made and replaced, and how blood clots.
- Use the ABO and Rh antigens and antibodies to decide which donor blood is safe for a patient.

> **Warm-up.** Before Landsteiner, doctors sometimes tried to transfuse blood from one person to another. Sometimes the patient recovered; sometimes the patient developed fever, dark urine and shock, and died. Why might the same treatment help one patient and kill another?

WATCH

Blood, Part 1 - True Blood: Crash Course Anatomy & Physiology #29

CrashCourse · 10:00

https://www.youtube.com/watch?v=HQWlcSp9Sls

> **WHEN TO WATCH**
> After the parts of blood and red cells.

BACKUP VIDEO

Multiple Alleles (ABO Blood Types) and Punnett Squares

Amoeba Sisters · 7:05

https://www.youtube.com/watch?v=9O5JQqlngFY

With blood types, as a review of the genetics from Biology 5.3.

KEY TERMS

plasma

The straw-colored liquid part of blood: about 92% water, with proteins (albumin, antibodies, clotting factors), salts, nutrients, hormones and wastes.

formed elements

The cells and cell pieces in blood: red blood cells (erythrocytes), white blood cells (leukocytes) and platelets (thrombocytes).

hematocrit

The percent of a blood sample's volume taken up by packed red cells; about 42–52% in men and 37–47% in women.

hemoglobin

The iron-containing protein that fills red cells; each molecule has four heme groups and can carry four oxygen molecules.

erythropoietin (EPO)

A hormone made mainly by the kidneys when oxygen delivery is low; it tells the red bone marrow to make more red cells.

hemostasis

Stopping bleeding: the vessel narrows, platelets form a plug, and a fibrin clot seals the plug.

antigen

A molecule, often on a cell surface, that the immune system can recognize; the A, B and Rh(D) antigens sit on red cells.

agglutination

Clumping of red cells when antibodies bind the antigens on them; the basis of blood typing.

CORE IDEAS

The story. In 1900 Karl Landsteiner, a young physician working in a pathology institute in Vienna, took blood from himself and five colleagues, separated each sample into cells and serum, and mixed every serum with every set of cells. Some mixtures stayed smooth; others clumped into red grains within minutes. The pattern was not random. In 1901 he published three groups, which he called A, B and C (C is now O). In 1902 two of his students, Alfred von Decastello and Adriano Sturli, found the fourth and rarer group, AB.

How they figured it out. Landsteiner reasoned that red cells carry surface markers (antigens) and that serum carries ready-made antibodies against the markers a person lacks. In 1907 Reuben Ottenberg in New York began typing and cross-

matching donor and patient before transfusion, and the deadly reactions became rare. In 1940 Landsteiner, by then at the Rockefeller Institute in New York, and Alexander Wiener found the Rh factor, named for the rhesus monkey blood used in their tests. Landsteiner received the Nobel Prize in 1930.

What blood is made of. An adult has about 70 mL of blood per kilogram of body mass, about 5 liters. Spin a tube of blood in a centrifuge and it separates into three layers: plasma on top (about 55%), a thin pale buffy coat of white cells and platelets (under 1%), and packed red cells at the bottom (about 45%, the hematocrit). Blood carries oxygen, carbon dioxide, nutrients, hormones and heat; it fights infection; it buffers pH; and it seals its own leaks.

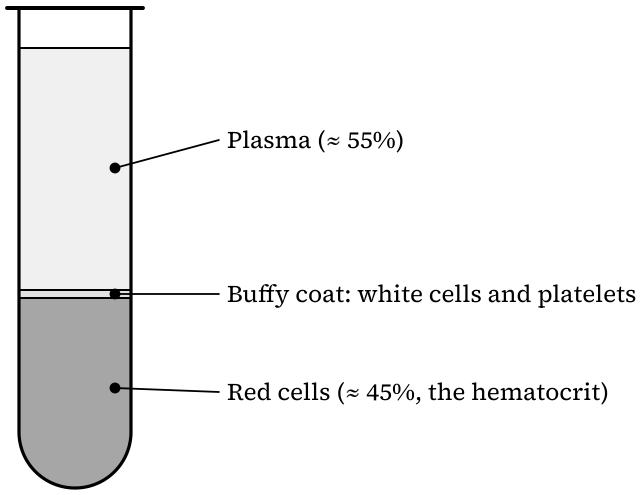
Red cells and hemoglobin. A red cell is a flexible biconcave disc about 7.5 micrometers across with no nucleus and no mitochondria, so it uses none of the oxygen it carries and has more room for hemoglobin. Each microliter of blood holds about 4–6 million red cells. They live about 120 days; old cells are broken down in the spleen and liver, the iron is recycled, and the heme becomes the yellow pigment bilirubin. When oxygen delivery falls (blood loss, high altitude), the kidneys release erythropoietin and the red marrow speeds up production. White cells (4,500–11,000 per microliter) fight infection (Lesson 7.4); platelets (150,000–400,000 per microliter) are cell fragments that start clotting.

Clotting. When a vessel is cut, three things happen in order. The vessel's smooth muscle contracts (vascular spasm). Platelets stick to the exposed collagen, release chemicals that call more platelets, and form a plug. Then a chain of clotting factors in the plasma, each activating the next, produces the enzyme thrombin, which turns the soluble plasma protein fibrinogen into threads of fibrin that weave the plug into a firm clot. Vitamin K is needed to make several of the factors. The chain is built to amplify a small signal into a fast response and to stay switched off in healthy vessels.

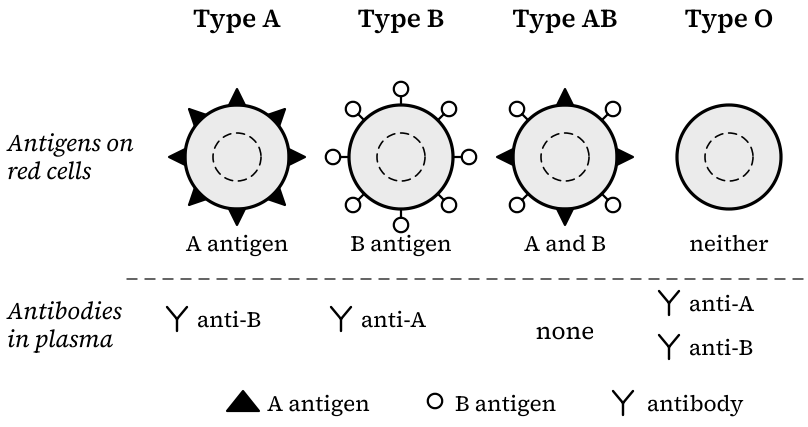
Blood types and transfusion. Type A cells carry A antigens and the plasma carries anti-B antibodies; type B is the reverse; type AB has both antigens and neither antibody; type O has neither antigen and both antibodies. If donor cells carry an antigen the patient's plasma attacks, the cells clump and burst (a hemolytic transfusion reaction). So for red-cell transfusions, O-negative cells can go to nearly anyone in an emergency (universal donor), and AB-positive patients can receive any ABO and Rh type of red cells (universal recipient). Rh is simpler: Rh-positive cells

carry the D antigen; an Rh-negative person makes anti-D only after being exposed to Rh-positive blood. The inheritance of these types, with codominant I^A and I^B alleles, is in Biology 5.3.

Where it is used. Hospital labs type and cross-match every unit before a transfusion, and blood banks store red cells, plasma and platelets separately so one donation can help several patients. A complete blood count (CBC) reports the hematocrit, hemoglobin and cell counts and is among the most common lab tests. An Rh-negative mother carrying an Rh-positive baby is given anti-D immune globulin so that she does not make antibodies that could harm a later baby.



Spun blood separates into plasma, a thin buffy coat and packed red cells. The red-cell fraction is the hematocrit.



Each ABO type carries the antibodies against the antigens it lacks. Type O plasma attacks both A and B cells.

> **Safety first.** This lab uses simulated blood only. Do not prick fingers or handle anyone's real blood at home; real blood typing is done by trained workers with sterile lancets and sharps containers. Simulated typing sera can stain clothes and are not to be tasted; wash hands afterward.

LAB

Simulated Blood Typing and a Transfusion Chart

You will type four "patients" with simulated blood and anti-sera, then build a chart of safe red-cell transfusions.

You will need

- A simulated blood typing kit (about $20–30 from a science supplier) with four "patient" samples and simulated anti-A, anti-B and anti-Rh sera, or the do-it-yourself version below
- Do-it-yourself version: whole milk tinted with red food coloring as "blood"; vinegar as the clumping "antiserum"; four labeled cups prepared secretly by a parent according to a key
- Typing trays or white plastic spoons, toothpicks, a marker, paper towels

Steps

1. Label three wells per patient: A, B and Rh. Put 2 drops of the patient's sample in each well.
2. Add 2 drops of anti-A serum to the A well, anti-B to the B well and anti-Rh to the Rh well. Stir each with a fresh toothpick.
3. After one minute, look for clumping (agglutination). Clumping in a well means that antigen is present. Record each patient's type, for example A-positive.
4. Make an 8 × 8 chart with donor types across the top and patient types down the side. Mark each box ✓ (safe red cells) or ✗.
5. Check your typing against the parent's key.

Check your work

- ☐ Which patient could give red cells to all four patients?
- ☐ Which patient could receive red cells from all four?
- ☐ Why does clumping in the anti-A well mean the cells carry A antigen?

LAB NOTEBOOK

1. A labeled drawing of a spun tube of blood with the percent of each layer.

2. Your typing results and the 8 × 8 red-cell compatibility chart.

From history. Charles Drew, an American surgeon, showed in 1939–1940 that plasma, unlike whole blood, could be separated, stored for long periods and shipped. In 1940 he directed the “Blood for Britain” program that sent plasma to wounded soldiers and civilians, and in 1941 he became the first director of the American Red Cross blood bank. Landsteiner kept working in his laboratory into his seventies; he died in 1943, two days after a heart attack at the bench.

Practice habit. When you solve a transfusion question, write the patient’s antibodies first, then cross out every donor whose cells carry a matching antigen; never start from the donor.

Career connection. Phlebotomists draw blood for tests and donations; most train in a certificate program of a few months and many earn a national certification. Medical laboratory technicians and scientists run the CBCs, blood typing and cross-matches behind every transfusion (usually an associate or bachelor’s degree). Both are steady entry points into health care.

WORKED EXAMPLES

Example 1. After spinning, a blood sample is 75 mm tall and the packed red cells are 33 mm tall. What is the hematocrit, and is it in the normal range for a woman (37–47%)?

Show solution

1. Hematocrit = red-cell height ÷ total height × 100%
2. 33 ÷ 75 × 100% = 44.0%

Answer: 44.0%, normal

Example 2. A patient is type A-negative. Which donor types of red cells can she safely receive?

Show solution

1. Her plasma has anti-B, so donor cells must not carry B: donor type A or O.
2. She is Rh-negative, so donor cells should not carry the D antigen: donor must be Rh-negative.
3. That leaves A-negative and O-negative.

Answer: A-negative or O-negative

Example 3. A 70 kg man has about 70 mL of blood per kg and 5.0 million red cells per microliter. Estimate his total number of red cells. (1 mL = 1,000 μL)

Show solution

1. Blood volume = 70 × 70 = 4,900 mL = 4,900,000 μL
2. Red cells = $4.9 \times 10^6 \times 5.0 \times 10^6 \approx 2.5 \times 10^{13}$

Answer: About 25 trillion red cells

PRACTICE

CONCEPT CHECKS

1. Easy Name the three layers of spun blood from top to bottom and give the approximate percent of the top and bottom layers.

   Show answer

   Plasma (about 55%), buffy coat (white cells and platelets, under 1%), red cells (about 45%).

2. Easy Why can a mature red cell not use the oxygen it carries?

   Show answer

   It has no mitochondria (and no nucleus), so it makes its ATP by glycolysis alone; the space is filled with hemoglobin.

3. Easy Put the three steps of hemostasis in order.

   Show answer

   Vascular spasm, platelet plug, coagulation (fibrin clot).

4. **Medium** A sample is 40 mm tall with 18 mm of packed red cells. Find the hematocrit.

   Show answer

   45.0%

5. **Medium** A patient is B-positive. List every donor type of red cells that is safe.

   Show answer

   B-positive, B-negative, O-positive, O-negative.

6. **Medium** Why can an O-negative patient receive red cells only from O-negative donors?

   Show answer

   Her plasma has both anti-A and anti-B, so donor cells must have neither antigen (type O); she may make anti-D, so the cells must also be Rh-negative.

7. **Medium** Red cells live about 120 days and an adult has about 25 trillion of them. About how many must the marrow make each second to keep up?

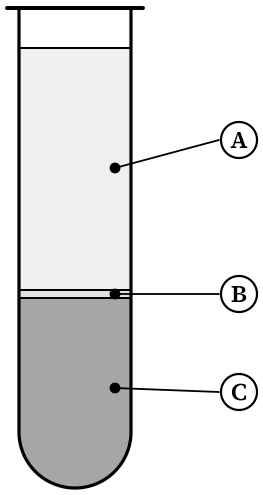
   Show answer

   About 2.4 million per second

   $2.5 \times 10^{13} \div (120 \times 86{,}400\ \text{s}) \approx 2.4 \times 10^{6}$

DIAGRAM AND DATA QUESTIONS

8. **Medium** Name the parts of the spun blood tube lettered A to C.



Show answer

A plasma; B buffy coat (white cells and platelets); C packed red cells.

9. **Hard** A climber spends six weeks at high altitude. Her hematocrit rises from 41% to 47%. Explain the chain of events, naming the organ and hormone involved.

Show answer

Less oxygen reaches the kidneys, which release more erythropoietin; EPO stimulates the red bone marrow to make more red cells; the higher hematocrit carries more oxygen per liter of blood (negative feedback, Lesson 1.3).

WHEN IT GOES WRONG

10. Hard **Disorder as a broken mechanism.** In hemophilia A one clotting factor (factor VIII) is missing. Using the three steps of hemostasis, explain why a small cut may still seal but a bruise or joint bleed can keep bleeding for hours. Why is it far more common in boys? (Biology 5.3)

Show answer

Vascular spasm and the platelet plug still work, which can be enough for a small cut; but without factor VIII the clotting chain cannot amplify to make enough thrombin and fibrin, so the plug is never reinforced and deeper bleeding continues. The gene is on the X chromosome and is recessive; boys have one X, so one faulty copy causes the disease.

11. Challenge An Rh-negative mother has an Rh-positive first baby. At delivery some of the baby's cells enter her blood. Explain why her first baby was unharmed but a second Rh-positive baby could be in danger, and how anti-D immune globulin prevents it.

Show answer

Anti-D is not present at first; she makes it only after exposure at delivery, too late to affect the first baby. In a later pregnancy her anti-D antibodies (IgG) can cross the placenta and destroy the baby's red cells (hemolytic disease of the newborn). Anti-D immune globulin given to the mother clears the baby's cells before her immune system responds, so she never makes her own anti-D.

COMMON MISTAKES

- Saying type O blood has "no antibodies"; type O has no antigens and both antibodies. Type AB has no ABO antibodies.
- Matching donor plasma rules to red-cell rules. For plasma the rules reverse: AB plasma is the universal plasma donor.
- Thinking an Rh-negative person always carries anti-D; it is made only after exposure to Rh-positive cells.
- Calling platelets cells; they are fragments of large marrow cells called megakaryocytes.
- Reading the hematocrit as the red cells' share of the plasma rather than of the whole sample.

Make it a game · Donor Match. Write the eight types (A+, A−, B+, B−, AB+, AB−, O+, O−) on cards and deal one “patient” card face up. The student has 10 seconds to pull every safe red-cell donor from the rest of the deck. One point per correct card, minus one for each wrong card. After five rounds, switch to plasma rules for a bonus round.

Scripture. “And hath made of one blood all nations of men for to dwell on all the face of the earth, and hath determined the times before appointed, and the bounds of their habitation.” (Acts 17:26, KJV)

All four ABO types and both Rh types are found among peoples all over the world. A transfusion can pass from a stranger of any nation to any other when the types match: one blood.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | Mark up this lesson

7.2 The Heart and Its Electrical System: Laennec's Stethoscope (1816) and Einthoven's ECG (1903)

Mark up this lesson

OBJECTIVES

- Trace blood through the four chambers and four valves and explain the two heart sounds.
- Describe the conduction system from the SA node to the Purkinje fibers and match each part of an ECG to an electrical event.
- Calculate cardiac output, stroke volume, ejection fraction and heart rate from an ECG strip.

> **Warm-up.** Put two fingers on the side of your neck and find your pulse. Now hold your breath gently for 10 seconds while still feeling it (do not strain). The heart kept beating without any thought from you. Where do you think the signal for each beat comes from: the brain, or the heart itself?

WATCH

Conduction System of the Heart

Amoeba Sisters · 12:08

https://www.youtube.com/watch?v=bzZdJn7elaU

> **WHEN TO WATCH**
> After the conduction system, before reading ECG strips.

BACKUP VIDEO

Electrical system of the heart | Circulatory system physiology | NCLEX-RN | Khan Academy

khanacademymedicine · 9:43

https://www.youtube.com/watch?v=7K2icszdxQc

With the conduction system.

KEY TERMS

atrioventricular (AV) valves

The tricuspid (right) and mitral or bicuspid (left) valves between each atrium and ventricle; their closing makes the first heart sound, “lub.”

semilunar valves

The pulmonary and aortic valves at the exits of the ventricles; their closing makes the second heart sound, “dub.”

sinoatrial (SA) node

The heart’s natural pacemaker, a cluster of cells in the right atrium wall that fires on its own about 60–100 times a minute.

atrioventricular (AV) node

Tissue between atria and ventricles that delays the signal about a tenth of a second so the atria can finish emptying.

bundle of His and Purkinje fibers

Fast-conducting fibers that carry the signal down the septum and spread it through the ventricle walls from the apex upward.

electrocardiogram (ECG or EKG)

A recording of the heart’s electrical activity from electrodes on the skin: P wave, QRS complex and T wave.

stroke volume

The volume pumped by one ventricle in one beat: end-diastolic volume minus end-systolic volume.

ejection fraction

Stroke volume divided by end-diastolic volume; normally about 55–70% for the left ventricle.

CORE IDEAS

The story. In 1816 the French physician René Laennec was asked to examine a young woman with heart trouble. Pressing an ear to her chest was improper, and tapping told him little. Remembering children who sent scratching sounds through a long beam of wood, he rolled a quire of paper into a tight tube, put one end on her chest and the other to his ear, and heard the heart more clearly than ever before. He refined it into a wooden cylinder, the stethoscope (Greek *stethos*, chest + *skopein*, to examine), and in 1819 published a book matching the sounds he heard with what he later found at autopsy.

How they figured it out. The heart’s beat is electrical. In 1887 Augustus Waller in London recorded the first human heart tracing from the skin, but his instrument

was crude. Willem Einthoven in Leiden built a far more sensitive string galvanometer: a silver-coated quartz thread thinner than a hair, stretched between the poles of a strong electromagnet, that twitched with the heart's tiny currents; its shadow was photographed on moving film. He published clear tracings by 1903, named the waves P, Q, R, S and T, standardized the limb leads (Einthoven's triangle) and won the Nobel Prize in 1924.

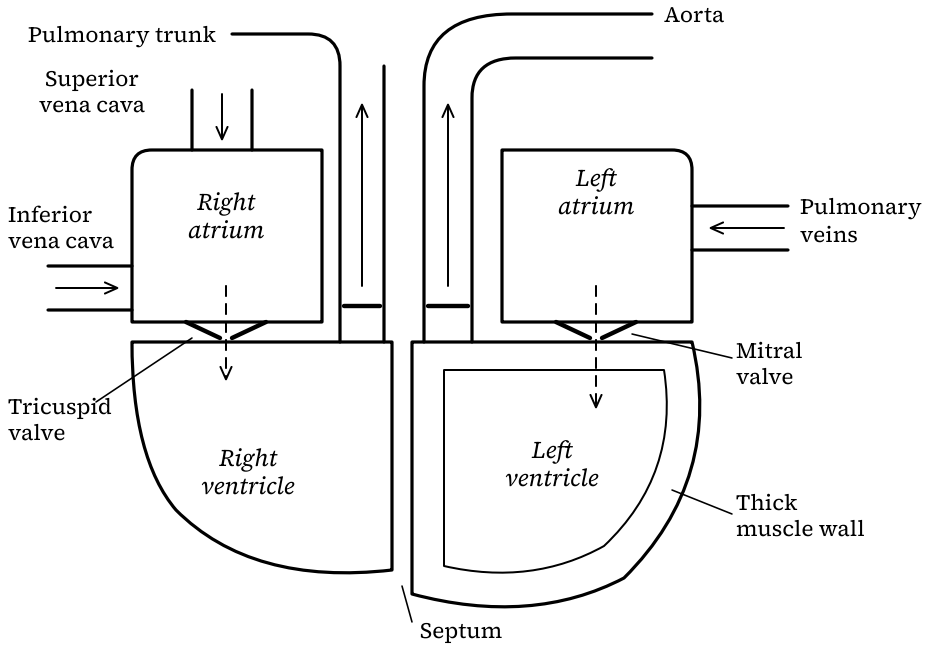
Chambers, valves and sounds. The right side pumps blood to the lungs and the left side to the body (the full route is in Biology 10.2). The left ventricle's wall is about three times thicker than the right's because it must push blood through the whole body. Valves keep flow one way. When the ventricles begin to contract, pressure snaps the AV valves shut (lub, S1); when they relax, blood in the aorta and pulmonary trunk pushes back and snaps the semilunar valves shut (dub, S2). Tendon-like chordae tendineae hold the AV valves so they do not flip backward. The heart's own muscle is fed by the coronary arteries, the first branches of the aorta.

The conduction system. Cardiac muscle cells are joined by intercalated discs with gap junctions, so an electrical signal spreads from cell to cell and the chambers contract as units. The SA node fires on its own, without any nerve, and the wave spreads across both atria. It reaches the AV node, the only electrical doorway to the ventricles, which holds it back about 0.1 second while the atria finish filling the ventricles. Then the bundle of His, the right and left bundle branches and the Purkinje fibers carry it rapidly to the apex and up the ventricle walls, so the ventricles squeeze from the bottom up, like squeezing a tube of toothpaste from the closed end. Nerves only adjust the rate: sympathetic nerves speed it, the vagus nerve slows it.

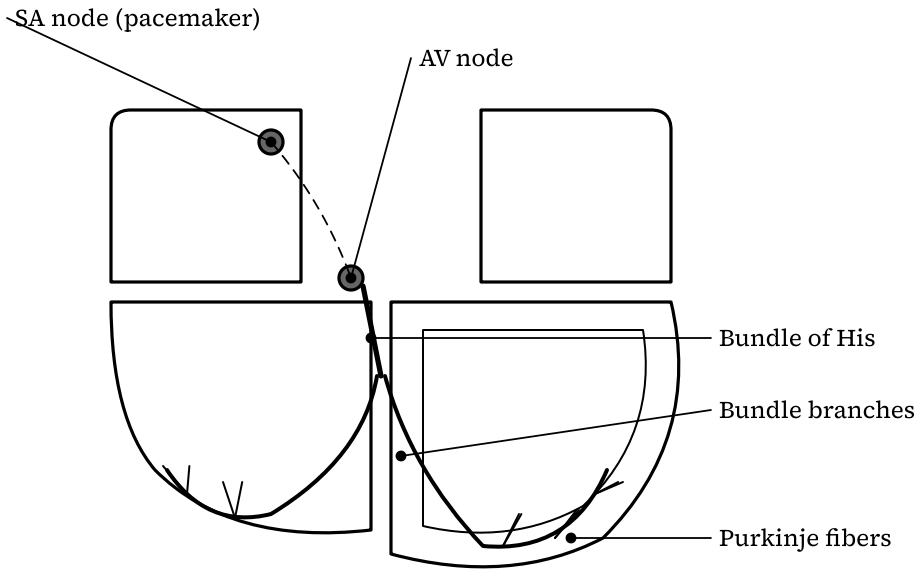
Reading an ECG. The P wave is the atria depolarizing (the electrical event just before they contract). The QRS complex is the ventricles depolarizing; it is tall because the ventricles have the most muscle, and it hides the atria repolarizing. The T wave is the ventricles repolarizing. On standard ECG paper moving at 25 mm per second, one small box is 0.04 s and one large box (5 small) is 0.20 s. The PR interval, from the start of P to the start of QRS, is normally 0.12–0.20 s and shows the AV delay; a normal QRS lasts less than about 0.12 s. Heart rate ≈ 300 ÷ (large boxes between R waves), or 60 ÷ (R-to-R time in seconds).

The cardiac cycle and output. Each beat has a filling phase (diastole) and a pumping phase (systole). A resting left ventricle fills to about 120 mL (end-diastolic volume, EDV) and squeezes down to about 50 mL (end-systolic volume, ESV), so it ejects about 70 mL. Cardiac output is $\mathrm{CO} = \mathrm{HR} \times \mathrm{SV}$, about 5 L/min at rest and four or more times that in a trained athlete at full effort. Stroke volume rises when more blood returns to the heart, because a stretched heart muscle contracts more forcefully (the Frank–Starling law).

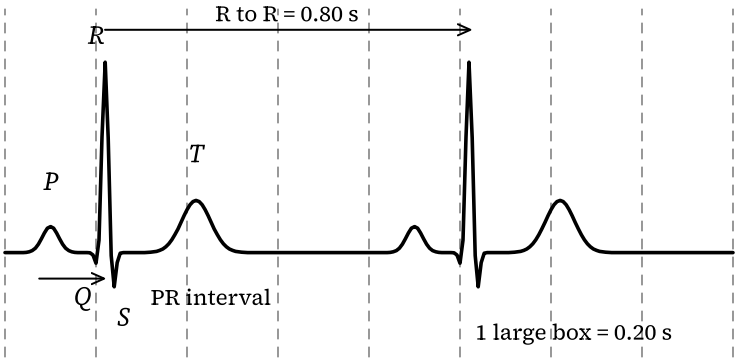
Where it is used. A 12-lead ECG takes about ten minutes and is one of the first tests in any emergency department for chest pain, fainting or a racing heart. Automated external defibrillators (AEDs) in schools and churches read the rhythm themselves and shock only a rhythm that a shock can fix. Pacemakers take over when the SA node or AV node fails.



The heart drawn as if facing the person: right side on the viewer's left. Dashed arrows pass the AV valves; the left ventricle's wall is the thickest.



The conduction path: SA node → atria → AV node (delay) → bundle of His → bundle branches → Purkinje fibers.



A normal ECG at 25 mm/s. P = atria depolarize, QRS = ventricles depolarize, T = ventricles repolarize. R-to-R of 0.80 s means 75 beats per minute.

> **Safety first.** Stethoscope earpieces should point slightly forward and never be tapped while in someone's ears. Anyone with a heart condition, asthma or an injury should skip the exercise step. Stop if you feel dizzy or faint.

LAB

Heart Sounds and a Paper ECG Lab

You will hear the two heart sounds, measure how exercise changes rate and output, and read three printed ECG strips.

You will need

- A stethoscope (about $10) or a cardboard paper-towel tube
- A stopwatch, a partner, a ruler marked in millimeters
- Three practice ECG strips: print the tracing from this lesson's figure at full width, or draw your own on graph paper using the box values below

Steps

1. Listen just left of the lower breastbone (the mitral area) and at the second space to the right of the breastbone (the aortic area). Which sound, lub or dub, is louder at each place?
2. Count the resting pulse for 30 seconds and double it, three times. Average.
3. March in place briskly for 2 minutes. Count the pulse at once and every minute for 4 minutes.
4. Estimate cardiac output at rest (assume 70 mL per beat) and right after exercise (assume 100 mL per beat).
5. On each ECG strip measure the R-to-R distance and the PR interval in small boxes. Convert to seconds (1 small box = 0.04 s) and find the heart rate.

Check your work

- ☐ Did the pulse return to resting within 4 minutes?
- ☐ Which heart sound is made by the AV valves closing?
- ☐ Is each PR interval between 0.12 and 0.20 s?

LAB NOTEBOOK

1. A heart diagram with chambers, valves and the conduction path in a second pencil color.
2. A sketch of one ECG beat with P, QRS and T labeled and the electrical event for each written beside it.

KEY FORMULAS

$$\mathrm{CO} = \mathrm{HR} \times \mathrm{SV}$$

$$\mathrm{SV} = \mathrm{EDV} - \mathrm{ESV} \qquad \mathrm{EF} = \frac{\mathrm{SV}}{\mathrm{EDV}}$$

$$\mathrm{HR} = \frac{300}{\text{large boxes between R waves}} = \frac{1500}{\text{small boxes}}$$

From history. Einthoven's galvanometer filled two rooms and needed five people to run, and water cooling for its electromagnet. In 1905 he connected it to the Leiden hospital about a mile away by telephone wire and recorded patients' hearts from his laboratory. Laennec, a devout Catholic, died of tuberculosis in 1826, diagnosed, it is said, with his own stethoscope.

Practice habit. Every time you look at an ECG strip, measure before you judge: rate, then PR interval, then QRS width, each in boxes and then in seconds.

Career connection. EKG (ECG) technicians attach the electrodes, record tracings and run heart monitors; many train in a short certificate program and earn a national certification. Cardiovascular technologists go further, assisting with heart ultrasound (echocardiography) or catheter procedures, usually after an associate degree.

WORKED EXAMPLES

Example 1. A student's resting heart rate is 68 beats per minute and her stroke volume is 75 mL. Find her cardiac output in liters per minute.

Show solution

1. $\mathrm{CO} = 68 \times 75 = 5{,}100\ \mathrm{mL/min}$
2. 5,100 mL/min = 5.1 L/min

Answer: 5.1 L/min

Example 2. A left ventricle fills to 120 mL and empties to 50 mL. The heart rate is 72. Find the stroke volume, the ejection fraction and the cardiac output.

Show solution

1. SV = 120 − 50 = 70 mL
2. EF = 70 ÷ 120 = 0.583 = 58%
3. CO = 72 × 70 = 5,040 mL/min ≈ 5.0 L/min

Answer: SV 70 mL, EF 58% (normal), CO 5.0 L/min

Example 3. On an ECG strip the R waves are 4 large boxes apart and the PR interval is 4 small boxes. Find the heart rate and the PR interval in seconds. Is the AV delay normal?

Show solution

1. Rate = 300 ÷ 4 = 75 beats per minute (or R-to-R = 4 × 0.20 = 0.80 s; 60 ÷ 0.80 = 75)
2. PR = 4 × 0.04 s = 0.16 s

Answer: 75 bpm; PR 0.16 s, within the normal 0.12–0.20 s

PRACTICE

CONCEPT CHECKS

1. Easy Which valves close to make the first heart sound (lub), and which make the second (dub)?

   Show answer

   Lub: the AV valves (tricuspid and mitral). Dub: the semilunar valves (pulmonary and aortic).

2. Easy Why is the left ventricle's wall thicker than the right's?

   Show answer

   It pumps blood through the whole body against much higher pressure; the right side pumps only to the nearby lungs.

3. **Easy** What electrical event does each part of the ECG show: P wave, QRS complex, T wave?

Show answer

P: atria depolarize. QRS: ventricles depolarize (atrial repolarization hidden). T: ventricles repolarize.

4. **Medium** Why is the 0.1-second delay at the AV node useful?

Show answer

It lets the atria finish contracting and topping up the ventricles before the ventricles contract.

5. **Medium** A trained cyclist at rest has a heart rate of 50 and a stroke volume of 100 mL. During a hard climb her rate is 150 and her stroke volume 120 mL. Find both cardiac outputs.

Show answer

Rest 5.0 L/min; climbing 18.0 L/min

6. **Medium** A ventricle fills to 140 mL and empties to 85 mL. Find the ejection fraction. Is it normal?

Show answer

39%, below the normal 55–70%; the ventricle is pumping weakly.

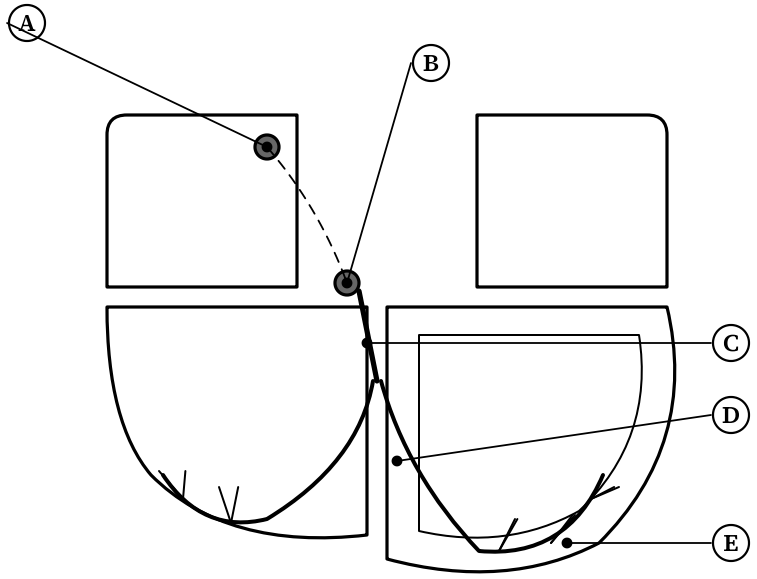
7. **Medium** R waves on an ECG are 25 small boxes apart. Find the heart rate.

Show answer

1500 ÷ 25 = 60 beats per minute

DIAGRAM AND DATA QUESTIONS

8. Medium Name the parts of the conduction system lettered A to E in the order the signal reaches them.



Show answer

A SA node; B AV node; C bundle of His; D right and left bundle branches; E Purkinje fibers.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** On one patient's ECG every P wave is followed by a normal QRS, but each PR interval is 7 small boxes. On another, the P waves march regularly but some are followed by no QRS at all. Which part of the conduction system is failing in each, and why would the second patient feel faint?

Show answer

PR = 7 × 0.04 = 0.28 s, longer than 0.20 s: the AV node is slow but still passes every beat (first-degree heart block). In the second, the AV node fails to pass some signals (a higher-degree block), so the ventricles skip beats, cardiac output falls and the brain gets too little blood; a pacemaker may be needed.

10. Hard In atrial fibrillation the atria quiver with chaotic electrical activity instead of beating. Predict what the ECG shows in place of P waves and why the pulse feels irregular.

Show answer

No clear P waves, only a wavy baseline; the AV node passes signals at random times, so the QRS complexes and the pulse are irregularly irregular.

11. Challenge A heart transplant patient's new heart has no nerve connections. At rest it beats about 100 times a minute, and during exercise its rate rises only slowly. Explain both facts.

Show answer

The SA node fires on its own at about 100 per minute; normally the vagus nerve slows it to about 70, but that nerve is cut. During exercise there are no sympathetic nerves to speed it at once; the rate rises only as adrenal hormones (epinephrine) reach it through the blood, and stroke volume rises as more blood returns (Frank–Starling).

COMMON MISTAKES

- Reading a heart diagram as if it were your own chest; it is drawn as if facing the person, so the right side is on the viewer's left.
- Saying the P wave is the atria contracting; it is the electrical signal (depolarization) that triggers contraction a moment later.
- Thinking the brain starts each heartbeat; the SA node does, and nerves only speed or slow it.
- Forgetting to convert mL to L when giving cardiac output.
- Counting small boxes but dividing into 300 (the large-box rule); use 1500 with small boxes.

> **Make it a game · Spark Relay.** Tape five paper signs on the floor in a path: SA node, AV node, bundle of His, bundle branches, Purkinje fibers. The student is the electrical impulse and must walk the path, pausing for a slow count of "one-tenth" at the AV node, while naming what each part does. Then the parent calls out an ECG wave (P, QRS, T) and the student runs to where that event is happening. Swap roles and add a "heart block" round where the AV node sign lets only every second impulse through.

> **Scripture.** “Keep thy heart with all diligence; for out of it are the issues of life.” (Proverbs 4:23, KJV)
>
> Solomon meant the inner person, but the picture fits the organ too: from the heart flow the streams that carry life to every cell, beat after beat, without our asking.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

7.3 Vessels and Blood Pressure: Hales's Glass Tube (1733) and Korotkov's Sounds (1905)

Mark up this lesson

OBJECTIVES

- Compare the structure and job of arteries, arterioles, capillaries and veins.
- Explain systolic, diastolic and mean arterial pressure and how the body keeps blood pressure steady.
- Measure blood pressure correctly with a cuff and classify readings.

> **Warm-up.** Hold one arm straight up above your head and let the other hang down for 30 seconds. Look at the backs of both hands. Which hand's veins stand out, and why might gravity matter to the blood in your veins?

WATCH

Blood Vessels, Part 1 - Form and Function: Crash Course Anatomy & Physiology #27

CrashCourse · 9:30

https://www.youtube.com/watch?v=v43ej5lCeBo

> **WHEN TO WATCH**
> After the vessel types, before blood pressure.

BACKUP VIDEO

How to Take a Blood Pressure Measurement (Systolic and Diastolic Sounds) Nursing Clinical Skill

RegisteredNurseRN · 3:03

https://www.youtube.com/watch?v=soR8THwQzBw

Before the lab, to see the cuff and stethoscope method.

KEY TERMS

tunica intima, media and externa

The three layers of a vessel wall: a smooth inner lining (endothelium), a middle layer of smooth muscle and elastic fibers, and an outer layer of connective tissue.

arteriole

A small artery whose muscular wall can narrow or widen; arterioles set most of the resistance to flow and so control blood pressure and where blood goes.

capillary

A vessel whose wall is a single layer of endothelial cells, just wide enough for red cells to pass in single file; all exchange with tissues happens here.

systolic and diastolic pressure

The highest arterial pressure, as the ventricles eject blood, and the lowest, as they relax; written systolic/diastolic, as in 120/80 mmHg.

mean arterial pressure (MAP)

The average pressure pushing blood into the tissues over a whole beat; estimated as diastolic + one-third of the pulse pressure.

pulse pressure

Systolic minus diastolic pressure.

baroreceptors

Stretch sensors in the carotid arteries and the arch of the aorta that report blood pressure to the brainstem.

Korotkoff sounds

The tapping sounds heard below a blood-pressure cuff as it deflates; the first marks systolic pressure and their disappearance marks diastolic.

CORE IDEAS

The story. In 1733 the English clergyman and scientist Stephen Hales (whose measurements of sap pressure in plants appear in Biology 8.3) tied a mare on her back, opened an artery in her neck and connected it, through a brass pipe and a goose's windpipe, to a tall glass tube. The blood rose more than eight feet up the tube and rose and fell a little with every heartbeat. It was the first measurement of blood pressure. Nobody could do that to a patient, and a practical method had to wait 160 years.

How they figured it out. In 1896 the Italian physician Scipione Riva-Rocci wrapped an inflatable cuff around the upper arm and connected it to a mercury column:

pump the cuff until the wrist pulse vanishes, and the cuff pressure equals the systolic pressure. In 1905 the Russian surgeon Nikolai Korotkov added a stethoscope below the cuff. As the cuff slowly deflates, blood first spurts through the squeezed artery with a tapping sound (systolic); when the cuff no longer narrows the artery at all, the sounds disappear (diastolic). Nurses still use his method, and automatic cuffs use the related pulsing of the cuff itself.

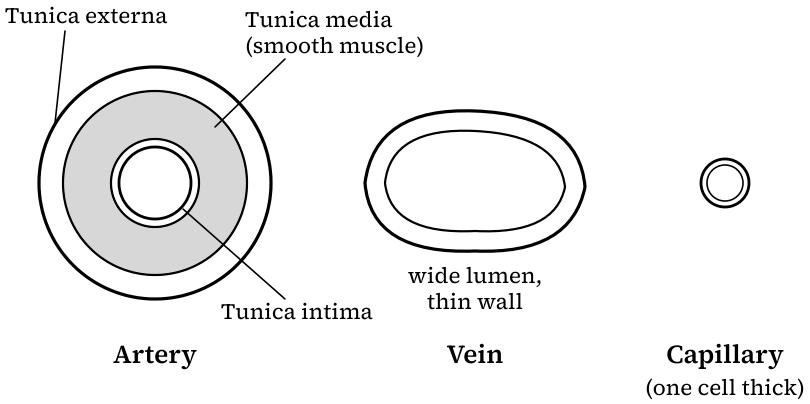
The vessels. Arteries have a thick middle layer of elastic tissue and smooth muscle; the big arteries stretch with each beat and recoil, keeping blood moving between beats. Arterioles have the most muscle for their size and act as adjustable taps. Capillaries are one cell thick and so numerous that no living cell is more than a few cell widths from one; together they have enormous cross-sectional area, so blood moves slowly through them, giving time for exchange. Veins have thin walls, wide openings and, in the limbs, one-way valves. At rest about two-thirds of the blood is in the veins, which act as a reservoir.

Getting blood back uphill. Blood pressure in the veins is low, so the return from the legs needs help. When leg muscles contract they squeeze the veins, and the valves let blood go only toward the heart (the skeletal muscle pump). Breathing helps too: each inhalation lowers pressure in the chest and draws blood up the large veins. This is why soldiers standing perfectly still for a long time can faint, and why walking around on a long flight is wise.

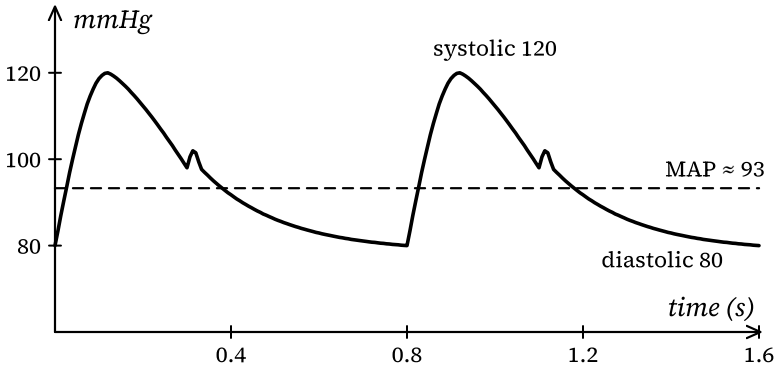
Pressure, flow and resistance. Blood flows from high to low pressure: flow $= \dfrac{\Delta P}{R}$. The biggest influence on resistance is the radius of the vessels; for steady flow in a tube, resistance varies as $1/r^4$ (Poiseuille's law), so halving an arteriole's radius raises its resistance 16 times. Mean arterial pressure is what actually drives blood into the organs; it is closer to diastolic than to systolic because the heart spends longer relaxing than ejecting: $\text{MAP} \approx \text{DBP} + \tfrac{1}{3}(\text{SBP} - \text{DBP})$.

Keeping pressure steady. If you stand up quickly, blood pools in the legs and pressure in the head drops. Within a heartbeat or two the baroreceptors in the carotid arteries and aorta sense less stretch and signal the cardiovascular center in the medulla, which sends sympathetic signals to raise the heart rate and narrow the arterioles. Pressure returns to normal: a negative-feedback loop (Lesson 1.3). Over hours and days the kidneys set the long-term pressure by adjusting how much salt and water the body keeps, with hormones such as ADH and aldosterone (Unit 9).

Where it is used. The American Heart Association classifies adult readings as normal (below 120 and below 80), elevated (120–129 and below 80), stage 1 high blood pressure (130–139 or 80–89) and stage 2 (140 or higher, or 90 or higher). Readings above 180 and/or above 120 call for prompt medical attention. High blood pressure often has no symptoms but strains the heart, kidneys and the vessels of the brain over years. One reading is never a diagnosis; doctors average several readings taken on different days.



An artery's thick muscular wall keeps its round shape; a vein's thin wall and wide lumen hold a reservoir of blood; a capillary's single cell layer allows exchange.



Arterial pressure swings between systolic (120) and diastolic (80) each beat. The dashed line is the MAP estimate, 80 + 40/3 ≈ 93 mmHg.

Safety first. Do not inflate a cuff above about 180 mmHg or leave it inflated for more than a minute; let the arm rest a minute between readings. Never use a cuff on an arm with an injury, an IV line, a dialysis access or on the side of a past breast or lymph-node surgery. This is a learning lab, not a medical test: an unusual reading goes to a parent and, if repeated, to a doctor.

LAB

Clinical Skills Lab: Measuring Blood Pressure

You will measure blood pressure the way nurses do, test how posture and exercise change it, and calculate MAP and pulse pressure.

You will need

- An upper-arm automatic blood pressure monitor (about $25–40), or a manual aneroid cuff with a stethoscope
- A chair with a back, a table, a stopwatch, a partner (a family member who agrees)

Steps

1. Have your partner sit with back supported and feet flat for 5 minutes, without talking, with the bare upper arm resting on the table at heart level.
2. Wrap the cuff snugly 2–3 cm above the bend of the elbow with the artery marker over the inner arm. Take three readings one minute apart and average them.
3. Manual cuff (with a parent's help): feel the wrist pulse, inflate until it disappears, then 20–30 mmHg more. Place the stethoscope over the inner elbow and let the pressure fall about 2–3 mmHg per second. Record the first tapping sound (systolic) and the point where the sounds stop (diastolic).
4. Have your partner stand quietly for 1 minute and measure again, standing, with the arm supported at heart level.
5. After 2 minutes of marching in place, measure once more.
6. For each average reading calculate pulse pressure and MAP, and classify it.

Check your work

- ☐ How did the pressure change on standing, and what reflex brought it back?
- ☐ Which number rose most with exercise, systolic or diastolic? Why?
- ☐ Why must the arm be at heart level?

LAB NOTEBOOK

1. Labeled cross sections of an artery, a vein and a capillary.

2. Your data table (sitting, standing, after exercise) with pulse pressure and MAP for each.

KEY FORMULAS

$$\text{MAP} \approx \text{DBP} + \tfrac{1}{3}(\text{SBP} - \text{DBP})$$

$$\text{flow} = \frac{\Delta P}{R} \qquad R \propto \frac{1}{r^4}$$

From history. Hales was a parish priest at Teddington for more than fifty years and did his experiments between his pastoral duties; he also invented ventilators that brought fresh air into ships and prisons and saved many lives. Korotkov announced his discovery in a talk of only a few paragraphs in St. Petersburg in 1905; the sounds still bear his name, often spelled Korotkoff.

Practice habit. Before calculating MAP, write the pulse pressure first; it catches subtraction errors and you will need it anyway.

WORKED EXAMPLES

Example 1. A reading is 120/80 mmHg. Find the pulse pressure and estimate the mean arterial pressure.

Show solution

1. Pulse pressure = 120 − 80 = 40 mmHg
2. MAP ≈ 80 + 40/3 = 80 + 13.3 = 93.3 mmHg

Answer: Pulse pressure 40 mmHg; MAP ≈ 93 mmHg

Example 2. A man's average reading is 138/88 mmHg. Estimate his MAP and classify the reading.

Show solution

1. MAP ≈ 88 + (138 − 88)/3 = 88 + 16.7 = 104.7 mmHg
2. Systolic 130–139 or diastolic 80–89 → stage 1 high blood pressure

Answer: MAP ≈ 105 mmHg; stage 1

Example 3. Smooth muscle narrows an arteriole to half its radius. By what factor does its resistance change? If the pressure across it stays the same, what happens to the flow through it?

Show solution

1. $R \propto 1/r^4$
2. $\frac{R_2}{R_1} = \left(\frac{1}{0.5}\right)^4 = 16$
3. Flow = ΔP/R falls to 1/16 of its former value.

Answer: Resistance rises 16 times; flow falls to 1/16 (about 6%)

PRACTICE

CONCEPT CHECKS

1. Easy Which vessels have valves, and why are they needed there?

   Show answer

   Veins (especially in the limbs); venous pressure is low, so valves keep blood from flowing backward and pooling.

2. Easy Why is a capillary wall only one cell thick?

   Show answer

   So oxygen, nutrients and wastes have the shortest possible distance to diffuse between blood and tissues.

3. Easy Classify each reading: 118/76, 126/78, 134/82, 145/92.

   Show answer

   Normal; elevated; stage 1; stage 2.

4. Medium Estimate the MAP for 110/70 mmHg and for 150/95 mmHg.

   Show answer

   83 mmHg; 113 mmHg

5. Medium Three seated readings are 122/78, 118/76 and 120/80. Find the average reading, the pulse pressure and the MAP.

   Show answer

   Average 120/78; pulse pressure 42 mmHg; MAP 92 mmHg

6. **Medium** An arteriole narrows to 80% of its original radius. By about what factor does its resistance increase?

Show answer

About 2.4 times

$(1/0.8)^4 \approx 2.44$

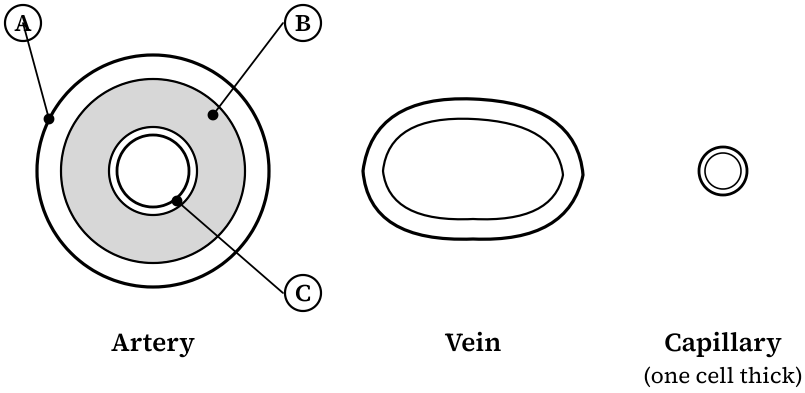
7. **Medium** Explain why the diastolic pressure in the arteries does not fall to zero between beats.

Show answer

The stretched elastic walls of the large arteries recoil during diastole, pushing blood onward, and the closed aortic valve keeps it from flowing back.

DIAGRAM AND DATA QUESTIONS

8. **Medium** Name the three layers of the artery wall lettered A to C, from outside to inside.



Show answer

A tunica externa (connective tissue); B tunica media (smooth muscle and elastic tissue); C tunica intima (endothelium).

9. Hard You stand up suddenly after lying on the floor and feel lightheaded for a second. Describe the reflex that corrects it, naming the sensor, control center and two effector responses.

Show answer

Baroreceptors in the carotid arteries and aortic arch sense lower stretch; the cardiovascular center in the medulla increases sympathetic output; the heart rate rises and arterioles constrict (and veins tighten), raising pressure.

WHEN IT GOES WRONG

10. Hard **Disorder as a broken mechanism.** In varicose veins the valves of the leg veins no longer close properly. Explain why the veins bulge and the ankles swell by the end of a day of standing.

Show answer

Without working valves the muscle pump cannot push blood upward in steps; gravity pulls blood back down, so it pools and stretches the veins. Higher pressure in the leg capillaries pushes more fluid into the tissues than can return, causing swelling (edema).

11. Challenge In atherosclerosis, fatty plaque narrows a coronary artery's opening from 3.0 mm to 1.5 mm in radius over part of its length. Why does this matter far more than "half as wide" suggests, and what happens if a clot forms on the plaque?

Show answer

Resistance in that segment rises by $(3.0/1.5)^4 = 16$ times, so flow can fall sharply, especially during exercise when the heart muscle needs more oxygen (chest pain, angina). A clot can close the narrowed opening completely, and the heart muscle beyond it starts to die: a heart attack (myocardial infarction).

COMMON MISTAKES

- Averaging systolic and diastolic to get MAP; the heart spends longer in diastole, so MAP is closer to diastolic.
- Measuring with the arm hanging down or the cuff over a sleeve; both give falsely high readings.
- Thinking veins carry blood only by heart pressure; the muscle pump, valves and breathing return most of it.

- Treating one high reading as a diagnosis; readings vary with stress, talking, caffeine and exercise.
- Forgetting the fourth power: a small change in radius makes a large change in resistance.

Make it a game · Pressure Detective. The parent reads a short scene ("Grandpa just climbed the stairs," "You stood up fast from the floor," "The arteriole to the stomach widens after lunch," "A marathon runner at rest"). The student says whether blood pressure, heart rate or local flow goes up or down, and names the sensor or vessel responsible. Two points for the direction, one for the mechanism. Then swap and let the student make up scenes.

Scripture. "A sound heart is the life of the flesh: but envy the rottenness of the bones." (Proverbs 14:30, KJV)

Steady pressure in the vessels is life to every organ, and Solomon ties the body's health to the heart's peace. Doctors today also count long-term stress among the things that strain the heart and vessels.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

7.4 The Lymphatic System and Innate Defense: Metchnikoff's Starfish (1882)

Mark up this lesson

OBJECTIVES

- Explain how lymph forms, where it flows and what lymph nodes, the spleen, the thymus and the tonsils do.
- Describe the innate defenses: barriers, phagocytes, natural killer cells, inflammation, fever and complement.
- Calculate lymph formation and absolute white-cell counts from data.

> **Warm-up.** Think of the last time you had a splinter. Around it the skin turned red, warm, swollen and sore. Is that redness a sign of damage, of your body defending you, or both?

WATCH

Lymphatic System

Amoeba Sisters · 7:41

https://www.youtube.com/watch?v=C_Bii6TfwuY

> **WHEN TO WATCH**
> After how lymph forms and flows.

BACKUP VIDEO

Immune System, Part 1: Crash Course Anatomy & Physiology #45

CrashCourse · 9:13

https://www.youtube.com/watch?v=GIJK3dwCWCw

With the innate defenses.

KEY TERMS

lymph

Tissue fluid that has entered lymphatic vessels; clear, with white cells, proteins and, from the intestine, fats.

lymph node

A small bean-shaped filter along lymphatic vessels, packed with lymphocytes and macrophages that check lymph for invaders.

thoracic duct

The largest lymphatic vessel; it collects lymph from most of the body and empties it into the left subclavian vein near the neck.

spleen

The largest lymphoid organ, in the upper left abdomen; it filters blood, removes worn-out red cells and houses lymphocytes.

innate immunity

Defenses present from birth that act within minutes to hours against any invader: barriers, phagocytes, natural killer cells, inflammation, fever and complement.

phagocyte

A cell that engulfs and digests microbes and debris; mainly neutrophils and macrophages.

inflammation

The local response to injury or infection: vessels widen and leak, bringing fluid and white cells; seen as redness, heat, swelling and pain.

natural killer (NK) cell

A lymphocyte that kills virus-infected and cancerous body cells without needing to recognize a particular antigen.

CORE IDEAS

The story. In 1882 the Russian zoologist Élie Metchnikoff was studying transparent starfish larvae in a home laboratory in Messina, Sicily, while his family was at the circus. He watched wandering cells inside the larvae and had an idea: perhaps these cells defend the body. He pushed small rose thorns into several larvae, and the next morning the thorns were surrounded by crowds of the moving cells. He named them phagocytes, "eating cells" (Greek *phagein*, to eat), and spent the rest of his life showing that our white cells do the same to bacteria.

How they figured it out. Many scientists in the 1880s thought white cells actually spread infection, since pus is full of them. Metchnikoff showed in water fleas, frogs and mammals that the cells engulf and digest microbes, and that animals whose phagocytes were overwhelmed died. Others, led by Paul Ehrlich, argued that dissolved substances in the blood (antibodies) were the main defense. Both were right; the two men shared the 1908 Nobel Prize. Their two ideas are today's cellular and humoral sides of immunity.

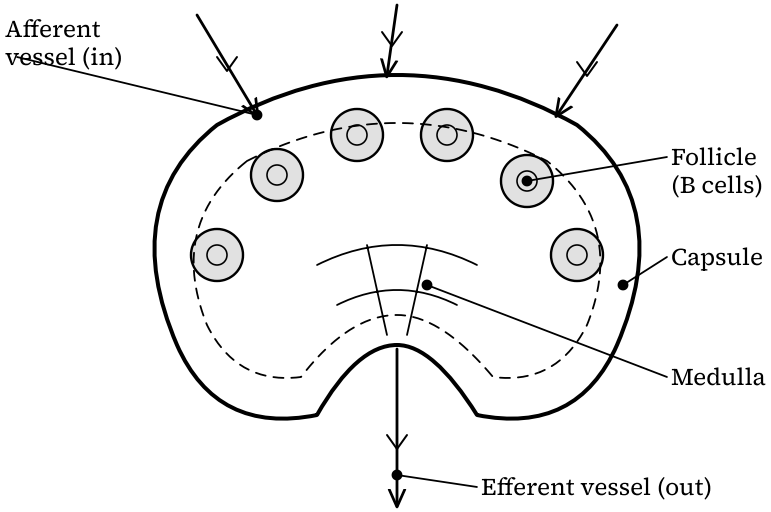
Where lymph comes from. Blood pressure pushes fluid out of the capillaries all day; most of it is drawn back in at the venous end, but not all. Of roughly 20 liters filtered each day, about 17 return directly, and about 3 liters remain in the tissues. Blind-ended lymphatic capillaries, with overlapping cells that open like one-way flaps, take up this fluid along with proteins and stray cells. Lymphatic vessels have valves like veins and are squeezed along by muscle movement and breathing. The thoracic duct and the smaller right lymphatic duct return the lymph to the blood in veins near the base of the neck. Without this return the blood would lose its volume within a day.

The lymphoid organs. Lymph passes through hundreds of lymph nodes, clustered in the neck, armpits, groin and abdomen. Inside each, macrophages trap debris and lymphocytes in round follicles inspect it for invaders; tender, swollen nodes under the jaw during a sore throat mean they are busy. The spleen filters blood the way nodes filter lymph and removes old red cells. The thymus, large in childhood and shrinking after puberty, is where T cells mature. The tonsils and patches of lymphoid tissue in the intestine guard the entrances to the body.

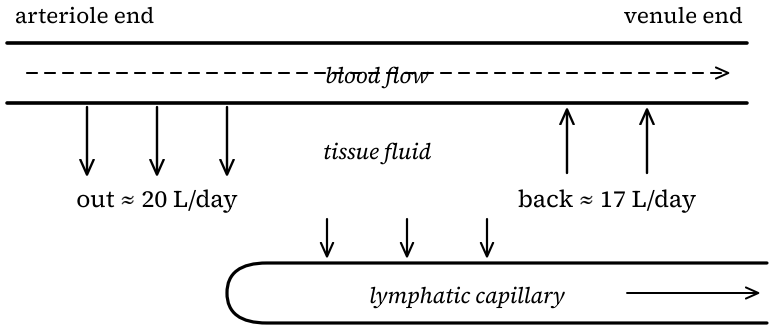
The first lines of defense. The skin is a dry, acidic, constantly shedding wall. Mucous membranes trap microbes in sticky mucus, and cilia sweep it out of the airways (Lesson 8.1). Tears and saliva contain lysozyme, an enzyme that breaks bacterial cell walls, and stomach acid kills most swallowed microbes. Behind these barriers wait phagocytes: neutrophils, the most numerous white cells, which arrive first and die in the fight (pus), and macrophages, which live long and clean up. Natural killer cells destroy infected body cells. Complement proteins in the plasma punch holes in bacteria and tag them for phagocytes, and virus-infected cells release interferons that warn their neighbors.

Inflammation and fever. Damaged cells and mast cells release histamine and other signals. Nearby arterioles widen (redness and heat), capillaries leak fluid and proteins into the tissue (swelling), and pressure and chemicals stimulate pain nerves (pain); the Roman writer Celsus listed these four signs in the first century, and loss of function was added later. The leak brings in clotting proteins that wall off the area, and white cells squeeze through the capillary walls toward the invaders. Fever is a controlled reset of the hypothalamus's set point (Lesson 1.3) that slows some microbes and speeds immune cells; a fever that climbs very high, or that comes with a stiff neck, confusion or trouble breathing, needs a doctor.

Where it is used. A complete blood count with differential reports what percent of white cells are neutrophils (about 50–70%), lymphocytes (about 20–40%), monocytes, eosinophils and basophils; a high neutrophil count suggests a bacterial infection. Surgeons check lymph nodes because cancer cells can spread through lymphatic vessels. Compression sleeves and gentle massage help patients whose lymphatic flow has been damaged.



Lymph enters a node through several afferent vessels, is filtered past macrophages and lymphocyte follicles, and leaves through one efferent vessel.



About 20 L of fluid leaves the blood capillaries each day; about 17 L returns directly and about 3 L returns as lymph.

LAB

Glitter Germs and the Barrier Test

You will model how germs spread and how the body's barriers and handwashing stop them, and see inflammation's leak with a simple model.

You will need

- Hand lotion and fine craft glitter (the "germs"), soap, a timer, a paper towel
- Two clear cups, water, food coloring, a coffee filter and a rubber band

Steps

1. Rub a pea-sized drop of lotion and a pinch of glitter on one person's hands. Shake hands with a second person, who touches a doorknob, a pencil and a third person. Count where glitter ends up.
2. Have one person rinse with water only for 5 seconds and another wash with soap for 20 seconds. Compare how much glitter remains.
3. Inflammation model: stretch a coffee filter over a cup with a rubber band (the capillary wall). Pour colored water on it slowly (normal leak), then poke three pinholes and pour again (inflamed, leaky capillary). Compare how much passes through.
4. Write which innate defense each part of the model stands for.

Check your work

- ☐ Which objects carried the most "germs"?
- ☐ How much better was soap than a quick rinse?
- ☐ In real inflammation, why is a leakier capillary helpful?

LAB NOTEBOOK

1. A labeled lymph node and a sketch of the capillary-to-lymph fluid budget with the numbers.
2. A list of the body's innate defenses, sorted into barriers, cells and chemicals.

From history. Metchnikoff was a restless, intense scientist; he worked for the last 28 years of his life at the Pasteur Institute in Paris, where Pasteur himself welcomed him. In 1908 he shared the Nobel Prize with Ehrlich, the rival whose antibodies he had long argued against.

Practice habit. When you meet a new defense, file it in one of three columns, barrier, cell or chemical, and add whether it is innate or adaptive; review the columns before each test.

WORKED EXAMPLES

Example 1. Blood capillaries filter about 20 L of fluid a day and reabsorb about 17 L. How much fluid must the lymphatic system return, and what percent of the filtered fluid is it?

Show solution

1. 20 − 17 = 3 L/day
2. 3 ÷ 20 × 100% = 15%

Answer: About 3 L/day, 15% of the filtered fluid

Example 2. A patient's white-cell count is 7,500 per µL and 60% of the white cells are neutrophils. Find the absolute neutrophil count.

Show solution

1. 7,500 × 0.60 = 4,500

Answer: 4,500 neutrophils per µL (normal)

Example 3. A child has a fever of 38.5 °C. Convert it to °F and say whether it is a fever (above about 38.0 °C, 100.4 °F).

Show solution

1. $F = \frac{9}{5}C + 32$
2. $\frac{9}{5}(38.5) + 32 = 69.3 + 32 = 101.3$

Answer: 101.3 °F, a fever

PRACTICE

CONCEPT CHECKS

1. Easy Where does lymph come from, and where does it finally go?

Show answer

From tissue fluid left behind by blood capillaries; it returns to the blood in veins at the base of the neck (through the thoracic duct and right lymphatic duct).

2. Easy Name three barriers of the first line of defense.

Show answer

Any three: skin, mucous membranes and mucus, cilia, tears and saliva with lysozyme, stomach acid.

3. Easy Give the four classic signs of inflammation and the cause of each.

Show answer

Redness and heat (widened arterioles bring more blood), swelling (leaky capillaries), pain (pressure and chemicals on nerve endings).

4. Medium Why do the lymph nodes under your jaw swell during a throat infection?

Show answer

Lymph from the throat drains to them; lymphocytes there multiply as they respond to the invaders, and the node fills with cells.

5. Medium A white-cell count is 12,000 per µL with 80% neutrophils. Find the absolute neutrophil count and suggest what kind of infection it hints at.

Show answer

9,600 per µL, high; it suggests a bacterial infection.

6. Medium In one person the lymphatics return 2.8 L of the 20 L filtered each day. What percent is that?

Show answer

14%

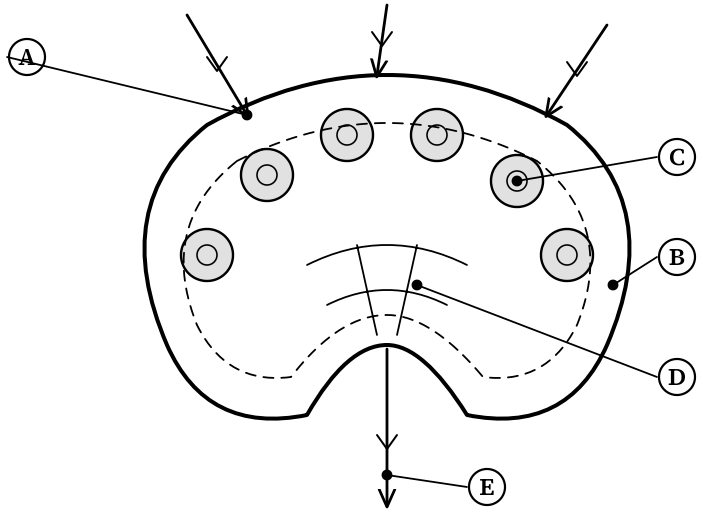
7. Medium How is a natural killer cell different from a neutrophil?

Show answer

A neutrophil engulfs microbes (phagocytosis); an NK cell kills the body's own infected or cancerous cells by inducing them to die, without engulfing them.

DIAGRAM AND DATA QUESTIONS

8. Medium Name the parts of the lymph node lettered A to E.



Show answer

A afferent lymphatic vessel; B capsule; C follicle (B-cell area); D medulla; E efferent lymphatic vessel.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** After surgery that removed many lymph nodes from one armpit, a woman's arm on that side slowly swells (lymphedema). Using the fluid budget, explain why.

Show answer

Blood capillaries keep filtering fluid into the arm's tissues, but with nodes and vessels removed the lymph cannot drain away fast enough; the 15% or so that should return as lymph builds up in the tissues, and protein left behind holds more water there.

10. Hard Why might lowering a mild fever with medicine make a person feel better without making the infection end faster? When is it right to treat it?

Show answer

Fever is a defense the hypothalamus turns on deliberately; lowering it eases discomfort but does not kill the microbes. It is right to treat it for comfort, rest and fluids, and to call a doctor when it is very high, lasts several days or comes with warning signs.

11. Challenge Some people are born with neutrophils that can engulf bacteria but cannot make the chemicals that kill them. Predict what kind of infections they suffer and why ordinary barriers are not enough.

Show answer

Repeated, unusually severe bacterial and fungal infections, with abscesses in skin, lungs and lymph nodes; microbes that get past the barriers are swallowed but survive inside the neutrophils, so the second line of defense fails.

COMMON MISTAKES

- Thinking lymph is pumped by the heart; it moves by muscle squeezing, breathing and valves.
- Calling inflammation a disease in itself; it is a defense, though it can do harm when too strong or too long.
- Mixing up innate and adaptive defenses; innate defenses do not need to have met the invader before.
- Treating every swollen lymph node as cancer; most are simply reacting to an infection nearby.

> **Make it a game · Castle Defense.** Draw a castle: walls (skin and mucous membranes), moat (stomach acid and mucus), guards on patrol (neutrophils and macrophages), watchtower alarm (histamine and inflammation), and a spy-hunter (NK cell). The parent names an invader event (“a splinter carrying bacteria,” “a cold virus in the nose,” “bacteria swallowed in spoiled food”). The student moves a token from wall to wall, naming each defense that meets it, until the invader is stopped. A round ends with the student saying what would happen if one defense were missing.

> **Scripture.** “The LORD shall preserve thee from all evil: he shall preserve thy soul.” (Psalm 121:7, KJV)
>
> Day and night, unnoticed, layers of defense guard the body. They are a small picture of a far greater keeping, and a reason to thank the God who made us.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

7.5 Adaptive Immunity and Vaccines: Von Behring's Antitoxin (1890)

Mark up this lesson

OBJECTIVES

- Explain how B cells, helper T cells and cytotoxic T cells recognize and respond to a particular antigen.
- Describe antibody structure and classes, the primary and secondary responses, and active and passive immunity.
- Explain how vaccines work, the main kinds, and their common and rare side effects; explain allergy and autoimmunity as misdirected immunity.

> **Warm-up.** Most people who have had chickenpox never get it again, but a person can catch a cold many times. What might be different about the immune system's memory in the two cases?

WATCH

Immune System

Amoeba Sisters · 8:56

https://www.youtube.com/watch?v=fSEFXl2XQpc

> **WHEN TO WATCH**
> After the B cells and T cells, before vaccines.

BACKUP VIDEO

Immune System, Part 2: Crash Course Anatomy & Physiology #46

CrashCourse · 9:44

https://www.youtube.com/watch?v=2DFN4IBZ3rI

With the humoral and cell-mediated responses.

KEY TERMS

adaptive immunity

Defense aimed at one particular antigen, carried out by lymphocytes; slower the first time but with memory, so it is faster and stronger the next time.

B cell and plasma cell

A lymphocyte that matures in the bone marrow and recognizes antigen with its surface antibody; when activated it becomes a plasma cell that releases large amounts of antibody.

helper T cell

A T cell (it matures in the thymus) that, when shown its antigen, releases signals that activate B cells and cytotoxic T cells.

cytotoxic T cell

A T cell that recognizes and kills body cells infected by viruses (or cancerous cells) that display its antigen.

antibody (immunoglobulin)

A Y-shaped protein with two identical antigen-binding sites; classes are IgG, IgM, IgA, IgE and IgD.

memory cell

A long-lived B or T cell left after a response, ready to respond quickly to the same antigen.

active and passive immunity

Active: your own body makes the antibodies and memory (after infection or vaccination). Passive: ready-made antibodies are received (through the placenta, breast milk or an injection); it works at once but fades in weeks to months.

vaccine

A preparation of a weakened or killed microbe, an inactivated toxin or a piece of a microbe, given to produce active immunity without the disease.

CORE IDEAS

The story. Diphtheria was a terror of childhood in the nineteenth century: a toxin made by bacteria in the throat formed a membrane that could choke a child and damage the heart. In 1890 Emil von Behring and Kitasato Shibasaburō, working in Robert Koch's institute in Berlin, showed that animals given small, nonlethal doses of diphtheria or tetanus toxin made something in their blood that neutralized the toxin, and that serum from such animals could protect or treat others. Diphtheria

antitoxin was used to treat children within a few years, and von Behring received the first Nobel Prize in Physiology or Medicine in 1901.

How they figured it out. The protective "antitoxin" was later identified as antibody. Jenner's cowpox vaccine (1796) and Pasteur's rabies vaccine (1885), told in Biology 8.1, had shown that the body can be trained ahead of time; von Behring showed that the trained defense lives in the blood and can be transferred. In the 1950s Frank Macfarlane Burnet proposed clonal selection: each lymphocyte is made with one antigen receptor, and an invader "selects" the few that fit, which then multiply. The idea has been confirmed again and again and explains why the response takes days and why it leaves memory.

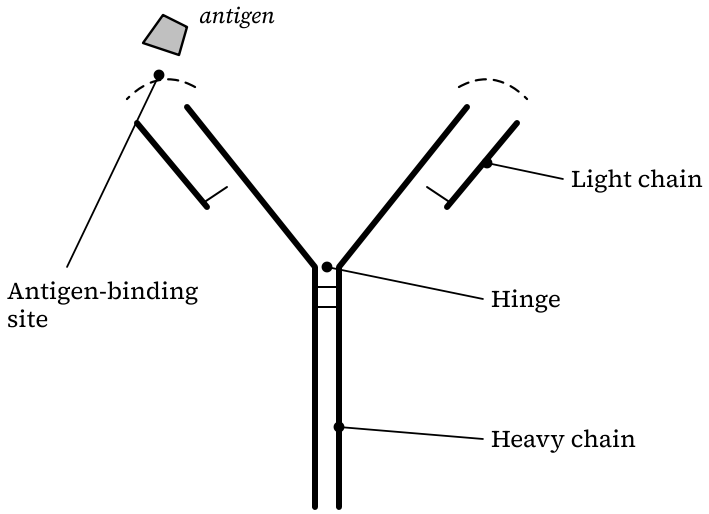
Antibodies and B cells. An antibody is a Y-shaped protein of two heavy and two light chains; the tips of the two arms are its antigen-binding sites. Antibodies do not kill directly. They neutralize toxins and viruses by covering the parts that attach to cells, clump microbes together, activate complement and tag invaders for phagocytes. IgG is the most common antibody in blood and the only one that crosses the placenta; IgM is a five-unit molecule made first in a new response; IgA guards tears, saliva, mucus and breast milk; IgE is involved in allergies and defense against worms; IgD sits on B-cell surfaces.

T cells and teamwork. T cells cannot see free antigen. They recognize fragments of antigen displayed on the surface of other cells. A macrophage or dendritic cell that has eaten an invader displays its pieces to helper T cells; the helper T cell that fits is activated, multiplies and releases signals that switch on the matching B cells and cytotoxic T cells. Cytotoxic T cells then find infected body cells displaying the same fragments and kill them before the virus inside can multiply. Because helper T cells coordinate both branches, losing them (as in untreated HIV infection) cripples the whole adaptive response.

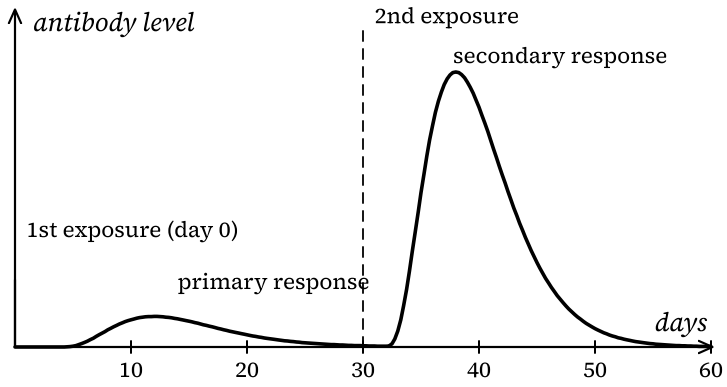
Primary and secondary responses. The first time an antigen appears, few cells fit it; it takes several days to activate and multiply them, and antibody levels peak about one to two weeks later. Meanwhile the person may be sick. Memory B and T cells remain for years, often for life. On a second exposure they respond within a day or two with far more antibody, mostly IgG, often clearing the invader before symptoms start. Some viruses, such as those causing colds and influenza, change their surface antigens often, so old memory may not fit the new strain.

Vaccines. A vaccine gives the primary response without the disease, so that a real exposure meets a secondary response. Kinds include live weakened (attenuated) vaccines such as measles–mumps–rubella; inactivated (killed) vaccines such as the Salk polio vaccine; toxoids, inactivated toxins, for tetanus and diphtheria; and subunit vaccines that contain only a piece of the microbe, such as the hepatitis B vaccine. Some need several doses or boosters to build strong memory. Like every medicine, vaccines have side effects: most commonly a sore arm, mild fever or tiredness for a day or two; serious reactions such as severe allergy are rare, and clinics keep epinephrine on hand for them. Families make vaccination decisions with their own doctor, weighing the risks of each disease against the risks of the vaccine.

When defense misfires. In an allergy the immune system treats a harmless substance, such as pollen, peanut protein or bee venom, as a threat. The first exposure produces IgE that coats mast cells; on later exposure the allergen binds this IgE and the mast cells release histamine within minutes. Anaphylaxis, the whole-body form, can close the airway and drop the blood pressure; it is treated at once with injected epinephrine. In autoimmune diseases the adaptive system attacks the body's own tissue: in type 1 diabetes T cells destroy the insulin-making cells of the pancreas (Lesson 6.4), and in celiac disease gluten triggers an attack on the lining of the small intestine.



An antibody: two heavy and two light chains joined into a Y. Each arm tip is an identical antigen-binding site.



The primary response is slow and small. A second exposure to the same antigen brings a fast, much larger secondary response from memory cells.

LAB

Titer by Serial Dilution

Doctors measure how much antibody a person has (the titer) by diluting serum step by step until it no longer reacts. You will model the method with food coloring.

You will need

- Eight clear cups or test tubes, a measuring spoon or syringe (no needle), water, dark food coloring
- A white card, a marker, a partner

Steps

1. The parent secretly prepares two “sera”: patient P (2 drops of coloring in 20 mL water) and patient S (8 drops in 20 mL water).
2. Label tubes 1:10, 1:20, 1:40, 1:80, 1:160, 1:320, 1:640, 1:1280. Put 9 mL of water in the first tube and 5 mL in each of the others.
3. Add 1 mL of patient P’s serum to the first tube and mix (1:10). Move 5 mL from it into the second tube and mix (1:20), then 5 mL from the second into the third, and so on down the row; each step halves the concentration.
4. Hold each tube against the white card. The last tube with color you can clearly see is the titer.
5. Repeat for patient S and compare. Which patient had the “secondary response”?

Check your work

- ☐ How many times stronger was S than P?
- ☐ Why do labs dilute in steps of two instead of guessing?
- ☐ Why might a doctor test a titer before giving a booster?

LAB NOTEBOOK

1. A labeled antibody and a sketch of the primary and secondary response curves.
2. A flow chart: antigen → presenting cell → helper T → B cell (plasma cells, antibodies) and cytotoxic T cell.

From history. Kitasato returned to Japan and founded his own institute for infectious diseases; he also identified the plague bacterium in Hong Kong in 1894, at almost the same time as Alexandre Yersin. Von Behring was called the "savior of children" in Germany, where diphtheria had killed tens of thousands of children every year.

Practice habit. When you study immunity, draw the chain of cells every time (presenting cell → helper T → B cell or cytotoxic T) before answering; most errors come from skipping the helper T step.

WORKED EXAMPLES

Example 1. A serum is diluted in twofold steps starting at 1:10. Antibody is detected in the tubes up to 1:320 but not at 1:640. What is the titer, and how many dilution steps were positive?

Show solution

1. Tubes: 1:10, 1:20, 1:40, 1:80, 1:160, 1:320, 1:640
2. The last positive tube is 1:320; that is 6 positive tubes.

Answer: Titer 1:320 (6 positive steps)

Example 2. A child's titer was 1:40 after a first dose of a vaccine and 1:1280 after the booster. How many times higher is the second titer, and how many more twofold steps is that?

Show solution

1. 1280 ÷ 40 = 32
2. $32 = 2^5$
3. 5 more twofold steps

Answer: 32 times higher; 5 more steps

Example 3. IgG antibody from a mother protects her newborn, but its level halves about every 21 days. If the baby starts with 800 units, how much is left after 63 days?

Show solution

1. $63 \div 21 = 3$ half-lives
2. $800 \times \left(\frac{1}{2}\right)^3 = 100$

Answer: 100 units (passive immunity fades)

PRACTICE

CONCEPT CHECKS

1. Easy Where do B cells and T cells mature?

   Show answer

   B cells in the bone marrow; T cells in the thymus.

2. Easy Name four ways antibodies help get rid of an invader.

   Show answer

   Neutralizing toxins and viruses, clumping microbes, activating complement, and tagging microbes for phagocytes.

3. Easy Classify each as active or passive immunity: recovering from chickenpox; antibodies in breast milk; a tetanus shot; antivenom after a snakebite.

   Show answer

   Active (natural); passive (natural); active (artificial); passive (artificial).

4. Medium Why is the secondary response faster and larger than the primary?

   Show answer

   Memory B and T cells specific for the antigen already exist in large numbers, so no time is lost finding and multiplying the rare matching cells.

5. Medium How many antigen-binding sites are on 1,000 IgM molecules (five units each) compared with 1,000 IgG molecules?

   Show answer

   10,000 compared with 2,000.

6. **Medium** A newborn has 1,200 units of maternal IgG with a half-life of 21 days. How much remains after 42 days?

Show answer

300 units

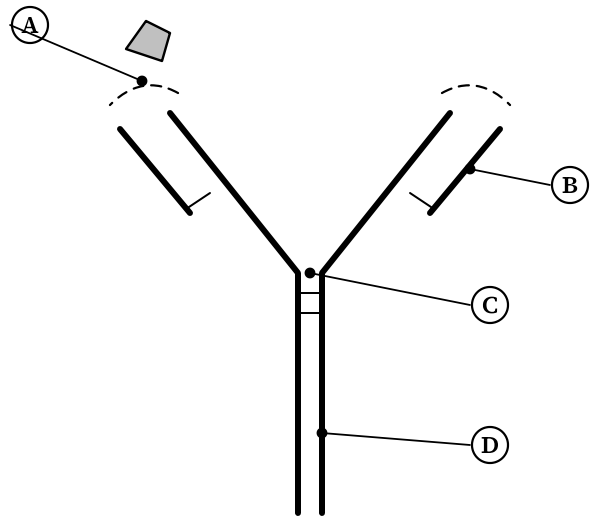
7. **Medium** Why do people need a new influenza vaccine more often than a measles vaccine?

Show answer

Influenza viruses change their surface antigens from year to year, so old memory cells may no longer fit; the measles virus's antigens stay much the same, so memory lasts.

DIAGRAM AND DATA QUESTIONS

8. **Medium** Name the parts of the antibody lettered A to D.



Show answer

A antigen-binding site; B light chain; C hinge; D heavy chain.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** A boy with a peanut allergy eats a cookie with peanut in it. Within minutes he has hives, a swelling throat and low blood pressure. Explain each step from his first, earlier exposure to this reaction, and why epinephrine is the first treatment.

Show answer

At an earlier exposure his B cells made IgE against peanut protein, which coated his mast cells. Now the protein binds that IgE and the mast cells release histamine everywhere: vessels widen and leak (hives, swelling, low pressure) and airway muscles tighten. Epinephrine narrows the vessels, raises blood pressure and opens the airways within minutes.

10. Hard Why would a disease that destroys helper T cells weaken both antibody production and the killing of virus-infected cells?

Show answer

Helper T cells release the signals that activate both B cells (which make antibodies) and cytotoxic T cells; without them neither branch is properly switched on.

11. Challenge A live attenuated vaccine usually gives long-lasting immunity from one or two doses, while many inactivated vaccines need boosters. Suggest a reason, and one kind of patient for whom a live vaccine may not be advised.

Show answer

Live weakened microbes multiply a little in the body, so the immune system sees more antigen for longer, in the way a real infection presents it, including activating cytotoxic T cells; killed vaccines give a single, smaller dose of antigen. Someone with a seriously weakened immune system (for example, during cancer chemotherapy) may not be advised to receive a live vaccine, because even the weakened microbe could cause illness; the decision is made by the patient's doctor.

COMMON MISTAKES

- Saying antibodies kill microbes; they mark and neutralize them, and other cells and complement do the killing.
- Confusing antigen (the thing recognized) with antibody (the protein that recognizes it).

- Thinking T cells bind free antigen the way B cells do; T cells see antigen fragments displayed on cells.
- Calling a newborn's maternal antibodies active immunity; they are passive and fade within months.
- Thinking every vaccine gives lifelong protection after one dose; some need boosters.

Make it a game · Lock and Key Lineup. Cut 12 paper "keys" with different notch patterns (lymphocytes) and 3 paper "locks" (antigens). The parent shows a lock; the student finds the one key that fits, then makes 5 photocopy-style copies of it by tracing (clonal expansion) and sets 2 aside as "memory." Next round the parent shows the same lock again: the student must answer in under 5 seconds using a memory key. Score how much faster round two is.

Scripture. "Bless the LORD, O my soul, and forget not all his benefits." (Psalm 103:2, KJV)

Memory cells may remember an enemy for a lifetime. The psalmist asks us to remember something better: every benefit God has given.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

UNIT 7

Blood, Heart and Defense

This unit follows the blood: what it is made of and how it is matched for transfusion, the heart that pumps it and the electrical system that times every beat, the vessels and pressure that drive it into every tissue, and the defenses it carries. The history runs from Harvey's circulation (Biology 10.2) through Laennec's stethoscope (1816), Landsteiner's blood groups (1901), Einthoven's ECG (1903) and Korotkov's blood-pressure sounds (1905) to Metchnikoff's phagocytes and von Behring's antitoxin.

The unit has the course's main clinical-skills lab: measuring blood pressure with a home cuff (Lesson 7.3). It also uses a stethoscope or cardboard tube, a simulated blood-typing kit or a homemade substitute, food coloring and simple household materials. No real blood is handled. Lessons 7.4 and 7.5 build on bacteria, viruses and vaccines in Biology 8.1; the vaccine lesson is factual and leaves health decisions to each family and its doctor.

PREREQUISITES

- Unit 1 (homeostasis and feedback loops) and Unit 2 (cells and tissues)
- Biology 10.2 (Harvey and the path of blood through the heart)
- Biology 5.3 (inheritance of ABO blood types) and 8.1 (bacteria, viruses and vaccines)

MASTERY CHECKLIST

- ☐ I can describe the parts of blood, calculate a hematocrit, explain clotting, and decide which donor red cells are safe for any ABO and Rh type.
- ☐ I can trace blood through the heart, explain the heart sounds and the conduction system, read rate and intervals from an ECG, and calculate cardiac output and ejection fraction.
- ☐ I can compare the vessels, measure blood pressure correctly, calculate MAP and pulse pressure, classify readings and explain the baroreceptor reflex.
- ☐ I can explain how lymph forms and returns, what the lymphoid organs do, and how barriers, phagocytes, inflammation and fever defend the body.
- ☐ I can explain B cells, T cells, antibodies, primary and secondary responses, active and passive immunity, how vaccines work, and allergy and autoimmunity as misdirected defense.

LESSONS IN THIS UNIT

7.1 Blood and Blood Typing: Landsteiner's Three Groups (1901)

4 sessions of 45 minutes

7.2 The Heart and Its Electrical System: Laennec's Stethoscope (1816) and Einthoven's ECG (1903)

4 sessions of 45 minutes

7.3 Vessels and Blood Pressure: Hales's Glass Tube (1733) and Korotkov's Sounds (1905)

4 sessions of 45 minutes

7.4 The Lymphatic System and Innate Defense: Metchnikoff's Starfish (1882)

3 sessions of 45 minutes

7.5 Adaptive Immunity and Vaccines: Von Behring's Antitoxin (1890)

3 sessions of 45 minutes

Unit 7 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **6 pts** **Lesson 7.1**
   Name the three layers of a spun blood sample from top to bottom, and give the job of red cells, white cells and platelets.

2. **7 pts** **Lesson 7.1**
   A spun sample is 50 mm tall with 21 mm of red cells. Find the hematocrit and say whether it is normal for a man (42–52%).

3. **8 pts** **Lesson 7.1**
   A patient is type AB-negative. Which donor types of red cells are safe? Which donor types of plasma are safe?

4. **7 pts** **Lesson 7.2**
   Put these in order of the electrical signal: AV node, Purkinje fibers, SA node, bundle branches, bundle of His. Which one sets the heart rate?

5. **8 pts** **Lesson 7.2**
   A ventricle fills to 130 mL and empties to 60 mL; the heart rate is 72. Find stroke volume, ejection fraction and cardiac output.

6. **7 pts** **Lesson 7.2**

   On an ECG strip, R waves are 3 large boxes apart and the PR interval is 4 small boxes. Find the heart rate and PR interval. Is either abnormal?

7. **7 pts** **Lesson 7.3**

   A reading is 150/95 mmHg. Find the pulse pressure and MAP, and classify the reading.

8. **7 pts** **Lesson 7.3**

   Explain why halving an arteriole's radius has such a large effect on flow.

9. **8 pts** **Lesson 7.3**

   List four things a person must do for an accurate blood-pressure reading.

10. **6 pts** **Lesson 7.4**

    Blood capillaries filter 20 L/day and reabsorb 17 L/day. How much lymph forms, and what happens if the lymphatic vessels of a limb are blocked?

11. **7 pts** **Lesson 7.4**

    Describe the sequence of events in inflammation after a splinter carries bacteria into the skin.

12. **7 pts** **Lesson 7.5**

    Compare the primary and secondary immune responses in speed, size and main antibody class, and explain why they differ.

13. **7 pts** **Lesson 7.5**

    Explain how a toxoid vaccine for tetanus protects a person, and why it is classed as active immunity.

SHORT ESSAY

14. **8 pts** **Lesson 7.1–7.5**

    Choose one: (a) hemophilia, (b) heart block, (c) varicose veins, (d) anaphylaxis. Explain it as a broken mechanism: what the normal mechanism is, which part fails, and how the symptoms follow.

ANSWER KEY

1. Plasma (top), buffy coat of white cells and platelets, packed red cells. Red cells carry oxygen (hemoglobin); white cells fight infection; platelets begin clotting.
2. 42.0%, at the low end of normal
3. Red cells: AB−, A−, B−, O− (any ABO type, Rh-negative). Plasma: AB only, because only AB plasma lacks both anti-A and anti-B.
4. SA node, AV node, bundle of His, bundle branches, Purkinje fibers. The SA node sets the rate.
5. SV 70 mL; EF 54%; CO 5,040 mL/min ≈ 5.0 L/min
6. 100 beats per minute (300 ÷ 3), at the upper limit of normal resting rate; PR 0.16 s, normal.
7. Pulse pressure 55 mmHg; MAP ≈ 95 + 55/3 ≈ 113 mmHg; stage 2 high blood pressure.
8. Resistance varies as $1/r^4$, so halving the radius multiplies resistance by 16; at the same pressure, flow falls to 1/16.
9. Any four: sit with back supported and feet flat for 5 minutes; arm bare, supported at heart level; correct cuff size and position; no talking; no caffeine or exercise just before; average two or three readings a minute apart.
10. 3 L/day. Fluid builds up in the limb's tissues (lymphedema).
11. Damaged cells and mast cells release histamine; arterioles widen (redness, heat); capillaries leak fluid (swelling); pain nerves fire; neutrophils and then macrophages leave the capillaries and engulf the bacteria; clotting proteins wall off the area.
12. Primary: slower (peak about 1–2 weeks), smaller, first mostly IgM. Secondary: within a day or two, much larger, mostly IgG. Memory cells already exist in large numbers the second time.
13. An inactivated tetanus toxin cannot cause disease but has the same antigens; the person's own B cells make antibodies and memory cells against it, so a real toxin is neutralized quickly. The body made its own antibodies, so it is active (artificial) immunity.
14. Look for: a correct normal mechanism (clotting cascade; AV conduction; venous valves and muscle pump; IgE and mast cells), the specific failing part, and a clear chain from that failure to the symptoms.

UNIT 8

Respiration

This unit follows a breath from the nose to the mitochondria. Students trace the airway to the alveoli, explain breathing with Boyle's law from Chemistry, follow oxygen and carbon dioxide across the respiratory membrane and through the blood, and learn how the brainstem keeps the whole system in balance. The history runs from Boyle's J-tube (1662) and Laennec's chest sounds (1819) to Hutchinson's spirometer (1846), Bohr and Krogh's blood-gas measurements and Haldane's discovery that carbon dioxide drives breathing (1905).

Labs are simple and safe: measuring breathing rate and tidal volume with a bottle, a homemade bell-jar lung, a balloon estimate of vital capacity, a pulse oximeter, and bromothymol blue to show the carbon dioxide in breath. No lab involves breath-holding or hyperventilating, and Lesson 8.4 explains why those are dangerous. The unit connects to cellular respiration in Biology 4.3, to the gas laws in Chemistry 7.1 and 7.4, and to blood, hemoglobin and the heart in Unit 7.

PREREQUISITES

- Unit 7 (blood, hemoglobin and cardiac output)
- Chemistry 7.1 and 7.4 (Boyle's law and Dalton's partial pressures)
- Biology 4.3 (cellular respiration: why cells need oxygen and make carbon dioxide)

MASTERY CHECKLIST

- ☐ I can trace air from the nose to the alveoli, explain the job of each structure, and calculate minute and alveolar ventilation.
- ☐ I can explain inhaling and exhaling with Boyle's law, name the muscles involved, and read and calculate lung volumes and the FEV_1/FVC ratio.
- ☐ I can use partial pressures to predict gas diffusion, read the oxygen–hemoglobin curve, explain the Bohr effect, and calculate oxygen content and delivery.
- ☐ I can describe the breathing-control loop, explain the body's response to altitude, and explain how smoking damages the lungs.

LESSONS IN THIS UNIT

8.1 The Airway and Lungs: Laennec Listens to the Chest (1819)

3 sessions of 45 minutes

8.2 How Breathing Works: Boyle's Law (1662) and Hutchinson's Spirometer (1846)

4 sessions of 45 minutes

8.3 Gas Exchange and Transport: Dalton's Partial Pressures and Bohr's Shift (1904)

3 sessions of 45 minutes

8.4 Control of Breathing, Altitude and Smoking: Haldane's Carbon Dioxide (1905) and Paul Bert's Mountains

3 sessions of 45 minutes

Unit 8 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. (7 pts) **Lesson 8.1**

   List the conducting-zone structures in order and give one job of the nose, the epiglottis and the cilia.

2. (8 pts) **Lesson 8.1**

   A person breathes 15 times a minute with a tidal volume of 400 mL and 150 mL of dead space. Find the minute ventilation and alveolar ventilation.

3. (8 pts) **Lesson 8.1**

   Explain how surfactant and the thinness of the respiratory membrane each help gas exchange.

4. (9 pts) **Lesson 8.2**

   Explain one quiet inhalation and exhalation in terms of muscles, volume, pressure and air flow.

5. **8 pts** **Lesson 8.2**

   Lungs holding 2.5 L at 760 mmHg are squeezed to 2.45 L before any air leaves. Find the new pressure and the direction of air flow.

6. **8 pts** **Lesson 8.2**

   A spirogram shows TV 500 mL, IRV 2,800 mL, ERV 1,200 mL and RV 1,300 mL. Find VC and TLC. If the FEV_1 is 2.4 L and FVC equals the VC, find the FEV_1/FVC ratio and interpret it.

7. **8 pts** **Lesson 8.3**

   Air is 21% oxygen. Find $P(O_2)$ in the airways at sea level (760 mmHg, minus 47 mmHg water vapor), and explain why oxygen moves from alveolus to blood.

8. **9 pts** **Lesson 8.3**

   Blood has 14 g/dL hemoglobin, 97% saturation and $P(O_2)$ 100 mmHg. Find the oxygen content, and the oxygen delivered per minute at a cardiac output of 5.0 L/min (50 dL/min).

9. **8 pts** **Lesson 8.3**

   Describe the Bohr effect and explain why it is useful during exercise.

10. **7 pts** **Lesson 8.4**

    Draw or describe the breathing-control loop, naming the stimulus, sensors, control center, effectors and response.

11. **8 pts** **Lesson 8.4**

    A town is at 2,400 m where air pressure is about 570 mmHg. Find the humidified $P(O_2)$ in the airways, and describe two ways the body adjusts over the first weeks.

SHORT ESSAY

12. **12 pts** **Lesson 8.1–8.4**

    Choose one: (a) pneumothorax, (b) carbon monoxide poisoning, (c) emphysema, (d) shallow-water blackout. Explain it as a broken mechanism: the normal mechanism, the part that fails, and how the symptoms follow.

ANSWER KEY

1. Nasal cavity, pharynx, larynx, trachea, bronchi, bronchioles (to terminal bronchioles). Nose: warms, moistens and filters air. Epiglottis: covers the larynx in swallowing. Cilia: sweep mucus up to the throat.
2. 6.0 L/min; 3.75 L/min
3. Surfactant lowers surface tension so alveoli stay open and are easy to inflate; a membrane about half a micrometer thick gives gases a very short distance to diffuse.
4. Inhale: diaphragm and external intercostals contract, chest volume rises, intrapulmonary pressure falls below atmospheric (Boyle's law), air flows in. Exhale: muscles relax, lungs recoil, volume falls, pressure rises above atmospheric, air flows out.
5. About 776 mmHg; above atmospheric, so air flows out.
6. VC 4,500 mL; TLC 5,800 mL; ratio 2.4/4.5 ≈ 53%, an obstructive pattern.
7. 0.21 × 713 ≈ 150 mmHg in the airways (alveolar air about 104); blood arrives at about 40 mmHg, so O_2 diffuses down its partial-pressure gradient into the blood.
8. 1.34 × 14 × 0.97 + 0.3 ≈ 18.2 + 0.3 = 18.5 mL/dL; 18.5 × 50 ≈ 925 mL O_2/min
9. More CO_2, acid and heat lower hemoglobin's affinity for oxygen, shifting the curve right; working muscles produce all three, so hemoglobin releases more oxygen exactly where it is needed.
10. Rising CO_2/falling pH → central (medulla) and peripheral (carotid and aortic bodies) chemoreceptors → respiratory centers in medulla and pons → phrenic and intercostal nerves to diaphragm and rib muscles → faster, deeper breathing lowers CO_2 (negative feedback).
11. 0.21 × (570 − 47) ≈ 110 mmHg. Faster, deeper breathing; kidney erythropoietin raises red-cell production and hematocrit (also more of the chemical that helps red cells release oxygen).
12. Look for: the correct normal mechanism (pleural seal and pressure; hemoglobin oxygen binding; alveolar surface area and recoil; the CO_2-driven urge to breathe), the specific failure, and a clear chain from failure to symptoms, with correct use of pressures or the control loop.

8.1 The Airway and Lungs: Laennec Listens to the Chest (1819)

Mark up this lesson

OBJECTIVES

- Trace air from the nose to the alveoli and give the job of each part of the conducting and respiratory zones.
- Describe the alveolus, the respiratory membrane, surfactant and the pleura.
- Calculate minute ventilation and alveolar ventilation and explain dead space.

> **Warm-up.** Breathe in through your nose on a cold morning (or imagine it), then breathe out onto a mirror. The air going out is warm and damp. Where did it get its warmth and water, and why might your lungs need air that way?

WATCH

Respiratory System, Part 1: Crash Course Anatomy & Physiology #31

CrashCourse · 9:22

https://www.youtube.com/watch?v=bHZsvBdUC2I

> **WHEN TO WATCH**
> After the path of air, before the alveoli.

BACKUP VIDEO

Respiratory System

Amoeba Sisters · 7:35

https://www.youtube.com/watch?v=v_j-LD2YEqg

As an overview of the whole lesson.

KEY TERMS

conducting zone

The airways that carry, clean, warm and moisten air but do not exchange gas: nose, pharynx, larynx, trachea, bronchi and bronchioles down to the terminal bronchioles.

respiratory zone

Where gas exchange happens: respiratory bronchioles, alveolar ducts and alveoli.

larynx and epiglottis

The voice box, framed by cartilage and holding the vocal folds; the epiglottis is a flap that tips over its opening during swallowing.

trachea

The windpipe, held open by 16–20 C-shaped rings of cartilage whose open backs face the esophagus.

alveolus

One of hundreds of millions of tiny air sacs at the ends of the airways, walled by thin type I cells and wrapped in capillaries.

surfactant

A soapy mix of lipids and proteins made by type II alveolar cells; it lowers surface tension so alveoli do not collapse.

pleura

The double membrane around each lung; a thin film of fluid between its layers lets the lungs glide and holds them to the chest wall.

anatomical dead space

The air in the conducting zone at the end of a breath, about 150 mL in an adult, which never reaches the alveoli.

CORE IDEAS

The story. Three years after he rolled his first paper stethoscope (Lesson 7.2), René Laennec published *De l'Auscultation Médiate* (1819), most of it about the lungs. Listening at the bedside and then examining the lungs of patients who died, he matched sounds to disease: crackles to fluid in the air sacs, wheezes to narrowed airways, and a lack of breath sounds to air or fluid around the lung. He was the first to describe several diseases from their sounds, and gave names to many of them that are still used.

How they figured it out. Laennec's method was careful comparison: hundreds of patients listened to while living, the same patients' lungs examined after death, and the sound linked to the structure. The same habit, matching function to structure, runs through all of anatomy. In the airway, every structure along the path does a job you can predict from its shape.

The upper airway. Air enters the nose, where hairs catch large particles and curled shelves of bone (the conchae) make the air tumble over a warm, moist, mucus-covered lining that warms, moistens and filters it. The pharynx (throat) is shared with food. At the larynx the paths divide: during swallowing the larynx rises and the

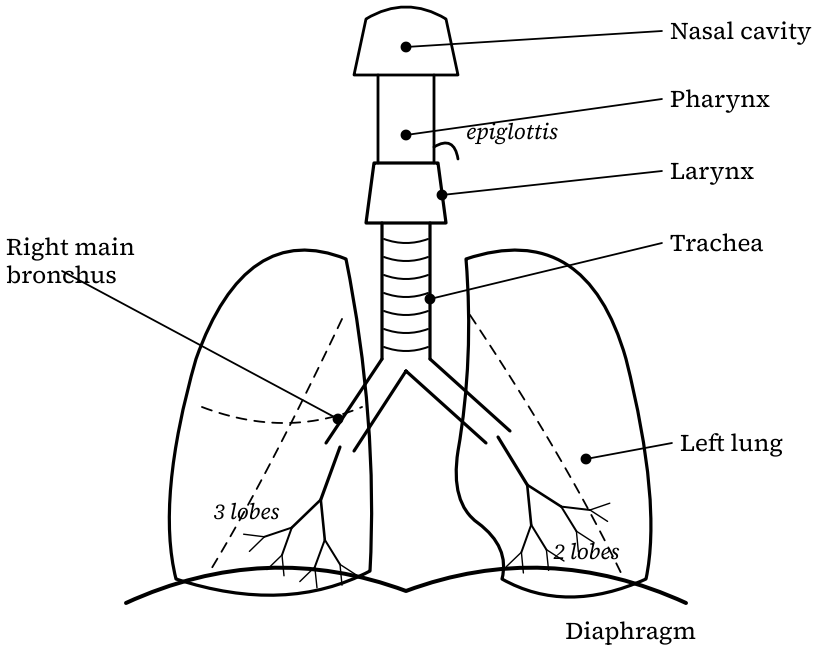
epiglottis tips over its opening so food goes to the esophagus behind. The larynx holds the vocal folds, whose vibration makes the voice; its largest cartilage is the thyroid cartilage, the "Adam's apple."

The branching tree. The trachea, about 10–12 cm long, is held open by C-shaped cartilage rings, open at the back so the esophagus can bulge forward during swallowing. It divides into the right and left main bronchi; the right one is wider, shorter and more vertical, so an inhaled peanut or bead usually lodges on the right. The bronchi branch about 23 times into smaller bronchi and bronchioles. Bronchioles have no cartilage but a ring of smooth muscle that can narrow them, as in asthma. The lining is covered in cilia and mucus-secreting cells: the mucus traps dust and microbes and the cilia beat it upward to the throat, the mucociliary escalator, where it is swallowed.

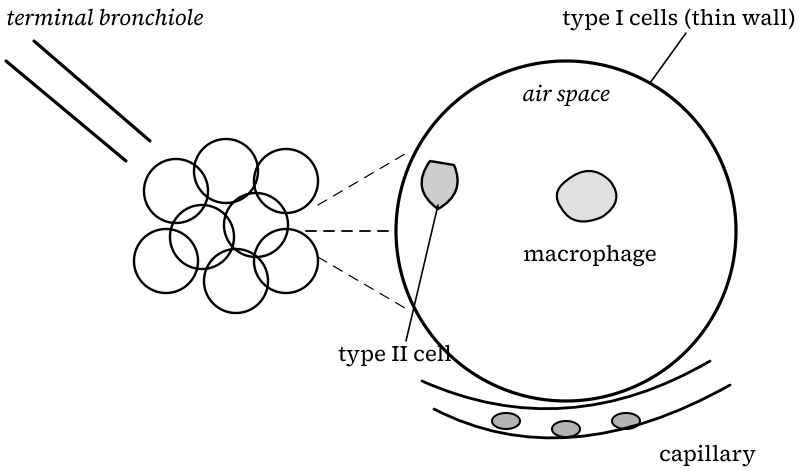
The alveoli. At the end of the tree are clusters of alveoli, roughly 300–500 million in an adult lung, with a total surface usually given as 50–75 square meters, about the floor of a classroom. Their walls are mostly flat type I cells; between the air and the blood are only that cell, a shared basement membrane and the capillary's cell, a respiratory membrane about half a micrometer thick. Rounder type II cells make surfactant, which keeps the wet inner surface from pulling the tiny sacs shut. Alveolar macrophages wander the surfaces eating dust and bacteria.

Lungs and pleura. The right lung has three lobes; the left has two and a notch for the heart. Each lung is wrapped in the pleura: an inner layer stuck to the lung and an outer layer lining the chest wall, with a thin film of fluid between. The fluid lets the lungs slide smoothly and, like a wet glass on a table, holds the lung against the chest wall so it follows the chest when it expands (Lesson 8.2).

Where it is used. Doctors listen to the lungs at every physical exam, front and back, comparing sides. A chest X-ray shows the lobes and any fluid or collapse. The Heimlich maneuver, abdominal thrusts first described by Henry Heimlich in 1974, uses a sudden push of air from the lungs to pop out food that has blocked the larynx or trachea; learn it in a first-aid course.



The conducting zone runs from the nasal cavity to the smallest bronchioles. The right main bronchus is steeper than the left, and the right lung has three lobes, the left two.



Alveoli cluster at the end of each terminal bronchiole. Thin type I cells, surfactant-making type II cells and macrophages line them, and capillaries press against their walls.

> **Safety first.** Do not share mouthpieces. Stop the long-tube breathing at once if you feel dizzy or out of breath. Never breathe through a tube under water.

LAB

Measuring Breaths and Dead Space

You will measure breathing rate and estimate tidal volume, then see why shallow breathing wastes air.

You will need

- A stopwatch, a 2-liter plastic bottle, a measuring cup, a basin, a 60 cm length of clean flexible tubing (aquarium tubing, about $5), a marker
- A drinking straw for each person and a 1-meter length of garden hose or wide tubing (optional)

Steps

1. Count a partner's breaths for 1 minute while they read quietly, without them knowing you are counting. Record the rate.
2. Calibrate the bottle: pour in water 250 mL at a time and mark each level. Fill the bottle completely, cover the mouth, and turn it upside down in a basin of water.
3. Slip one end of the tubing into the bottle. Have your partner breathe in normally, then breathe out normally (not forcefully) through the tubing. Read how much water was pushed out: the tidal volume. Repeat three times. Use a fresh tube end for each person.
4. Calculate minute ventilation (tidal volume × rate) and alveolar ventilation, using 150 mL of dead space.
5. Dead-space demonstration: breathe for 30 seconds through a long tube. Notice that you must breathe deeper, because the tube adds dead space.

Check your work

- ☐ How did your measured tidal volume compare with the typical 500 mL?
- ☐ Why did breathing through a long tube feel like hard work?
- ☐ Which number matters more for gas exchange, minute ventilation or alveolar ventilation?

LAB NOTEBOOK

1. A labeled drawing of the airway from nose to alveoli, conducting zone in one color and respiratory zone in another.
2. Your breathing rate, tidal volume and ventilation calculations.

From history. Laennec spent many years treating tuberculosis, the leading killer of young adults in his time, and died of it in 1826 at 45. His stethoscope was a simple wooden tube for decades; the two-eared rubber-tubed stethoscope came into wide use only in the later 1800s.

Practice habit. When you learn a new structure, write one line of the form "shape → job" (C-shaped rings → open airway, flexible esophagus). Structure explains function.

WORKED EXAMPLES

Example 1. A resting adult breathes 12 times a minute with a tidal volume of 500 mL and a dead space of 150 mL. Find the minute ventilation and the alveolar ventilation.

Show solution

1. Minute ventilation = 500 × 12 = 6,000 mL/min = 6.0 L/min
2. Alveolar ventilation = (500 − 150) × 12 = 350 × 12 = 4,200 mL/min = 4.2 L/min

Answer: 6.0 L/min moved; 4.2 L/min reaches the alveoli

Example 2. A frightened patient breathes fast and shallow: 24 breaths a minute at 250 mL. Compare with Example 1.

Show solution

1. Minute ventilation = 250 × 24 = 6,000 mL/min, the same
2. Alveolar ventilation = (250 − 150) × 24 = 100 × 24 = 2,400 mL/min

Answer: Same 6.0 L/min of air moved, but only 2.4 L/min reaches the alveoli, little more than half

Example 3. Model each alveolus as a sphere of radius 0.10 mm and take 480 million alveoli. Estimate the total surface area in square meters.

Show solution

1. $r = 0.10\ \text{mm} = 1.0 \times 10^{-4}\ \text{m}$
2. $A = 4\pi r^2 = 4\pi(1.0 \times 10^{-4})^2 \approx 1.26 \times 10^{-7}\ \text{m}^2$
3. $1.26 \times 10^{-7} \times 4.8 \times 10^{8} \approx 60\ \text{m}^2$

Answer: About 60 m^2, in line with the 50–75 m^2 usually quoted

PRACTICE

CONCEPT CHECKS

1. Easy List in order the structures air passes from the nostrils to an alveolus.

   Show answer

   Nasal cavity, pharynx, larynx, trachea, main bronchus, smaller bronchi, bronchioles, terminal bronchiole, respiratory bronchiole, alveolar duct, alveolus.

2. Easy Give three things the nose does to air.

   Show answer

   Filters it (hairs and mucus), warms it, and moistens it.

3. Easy Why are the tracheal cartilage rings C-shaped rather than complete circles?

   Show answer

   The open back lies against the esophagus, letting it expand when food is swallowed, while the rings still hold the airway open.

4. Medium A toddler inhales a small bead. Into which main bronchus is it more likely to go, and why?

   Show answer

   The right; it is wider, shorter and more nearly in line with the trachea.

5. **Medium** Find the minute ventilation and alveolar ventilation for 14 breaths a minute at 600 mL, with 150 mL dead space.

Show answer

8.4 L/min; 6.3 L/min

6. **Medium** What percent of a 500 mL breath is dead space (150 mL)?

Show answer

30%

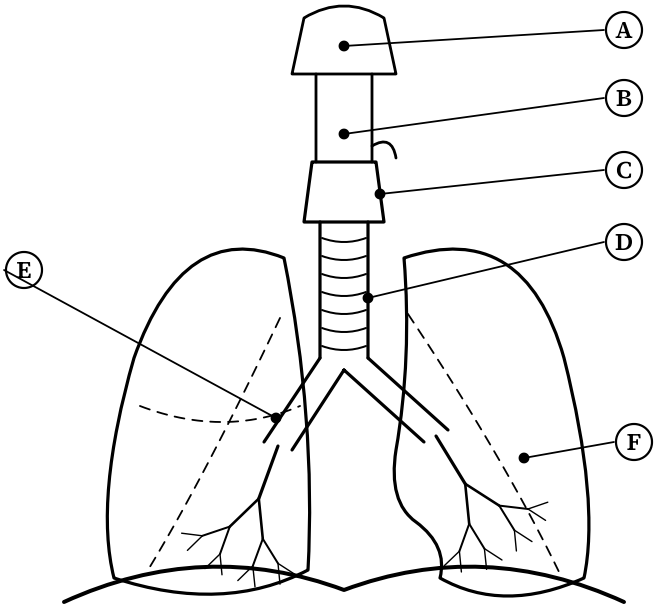
7. **Medium** What is the mucociliary escalator, and what would happen if the cilia stopped beating?

Show answer

Mucus traps particles and microbes and cilia sweep it up to the throat; without it, mucus and microbes would pool in the airways, causing cough and repeated infections.

DIAGRAM AND DATA QUESTIONS

8. **Medium** Name the structures lettered A to F.



Show answer

A nasal cavity; B pharynx; C larynx; D trachea; E right main bronchus; F left lung.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** Babies born many weeks early may not yet make enough surfactant. Explain why their alveoli tend to collapse after each breath and why they must work so hard to breathe.

   Show answer

   Without surfactant the water film lining each alveolus has high surface tension, which pulls the tiny sacs shut when air leaves; every breath must reopen collapsed alveoli, which takes great force, so the baby tires and gets too little oxygen (infant respiratory distress syndrome). Doctors can give surfactant into the airway and support breathing.

10. Hard In cystic fibrosis, a faulty channel in the airway cells makes the mucus thick and sticky. Predict two effects on the lungs.

    Show answer

    The cilia cannot move the thick mucus, so it blocks small airways (hard breathing) and traps bacteria, leading to repeated lung infections.

11. Challenge Snorkels are kept short. Using dead space, explain why a 2-meter snorkel would be dangerous even for a strong swimmer.

    Show answer

    A snorkel adds to the dead space. A very long tube could hold more air than a normal breath, so each breath would only pull stale exhaled air back from the tube; alveolar ventilation would fall toward zero and carbon dioxide would build up. (Water pressure on the chest at depth would also make breathing in through it very hard.)

COMMON MISTAKES

- Saying gas exchange happens in the bronchi; it happens only in the respiratory zone, mostly the alveoli.
- Forgetting dead space: not every milliliter breathed in reaches the alveoli.
- Thinking the lungs have muscle that inflates them; the lungs are passive and follow the chest wall (Lesson 8.2).
- Giving the left lung three lobes; the left has two, to make room for the heart.

Make it a game · Air Traffic Control. Lay out cards in a path on the floor: nose, pharynx, larynx, trachea, bronchus, bronchiole, alveolus. The student is a molecule of oxygen and walks the path, naming one job of each station. The parent calls out a "hazard" at random (dust, a crumb, cold air, a bacterium) and the student must say which station deals with it and how, before stepping on. A crumb sends you back to the larynx to explain the epiglottis.

Scripture. "And the LORD God formed man of the dust of the ground, and breathed into his nostrils the breath of life; and man became a living soul." (Genesis 2:7, KJV)

Every breath you take starts at the nostrils, where Scripture places the first breath God gave to man.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

8.2 How Breathing Works: Boyle's Law (1662) and Hutchinson's Spirometer (1846)

Mark up this lesson

OBJECTIVES

- Explain inhaling and exhaling with Boyle's law and the pressure differences that move air.
- Name the muscles of quiet and forced breathing and explain the role of the pleura and lung recoil.
- Read a spirogram and calculate lung volumes, capacities and the FEV1/FVC ratio.

> **Warm-up.** Squeeze an empty plastic bottle with the cap off, then let it spring back. Air rushes out and in. Nothing pushed the air in when the bottle sprang back. What made it move?

WATCH

Boyle's Law | Respiratory System

Dr Matt & Dr Mike · 8:53

https://www.youtube.com/watch?v=RcLnzU6Pk_Q

> **WHEN TO WATCH**
> After Boyle's law, before the muscles of breathing.

BACKUP VIDEO

How does lung volume change? | Respiratory system physiology | NCLEX-RN | Khan Academy

khanacademymedicine · 8:10

https://www.youtube.com/watch?v=dTsUyXXudvA

With the muscles of breathing.

KEY TERMS

Boyle's law

At constant temperature, the pressure of a fixed amount of gas is inversely proportional to its volume: $P_1V_1 = P_2V_2$.

diaphragm

The dome-shaped sheet of muscle under the lungs; when it contracts it flattens and enlarges the chest cavity. It is the main muscle of quiet breathing.

intercostal muscles

Muscles between the ribs; the external intercostals lift the ribs in inhaling, the internal intercostals pull them down in forced exhaling.

intrapulmonary pressure

The air pressure inside the alveoli; it falls slightly below atmospheric pressure in inhaling and rises slightly above it in exhaling.

tidal volume (TV)

The air moved in one quiet breath, about 500 mL in an adult.

vital capacity (VC)

The most air a person can breathe out after the deepest possible breath in: TV + IRV + ERV.

residual volume (RV)

The air left in the lungs after the strongest possible breath out, about 1,200 mL; it keeps the alveoli from collapsing.

FEV_1/FVC

The fraction of the forced vital capacity a person can blow out in the first second; normally about 70–85% or more in healthy young people.

CORE IDEAS

The story. In 1662 Robert Boyle poured mercury into the open end of a J-shaped glass tube and trapped air in the closed short end. When he had added about 29 inches of mercury, doubling the pressure on the trapped air, it shrank to half its volume; tripling the pressure shrank it to a third. The "spring of the air" pushed back in proportion. Boyle, a devout Christian who wrote as much on Scripture as on science, published the result to answer critics of his air-pump experiments. The law is in Chemistry 7.1; this lesson uses it to explain every breath you take.

How they figured it out. For breathing, the key question was how much air the lungs can move. In 1846 the London physician John Hutchinson built the spirometer, a calibrated bell floating upside down in water that rose as a person blew into it. He

measured more than a thousand men, from sailors and soldiers to wrestlers and gentlemen, named the vital capacity, and showed that it depends mainly on height and falls with lung disease and age. Modern spirometers are electronic, but they measure the same volumes.

Boyle's law and air flow. Air, like water, flows from high pressure to low pressure. The lungs have no muscle of their own to pull air in; instead the chest changes volume. When the chest volume grows, the air inside the lungs spreads into more space and its pressure falls slightly below the air pressure outside (by only about 1–3 mmHg in quiet breathing); air flows in until the pressures are equal. When the chest volume shrinks, the pressure inside rises above outside pressure and air flows out. $P_1V_1 = P_2V_2$ in action.

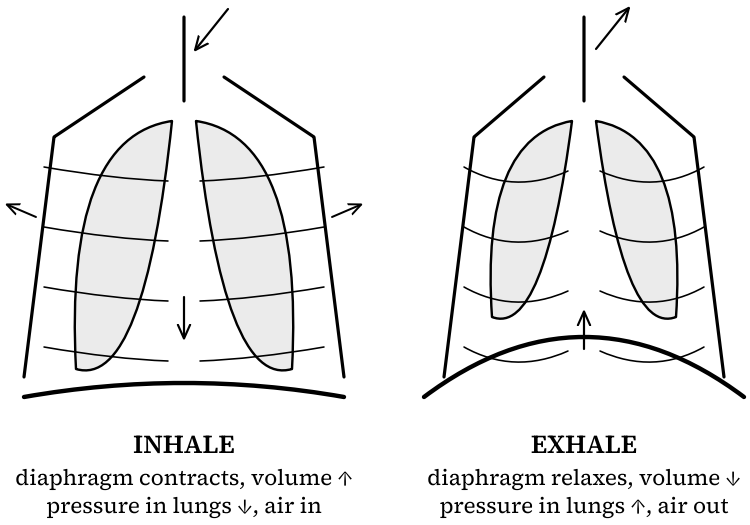
Inhaling. In quiet breathing the diaphragm contracts and flattens, moving down 1–2 cm, and the external intercostal muscles lift the ribs up and out like the handle of a bucket. The chest grows taller, wider and deeper. Because the pleural fluid holds the lungs to the chest wall, the lungs are pulled outward too. In deep or hard breathing, neck muscles (the sternocleidomastoids and scalenes) help lift the upper ribs. Inhaling always takes muscular work.

Exhaling. At rest exhaling is passive: the diaphragm and intercostals relax, and the elastic fibers of the stretched lungs recoil like a released balloon, shrinking the chest. During exercise, coughing, shouting or blowing out candles, the internal intercostals pull the ribs down and the abdominal muscles push the diaphragm up, making a forced exhale. The pressure in the pleural space normally stays slightly below atmospheric, which keeps the lungs from shrinking away from the chest wall.

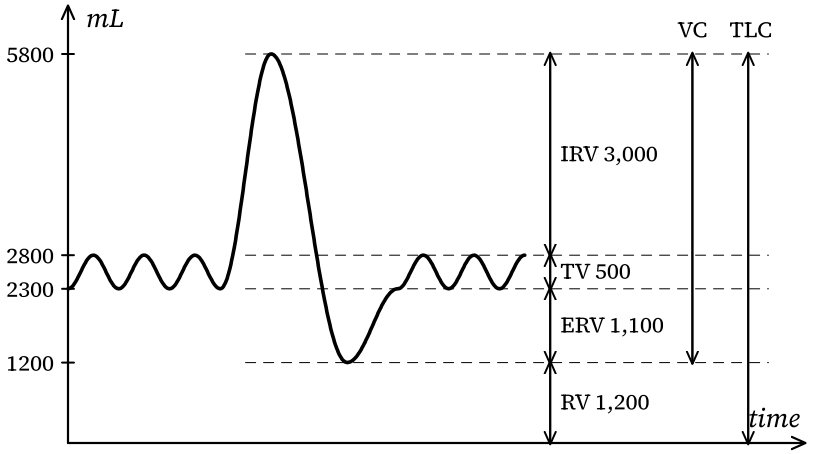
Lung volumes. A spirogram shows the volumes. Typical young-adult values: tidal volume 500 mL; inspiratory reserve volume (extra air you can still breathe in) about 3,000 mL; expiratory reserve volume (extra air you can still push out) about 1,100 mL; residual volume, which can never be breathed out, about 1,200 mL. Capacities are sums of volumes: vital capacity = TV + IRV + ERV, about 4,600 mL; total lung capacity adds RV, about 5,800 mL. Values are larger in taller people and in men, and smaller in older people.

Where it is used. In a spirometry test the patient takes the deepest breath possible and blows out as hard and fast as possible. If the airways are narrowed (asthma, chronic bronchitis), air comes out slowly: the FEV_1 is low compared with the forced

vital capacity, an obstructive pattern; a ratio below about 70% in an adult suggests obstruction. If the lungs or chest cannot expand fully (scarred lungs, a stiff chest wall), both values are small but the ratio stays normal or high, a restrictive pattern.



Inhaling: the diaphragm contracts and the ribs rise, the chest volume grows and lung pressure falls below outside pressure. Exhaling at rest is the passive reverse.



A spirogram: quiet tidal breaths, then the deepest breath in and fullest breath out. Volumes add up to capacities: VC = TV + IRV + ERV, TLC = VC + RV.

> **Safety first.** In the balloon test, blow out steadily; stop at once if you feel lightheaded, and never do repeated maximal breaths back to back. Anyone with asthma should keep a rescue inhaler nearby or skip the test. Pop and throw away balloons afterward; latex-allergic students use latex-free balloons. Small children must not play with balloons or balloon pieces.

LAB

Bell-Jar Lung Model and Balloon Vital Capacity

You will build a working model of the chest and estimate your own vital capacity.

You will need

- A clear plastic bottle (about 1–2 L) with the bottom cut off by a parent, two small balloons, a larger balloon or a piece of rubber glove, a straw, modeling clay, tape
- Several round balloons of the same kind (12-inch party balloons), a flexible tape measure or string and ruler

Steps

1. Model: put a small balloon on the end of the straw and push the straw through the bottle's cap, sealing it with clay. The balloon (lung) hangs inside the bottle (chest).
2. Cut the neck off the larger balloon and stretch it over the open bottom of the bottle as a diaphragm; tape it airtight.
3. Pull the bottom sheet down gently. Watch the lung balloon. Push it up. Explain each motion with Boyle's law.
4. Vital capacity: stretch a balloon a few times. Take the deepest breath you can, then blow everything you can into the balloon in one breath. Pinch it closed.
5. Measure the balloon's circumference C at its widest. Find the diameter $d = C/\pi$ and the volume $V = (4/3)\pi(d/2)^3$. Convert cm^3 to liters. Repeat three times and take the best.
6. Compare with the typical values in the lesson and with family members of different heights.

Check your work

- ☐ In the model, what do the bottle, the balloon and the rubber sheet stand for?
- ☐ Which part of a real chest does the model leave out?

- [ ] Why does the balloon method usually underestimate vital capacity?

LAB NOTEBOOK

1. A two-panel drawing of inhaling and exhaling with the pressure inside and outside written in each.
2. A spirogram sketch with every volume and capacity labeled, and your balloon calculation.

KEY FORMULAS

$$P_1 V_1 = P_2 V_2$$

$$\mathrm{VC} = \mathrm{TV} + \mathrm{IRV} + \mathrm{ERV} \qquad \mathrm{TLC} = \mathrm{VC} + \mathrm{RV}$$

$$V_{\text{sphere}} = \tfrac{4}{3}\pi r^3$$

From history. Hutchinson hoped vital capacity would help life-insurance companies spot early tuberculosis. Spirometry did become a standard medical test, and vital capacity remains one of the strongest single measures of lung health. Boyle refused to take the oaths required for the presidency of the Royal Society in 1680 because of scruples of conscience, and left money in his will to found lectures defending the Christian faith.

Practice habit. For every breathing question, write three words in a chain before answering: volume → pressure → flow.

Career connection. Respiratory therapists run spirometry and breathing treatments, manage ventilators in intensive care and teach patients with asthma or lung disease to use their inhalers. The usual path is an accredited associate or bachelor's degree, a national credential and a state license.

WORKED EXAMPLES

Example 1. The air in a person's lungs is at 760 mmHg in a volume of 2.40 L. The chest expands so that the lungs' volume becomes 2.46 L before any new air has entered. What is the pressure inside, and which way will air flow?

Show solution

1. $P_2 = \dfrac{P_1 V_1}{V_2} = \dfrac{760 \times 2.40}{2.46}$
2. $P_2 \approx 741$ mmHg

Answer: About 741 mmHg, below the 760 mmHg outside, so air flows in

Example 2. A breath-hold diver fills her lungs to 6.0 L at the surface (1 atm). Pressure increases by about 1 atm for every 10 m of seawater. What is her lung volume at 10 m and at 20 m?

Show solution

1. At 10 m: P = 2 atm; V = 1 × 6.0 ÷ 2 = 3.0 L
2. At 20 m: P = 3 atm; V = 1 × 6.0 ÷ 3 = 2.0 L

Answer: 3.0 L at 10 m; 2.0 L at 20 m. The air returns to 6.0 L as she rises

Example 3. A spirogram shows TV = 500 mL, IRV = 3,000 mL, ERV = 1,100 mL and RV = 1,200 mL. Find the vital capacity, total lung capacity and inspiratory capacity (TV + IRV).

Show solution

1. VC = 500 + 3,000 + 1,100 = 4,600 mL
2. TLC = 4,600 + 1,200 = 5,800 mL
3. IC = 500 + 3,000 = 3,500 mL

Answer: VC 4,600 mL; TLC 5,800 mL; IC 3,500 mL

PRACTICE

CONCEPT CHECKS

1. Easy Which muscle does most of the work of quiet breathing, and what does it do when it contracts?

   Show answer

   The diaphragm; it contracts, flattens and moves down, enlarging the chest cavity.

2. Easy Is quiet exhaling active or passive? Explain.

   Show answer

   Passive: the muscles relax and the stretched lungs and chest wall recoil.

3. Easy Why can you never breathe out your residual volume?

   Show answer

   The chest wall and pleura keep the lungs partly stretched, and the small airways close before the alveoli empty; the residual air keeps alveoli open.

4. Medium Lungs holding 3.0 L at 760 mmHg expand to 3.1 L before new air enters. Find the new pressure.

   Show answer

   About 735 mmHg

5. Medium A person with TV 450 mL, IRV 2,600 mL, ERV 1,000 mL and RV 1,100 mL. Find VC and TLC.

   Show answer

   VC 4,050 mL; TLC 5,150 mL

6. Medium A balloon blown up in one full breath has a diameter of 20 cm. Estimate the vital capacity in liters.

   Show answer

   About 4.2 L

   $(4/3)\pi(10\text{ cm})^3 \approx 4{,}189\text{ cm}^3$

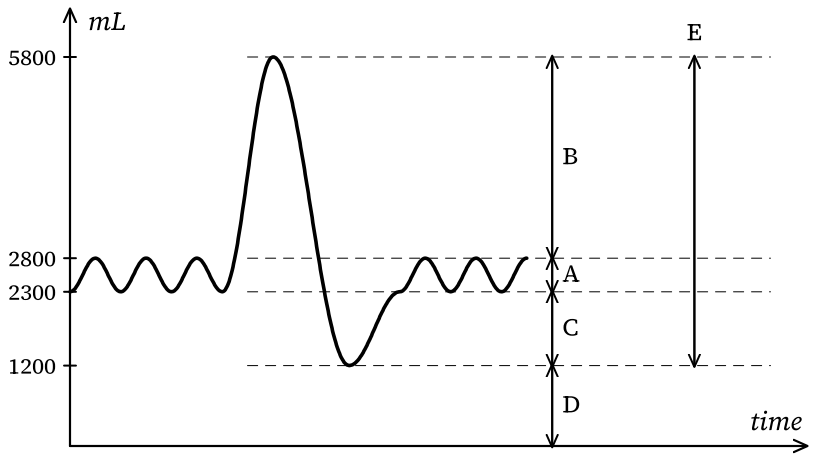
7. Medium Spirometry results: (a) FEV_1 3.2 L, FVC 4.0 L; (b) FEV_1 1.8 L, FVC 3.6 L. Find each ratio and say which suggests airway obstruction.

   Show answer

   (a) 80%, normal; (b) 50%, obstructive pattern.

DIAGRAM AND DATA QUESTIONS

8. Medium Name the volumes and capacity lettered A to E on the spirogram.



Show answer

A tidal volume; B inspiratory reserve volume; C expiratory reserve volume; D residual volume; E vital capacity.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** A stab wound lets air into the pleural space on one side (pneumothorax). Explain, with pressures, why the lung on that side collapses and why that side no longer fills when the chest expands.

Show answer

Normally the pleural pressure is slightly below atmospheric and the fluid seal holds the lung to the chest wall. Air entering the space raises the pleural pressure to atmospheric and breaks the seal; the lung's own elastic recoil then shrinks it. When the chest expands, air is simply drawn into the pleural space through the wound instead of into the lung.

10. Hard A scuba diver at 20 m (3 atm) fills her lungs with 4.0 L of air from her tank, then panics and swims to the surface holding her breath. What volume would that air try to occupy at the surface, and why is this dangerous?

Show answer

12 L (4.0 × 3/1), far more than total lung capacity; the expanding air would tear the alveoli (lung overexpansion injury) and can force air into the blood. Divers are trained to breathe out continuously while rising.

11. **Challenge** In asthma the bronchioles narrow. Explain why the patient has more trouble breathing out than breathing in, and why the residual volume grows.

Show answer

During inhaling, the expanding chest pulls the airways open; during exhaling, rising pressure in the chest squeezes the narrowed bronchioles further, so they close early and trap air behind them. Trapped air adds to the residual volume, and the patient breathes at a higher lung volume, which is tiring.

COMMON MISTAKES

- Saying the lungs suck air in; the chest enlarges and outside air pressure pushes air in.
- Reversing Boyle's law: larger volume means lower pressure, not higher.
- Adding residual volume into vital capacity; RV is in total lung capacity only.
- Thinking quiet exhaling needs muscles; at rest it is elastic recoil.
- Forgetting to convert cm^3 to liters (1,000 cm^3 = 1 L).

Make it a game · Pressure Push. Draw two columns, INSIDE and OUTSIDE, with a big arrow between them. The parent calls a change ("diaphragm contracts," "abdominal muscles squeeze," "intercostals relax," "air enters the pleural space"). The student says what happens to chest volume, then to inside pressure (higher or lower than outside), then points the arrow the way air will flow. Three right answers in a row earns a turn at calling changes.

Scripture. "The spirit of God hath made me, and the breath of the Almighty hath given me life." (Job 33:4, KJV)

Elihu confesses that his life and breath come from God. Boyle saw no conflict between measuring the spring of the air and worshiping its Maker.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

8.3 Gas Exchange and Transport: Dalton's Partial Pressures and Bohr's Shift (1904)

Mark up this lesson

OBJECTIVES

- Use partial pressures to explain the direction of oxygen and carbon dioxide diffusion in the lungs and tissues.
- Explain how hemoglobin loads and unloads oxygen, read the oxygen–hemoglobin curve, and describe the Bohr shift.
- Calculate partial pressures, oxygen content and oxygen delivery, and describe how carbon dioxide is carried.

> **Warm-up.** Open a bottle of soda and it fizzes; leave it open and it goes flat. A diver who comes up too fast can get bubbles in the blood. What do you think pressure has to do with how much gas stays dissolved in a liquid?

WATCH

Respiratory System, Part 2: Crash Course Anatomy & Physiology #32

CrashCourse · 10:23

https://www.youtube.com/watch?v=Cqt4LjHnMEA

> **WHEN TO WATCH**
> After partial pressures, before hemoglobin.

BACKUP VIDEO

Hemoglobin moves O2 and CO2 | Human anatomy and physiology | Health & Medicine | Khan Academy

khanacademymedicine · 14:57

https://www.youtube.com/watch?v=QP8ImP6NCk8

With oxygen and carbon dioxide transport.

KEY TERMS

partial pressure

The share of a gas mixture's total pressure due to one gas: fraction of that gas × total pressure (Dalton's law). Written $P(O_2)$, $P(CO_2)$.

respiratory membrane

The thin barrier between alveolar air and capillary blood: alveolar cell, shared basement membrane and capillary cell.

oxyhemoglobin

Hemoglobin with oxygen bound to its iron; each hemoglobin molecule carries up to four O_2.

percent saturation

The percent of hemoglobin's oxygen-binding sites that are filled; measured at the fingertip by a pulse oximeter (SpO_2).

oxygen–hemoglobin dissociation curve

The S-shaped graph of percent saturation against $P(O_2)$.

Bohr effect

Lower pH (more acid), more CO_2 and higher temperature lower hemoglobin's grip on oxygen, shifting the curve right and unloading more oxygen in active tissues.

bicarbonate

HCO_3^-; most carbon dioxide (about 70%) travels in plasma as bicarbonate, formed inside red cells by the enzyme carbonic anhydrase.

carbon monoxide

A colorless, odorless gas that binds hemoglobin more than 200 times more tightly than oxygen.

CORE IDEAS

The story. In 1904 the Danish physiologist Christian Bohr, with Karl Hasselbalch and his young assistant August Krogh, measured how much oxygen blood would hold at different oxygen pressures. They found that adding carbon dioxide made the blood give up more of its oxygen. The effect, now named for Bohr, means that the busiest tissues, which make the most carbon dioxide, automatically get the most oxygen. Bohr also believed the lungs actively secreted oxygen into the blood; Krogh and his wife, the physician Marie Krogh, tested the idea with careful measurements around 1910 and showed that simple diffusion explains it.

How they figured it out. The key is the partial pressure of each gas. John Dalton showed in 1801 that each gas in a mixture contributes to the total pressure as though it were alone (Chemistry 7.4), and William Henry showed in 1803 that the amount of a gas that dissolves in a liquid is proportional to its partial pressure. Gases diffuse from higher to lower partial pressure, and the Kroghs showed the pressures in the lungs and blood were always in the right direction for diffusion alone.

Partial pressures in the body. Dry air at sea level is about 21% oxygen, so $P(\mathrm{O_2}) \approx 0.21 \times 760 \approx 160$ mmHg. In the airways the air is saturated with water vapor (47 mmHg at body temperature) and mixed with old air, so alveolar air has P(O2) about 104 mmHg and P(CO2) about 40. Blood arriving in the lung capillaries has P(O2) about 40 and P(CO2) about 45. So oxygen diffuses into the blood and carbon dioxide out, and in a fraction of a second the blood leaves with P(O2) near 100 and P(CO2) 40. In the tissues the gradients reverse. The membrane's thinness and huge area (Lesson 8.1) make this fast.

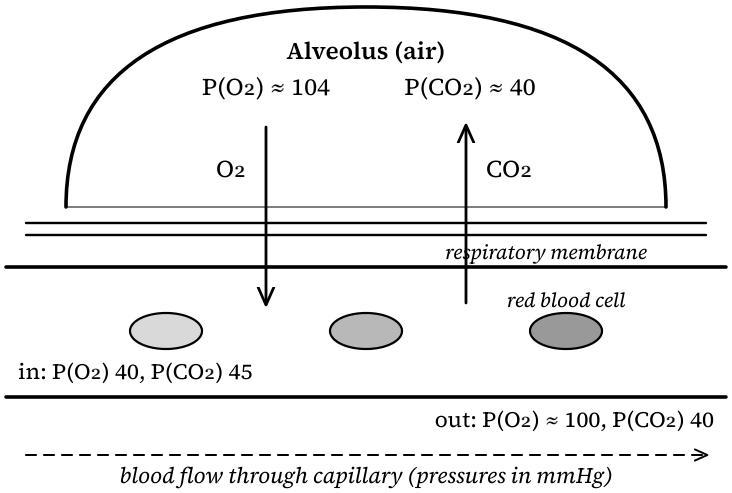
Hemoglobin carries the oxygen. Oxygen dissolves poorly in plasma: only about 1.5% of the oxygen in blood is dissolved; about 98.5% rides on hemoglobin. Each gram of hemoglobin can carry about 1.34 mL of oxygen, so blood with 15 g of hemoglobin per deciliter carries about 20 mL of oxygen per deciliter when fully loaded. When one oxygen binds, the molecule changes shape and the next ones bind more easily; this cooperation gives the S-shaped curve.

Reading the curve. At the lungs' P(O2) of 100 mmHg, hemoglobin is about 97% saturated, on the flat top of the curve; even if P(O2) falls to 70 or 80 at moderate altitude, saturation barely drops, a built-in safety margin. In resting tissues (P(O2) about 40) saturation falls to about 75%, so a quarter of the oxygen is unloaded and three-quarters is held in reserve. In working muscle P(O2) falls further, onto the steep part of the curve, so much more is released. More CO2, more acid and a higher temperature shift the curve right (the Bohr effect): at the same P(O2), hemoglobin lets go of even more.

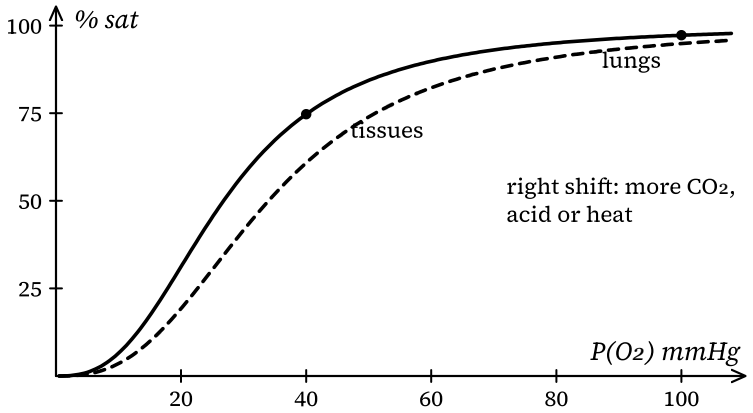
Carbon dioxide transport. Carbon dioxide travels three ways: about 7–10% dissolved in plasma, about 20–23% bound to hemoglobin's protein chains, and about 70% as bicarbonate. Inside red cells the enzyme carbonic anhydrase speeds $\mathrm{CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-}$. The bicarbonate moves out into the plasma in exchange for chloride (the chloride shift), and hemoglobin soaks up the $\mathrm{H^+}$, buffering the blood. In

the lungs every step runs backward and CO_2 is breathed out. This is why breathing helps control blood pH (Lesson 8.4 and Unit 9).

Where it is used. A pulse oximeter shines red and infrared light through a fingertip and reports SpO_2; healthy people at sea level read about 95–100%. Arterial blood gases, drawn from the wrist, report $P(O_2)$, $P(CO_2)$ and pH directly. Carbon monoxide from faulty furnaces, car exhaust in closed garages or generators run indoors binds hemoglobin and blocks oxygen, yet a basic pulse oximeter may read normal because it cannot tell the two apart; every home with fuel-burning appliances should have a carbon monoxide alarm.



Each gas diffuses down its own partial-pressure gradient across the thin respiratory membrane: O_2 from alveolus to blood, CO_2 from blood to alveolus.



The oxygen–hemoglobin curve is flat at lung pressures (safe loading) and steep at tissue pressures (easy unloading). More CO_2, acid or heat shifts it right.

> **Safety first.** Iodine stains and is poisonous if swallowed: an adult handles it, and nothing from the lab is tasted. A healthy student's SpO_2 should stay above about 95%; a lower reading that persists is a reason to stop and tell a parent. Anyone with a heart or lung condition skips the exercise step.

LAB

Pulse Oximeter and Diffusion Lab

You will measure oxygen saturation and pulse at rest and after exercise, and model diffusion across a membrane.

You will need

- A fingertip pulse oximeter (about $20–30), or skip that part and use the data table below
- Two clear cups, a resealable bag, water, iodine solution (adult handles) and cornstarch, or food coloring and a tea bag

Steps

1. Rest seated 5 minutes. Record SpO_2 and pulse from the oximeter on a warm finger without nail polish.
2. March in place for 2 minutes and record again, then every minute for 3 minutes.
3. No oximeter? Use these sample readings: rest 98%, 68 bpm; after exercise 97%, 132 bpm; 3 minutes later 98%, 84 bpm.
4. Diffusion model: put cornstarch-water in a zip bag, seal it, and set it in a cup of water with a few drops of iodine (adult adds the iodine). After 20 minutes look for blue-black color inside the bag: small iodine molecules crossed the membrane; large starch molecules did not.
5. Write a paragraph comparing the bag membrane with the respiratory membrane.

Check your work

- ☐ Did SpO_2 fall much during exercise? Use the shape of the curve to explain.
- ☐ Which molecules crossed the bag membrane, and why?
- ☐ Why does a healthy person's SpO_2 stay high while the pulse nearly doubles?

LAB NOTEBOOK

1. The alveolus–capillary diagram with every partial pressure written in and the arrows of diffusion.

2. A hand-drawn oxygen–hemoglobin curve with the lung and tissue points, and a dashed right-shifted curve.

KEY FORMULAS

$$P_{\text{gas}} = (\text{fraction of gas}) \times P_{\text{total}}$$

$$\text{O}_2 \text{ content} \approx 1.34 \times [\text{Hb}] \times \text{Sat} + 0.003 \times P(\text{O}_2)$$

$$\text{O}_2 \text{ delivery} = \text{CO} \times \text{O}_2 \text{ content}$$

From history. August Krogh went on to win the 1920 Nobel Prize for showing that resting muscles keep many capillaries closed and open them during exercise. Christian Bohr was the father of the physicist Niels Bohr, whose model of the atom appears in Chemistry 3.1.

Practice habit. In every gas question, write the partial pressure on each side of the membrane before you say which way the gas moves.

WORKED EXAMPLES

Example 1. Air is 21% oxygen. Find P(O2) in dry air at sea level (760 mmHg) and in the airways, where water vapor takes 47 mmHg of the total.

Show solution

1. Dry air: 0.21 × 760 = 159.6 ≈ 160 mmHg
2. Humidified: 0.21 × (760 − 47) = 0.21 × 713 = 149.7 ≈ 150 mmHg

Answer: About 160 mmHg dry; about 150 mmHg in the airways

Example 2. Arterial blood has 15 g/dL hemoglobin, 98% saturation and P(O_2) 100 mmHg; venous blood is 75% saturated with P(O_2) 40. Find the oxygen content of each, the oxygen unloaded per deciliter, and the oxygen used per minute if cardiac output is 5.0 L/min (50 dL/min).

Show solution

1. Arterial: $1.34 \times 15 \times 0.98 + 0.003 \times 100 = 19.7 + 0.3 = 20.0$ mL/dL
2. Venous: $1.34 \times 15 \times 0.75 + 0.003 \times 40 = 15.1 + 0.1 = 15.2$ mL/dL
3. Unloaded: $20.0 - 15.2 = 4.8$ mL/dL
4. Per minute: $4.8 \times 50 = 240$ mL O_2/min

Answer: 20.0 and 15.2 mL/dL; 4.8 mL/dL unloaded; about 240 mL O_2 per minute (about a quarter of what arrives)

Example 3. An anemic patient has only 9 g/dL hemoglobin but normal lungs (98% saturated, P(O_2) 100). Find her arterial oxygen content and compare with Example 2.

Show solution

1. $1.34 \times 9 \times 0.98 + 0.3 = 11.8 + 0.3 = 12.1$ mL/dL
2. $12.1 \div 20.0 = 0.61$

Answer: 12.1 mL/dL, about 60% of normal, even though her saturation and SpO_2 are normal

PRACTICE

CONCEPT CHECKS

1. Easy In which direction does oxygen diffuse in the lungs, and in the tissues? Why?

   Show answer

   Lungs: alveolus (104 mmHg) into blood (40). Tissues: blood (about 100) into cells (40 or less). Gases diffuse from higher to lower partial pressure.

2. Easy About what percent of oxygen in the blood is bound to hemoglobin?

   Show answer

   About 98.5%; only about 1.5% is dissolved.

3. Easy Name the three ways carbon dioxide is carried in the blood, from largest share to smallest.

Show answer

As bicarbonate (about 70%), bound to hemoglobin (about 20–23%), dissolved (about 7–10%).

4. Medium Denver's air pressure is about 630 mmHg. Find $P(O_2)$ in dry air and in the humidified airways.

Show answer

About 132 mmHg; about 122 mmHg

5. Medium Use the curve: about what percent saturation is hemoglobin at $P(O_2)$ 100 mmHg, and at 40 mmHg? What fraction of the oxygen is unloaded in resting tissue?

Show answer

About 97% and 75%; roughly a quarter (about 22 percentage points of 97) is unloaded.

6. Medium Why does exercising muscle get more oxygen from each deciliter of blood than resting muscle? Give two reasons.

Show answer

Its $P(O_2)$ is lower, on the steep part of the curve; and its extra CO_2, acid and heat shift the curve right (Bohr effect), so hemoglobin releases more at the same pressure.

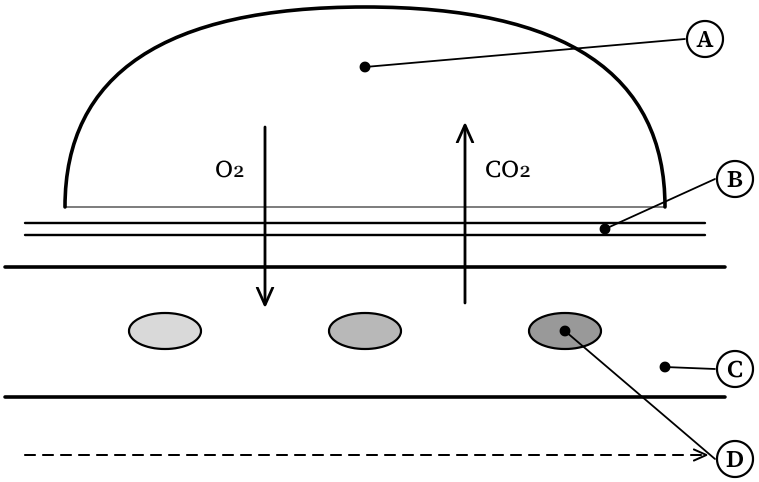
7. Medium Write the reaction that carbonic anhydrase speeds up in red cells, and say which way it runs in the tissues and in the lungs.

Show answer

$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$. To the right in the tissues (CO_2 picked up); to the left in the lungs (CO_2 released and breathed out).

DIAGRAM AND DATA QUESTIONS

8. Medium Name the parts lettered A to D.



Show answer

A alveolus (air space); B respiratory membrane; C capillary (blood plasma); D red blood cell.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** A family runs a gasoline generator in a closed garage beside the house. Several people develop headaches and confusion, yet a basic pulse oximeter reads 99%. Explain what is happening in their blood and why the reading misleads.

Show answer

Carbon monoxide binds hemoglobin more than 200 times more tightly than oxygen, so much of their hemoglobin cannot carry oxygen, and the bound CO also makes the remaining hemoglobin release oxygen less readily in the tissues. The brain is starved of oxygen. A basic oximeter reads the color of hemoglobin and counts CO-bound hemoglobin as if it were carrying oxygen. They need fresh air and emergency care at once.

10. Hard A patient has hemoglobin 12 g/dL, 97% saturation and P(O2) 95 mmHg. Find the arterial oxygen content.

Show answer

About 15.9 mL/dL

$1.34 \times 12 \times 0.97 + 0.003 \times 95 = 15.6 + 0.3$

11. **Challenge** In pneumonia, fluid fills some alveoli and thickens the respiratory membrane. Explain why the patient's blood oxygen falls more than its carbon dioxide rises, using what you know about diffusion and the two gases.

Show answer

Thickening slows diffusion of both gases, but CO_2 is about 20 times more soluble in water than O_2 and so crosses a wet membrane far more easily; in addition the patient breathes faster, which readily blows off CO_2 but cannot raise O_2 much in blood leaving the fluid-filled alveoli. So low oxygen appears first, while CO_2 often stays normal or even low.

COMMON MISTAKES

- Saying gases move from high concentration of the whole air to low; each gas follows its own partial-pressure gradient.
- Thinking blood is fully emptied of oxygen in the tissues; at rest venous blood is still about 75% saturated.
- Treating SpO_2 as the amount of oxygen in blood; an anemic patient can have normal saturation and low oxygen content.
- Shifting the curve the wrong way: more CO_2, acid or heat moves it right, toward unloading.
- Forgetting to subtract water vapor (47 mmHg) when finding $P(O_2)$ in the airways.

Make it a game · Hemoglobin Taxi. A toy car or cup is a red cell with four seats (oxygen). At the "lungs" the student loads four paper O_2 tokens. At each "tissue" the parent rolls a die: 1–4 means resting tissue (unload one token), 5–6 means working muscle (unload two, Bohr effect). On the way back the student picks up CO_2 tokens and must say how each is carried (bicarbonate, on hemoglobin, dissolved). Add a "carbon monoxide" card that glues a seat shut for the rest of the game.

Scripture. "Neither is worshipped with men's hands, as though he needed any thing, seeing he giveth to all life, and breath, and all things;" (Acts 17:25, KJV)

Paul told the Athenians that God needs nothing from us, but gives us everything, down to the oxygen loaded on every red cell.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up

👎 Thumbs down

Too hard

Too easy

Video problem

Found an error

Took too long

Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

8.4 Control of Breathing, Altitude and Smoking: Haldane's Carbon Dioxide (1905) and Paul Bert's Mountains

Mark up this lesson

OBJECTIVES

- Describe how the brainstem sets the rhythm of breathing and how chemoreceptors adjust it.
- Explain the body's short- and long-term responses to high altitude.
- Explain how smoking damages the airways and alveoli, and calculate pack-years and altitude oxygen pressures.

> **Warm-up.** You can hold your breath for a while, but not forever; at some point your body forces you to breathe. Which do you think builds up the strong urge to breathe: too little oxygen, or too much carbon dioxide?

WATCH

The respiratory center | Respiratory system physiology | NCLEX-RN | Khan Academy

khanacademymedicine · 9:23

https://www.youtube.com/watch?v=_BFDgTci0ck

> **WHEN TO WATCH**
> After the respiratory centers, before chemoreceptors.

BACKUP VIDEO

Control of Ventilation (Respiration), Animation

Alila Medical Media · 5:16

https://www.youtube.com/watch?v=KITa-HNpJgU

As a summary of the whole control loop.

KEY TERMS

respiratory centers

Groups of neurons in the medulla oblongata (which set the basic rhythm) and the pons (which smooth the change between breathing in and out).

phrenic nerve

The nerve to the diaphragm, from spinal segments C3–C5 in the neck.

central chemoreceptors

Sensors in the medulla that respond to the acidity of the fluid around the brain, which rises when blood CO_2 rises.

peripheral chemoreceptors

The carotid bodies (in the neck) and aortic bodies (near the heart), which respond mainly to low oxygen (below about 60 mmHg) as well as to CO_2 and acid.

hyperventilation

Breathing faster or deeper than the body needs, which lowers blood CO_2.

acclimatization

The gradual adjustments to high altitude over days and weeks: deeper breathing, more red cells and other changes.

COPD

Chronic obstructive pulmonary disease: emphysema (destroyed alveolar walls) and chronic bronchitis (inflamed, mucus-filled airways), most often caused by smoking.

pack-year

A measure of smoking exposure: packs smoked per day × years smoked.

CORE IDEAS

The story. In 1875 three French scientists rose in the balloon *Zénith* to study the upper air. They carried bags of oxygen, but above about 8,000 meters they lost the strength and judgment to use them before they realized anything was wrong. Two died; Gaston Tissandier survived to tell how calm and pleasant the slide into unconsciousness felt. Paul Bert, who had advised them, studied people and animals in steel chambers in which he lowered and raised the air pressure, and in 1878 showed that the danger of altitude is the low partial pressure of oxygen.

How they figured it out. In 1905 John Scott Haldane and John Gillies Priestley at Oxford collected samples of the last air breathed out, which matches alveolar air, from people breathing at different pressures and while breathing mixtures with extra carbon dioxide. They found that alveolar P(CO_2) stayed remarkably constant and that even a small rise in CO_2 greatly increased breathing. The urge to breathe at sea level is driven mainly by carbon dioxide, not by a lack of oxygen. Low oxygen becomes the main driver only when it falls a long way, as at high altitude.

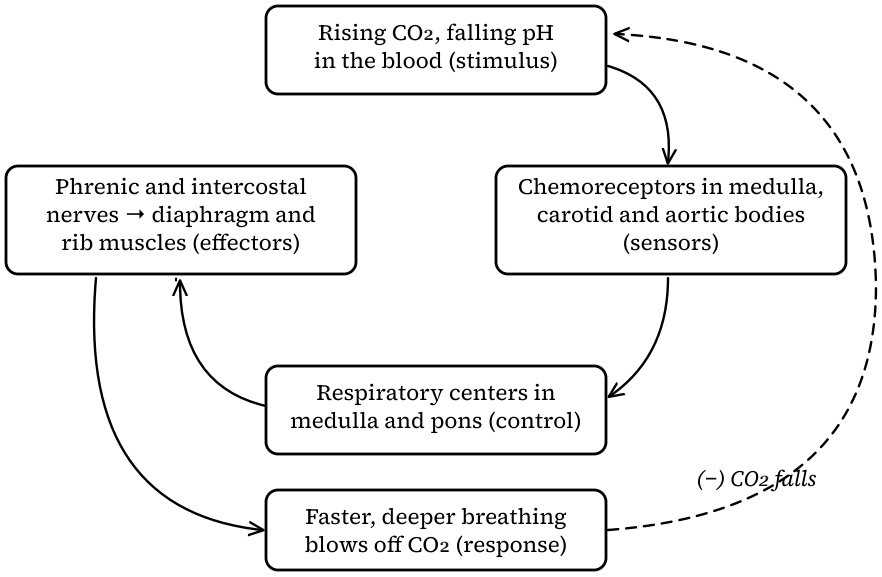
The rhythm generator. Breathing does not need thought. Neurons in the medulla oblongata fire in bursts that travel down the phrenic nerves to the diaphragm and the intercostal nerves to the rib muscles about 12–20 times a minute at rest, and centers in the pons smooth the switch between inhaling and exhaling. Stretch receptors in the airways help stop a very deep breath (the Hering–Breuer reflex). Higher brain areas can override the rhythm for a while, which is how we talk, sing, hold our breath and blow out candles.

The sensors and the loop. Rising CO_2 in the blood quickly crosses into the fluid around the brain, where it forms acid; central chemoreceptors in the medulla sense the acid and increase the rate and depth of breathing. The carotid and aortic bodies respond to CO_2 and acid too, and they are the only sensors for low oxygen. Breathing harder blows off CO_2, the acid falls and breathing slows: a negative-feedback loop like those in Lesson 1.3. During exercise, breathing rises at once, even before blood gases change, because signals from the moving muscles and the motor cortex stimulate the centers in advance.

Altitude. The fraction of oxygen in air is the same on a mountaintop, about 21%, but the total pressure is lower, so P(O_2) is lower: about two-thirds of sea level at 3,000 m, and only about one-third at the summit of Mount Everest (about 8,850 m). Within minutes the peripheral chemoreceptors raise breathing. Within hours to days the kidneys release erythropoietin (Lesson 7.1), and over weeks the red-cell count and hematocrit rise; red cells also make more of a chemical that helps them release oxygen. Too fast a climb can cause acute mountain sickness (headache, nausea, poor sleep) and, rarely, dangerous fluid in the lungs or brain; the cure for severe cases is to go down. In 1978 Reinhold Messner and Peter Habeler first climbed Everest without bottled oxygen, a feat physiologists had doubted was possible.

Smoking. In 1950 Richard Doll and Austin Bradford Hill in Britain, and Ernst Wynder and Evarts Graham in the United States, published careful studies showing that lung cancer patients were far more likely to have been smokers; Doll and Hill's later study of British doctors confirmed it. Tobacco smoke paralyzes and then destroys the cilia, so mucus and particles collect (smoker's cough); it inflames the airways (chronic bronchitis) and, over years, breaks down the alveolar walls into large, useless spaces (emphysema), cutting the surface for gas exchange. Its carbon monoxide occupies hemoglobin (Lesson 8.3), and its many cancer-causing chemicals cause most lung cancers. Nicotine is strongly addictive, whether smoked, chewed or vaped. Vaping also carries fine particles and chemicals deep into the lungs, and its long-term effects are still being studied. The lungs and heart recover part of their function after a person quits, and the risk of disease falls year by year.

Where it is used. Nurses count the breathing rate as a vital sign without telling the patient, because people change their breathing when they know it is being watched. Pilots and mountaineers learn the early signs of low oxygen. Doctors ask patients for their pack-years, because lung-cancer screening is recommended for older adults with heavy smoking histories.



Breathing control is a negative-feedback loop. Rising CO_2 is sensed by chemoreceptors, the brainstem centers increase breathing, and the extra breathing brings CO_2 back down.

> **Safety first.** Never hyperventilate on purpose before swimming underwater or hold your breath in competitions, in a pool or anywhere else: blowing off CO_2 delays the urge to breathe while oxygen keeps falling, and a swimmer can black out underwater without warning (shallow-water blackout). This lab uses only normal breathing and light exercise. Bromothymol blue is for blowing into, never sucking up; an adult supervises.

LAB

Carbon Dioxide and the Drive to Breathe

You will measure how breathing changes with exercise and watch the carbon dioxide in your breath turn an indicator from blue to yellow.

You will need

- Bromothymol blue indicator (about $10 from a science supplier), two clear cups, two straws, water, a dropper
- A stopwatch, a partner, graph paper

Steps

1. Count a partner's breaths for 30 seconds at rest without telling them, and double it. Repeat twice.
2. Put 50 mL water and 10 drops of bromothymol blue in each cup (it should be blue).
3. At rest, blow gently through a straw into the first cup. Time how many seconds it takes to turn green-yellow. Blow out only; never suck.
4. March in place for 2 minutes. Count the breaths for 30 seconds right away, then blow into the second cup and time the color change.
5. Count the breathing rate every minute for 4 more minutes and graph it.

Check your work

- ☐ Which cup changed color faster, and what does that tell you about the CO_2 in your breath after exercise?
- ☐ Which sensors noticed the rise in CO_2, and what did the brainstem do about it?
- ☐ Why must the person being counted not know they are being counted?

LAB NOTEBOOK

1. The breathing-control loop drawn as a feedback cycle: stimulus, sensors, control center, effectors, response.
2. Your breathing-rate graph and the timing of the color change in each cup.

From history. Haldane tested many of his ideas on himself, breathing poisonous gases in sealed chambers and climbing Pikes Peak in Colorado in 1911 to study altitude. He also designed early gas masks during the First World War and worked to make coal mines safer; miners' canaries, which collapse in carbon monoxide before people do, were one of his suggestions.

Practice habit. When you predict a breathing change, always name the sensor first, then the control center, then the muscles; the loop never skips a step.

WORKED EXAMPLES

Example 1. At the top of Mount Everest the air pressure is about 253 mmHg. Find the $P(O_2)$ of the humidified air in the airways (subtract 47 mmHg water vapor; air is 21% oxygen) and compare it with sea level (about 150 mmHg).

Show solution

1. $0.21 \times (253 - 47) = 0.21 \times 206 = 43.3$ mmHg
2. $43.3 \div 149.7 = 0.29$

Answer: About 43 mmHg, less than one-third of sea level

Example 2. One person smoked 1.5 packs a day for 20 years; another smoked half a pack a day for 15 years. Find their pack-years.

Show solution

1. $1.5 \times 20 = 30$ pack-years
2. $0.5 \times 15 = 7.5$ pack-years

Answer: 30 and 7.5 pack-years

Example 3. A student counts 4 breaths in 15 seconds at rest and 9 breaths in 15 seconds just after exercise. Find both rates per minute and the percent increase.

Show solution

1. Rest: $4 \times 4 = 16$ breaths/min
2. After exercise: $9 \times 4 = 36$ breaths/min
3. $(36 - 16) \div 16 \times 100\% = 125\%$

Answer: 16 and 36 breaths per minute, a 125% increase

PRACTICE

CONCEPT CHECKS

1. Easy Where in the brain is the basic rhythm of breathing generated?

   Show answer

   In the medulla oblongata, with help from the pons.

2. Easy At sea level, what is the main chemical signal that drives breathing?

   Show answer

   Carbon dioxide (through the acid it forms), not low oxygen.

3. Easy Name the two kinds of peripheral chemoreceptors and what they mainly sense.

   Show answer

   Carotid bodies and aortic bodies; they are the sensors of low oxygen (and also respond to CO_2 and acid).

4. Medium Denver's air pressure is about 630 mmHg. Find the humidified $P(O_2)$ in the airways.

   Show answer

   About 122 mmHg

   $0.21 \times (630 - 47)$

5. Medium Find the pack-years for 2 packs a day for 25 years.

   Show answer

   50 pack-years

6. Medium A breathing count gives 5 breaths in 15 seconds. Find the rate per minute. Is it in the normal adult resting range?

   Show answer

   20 breaths per minute, at the top of the normal 12–20.

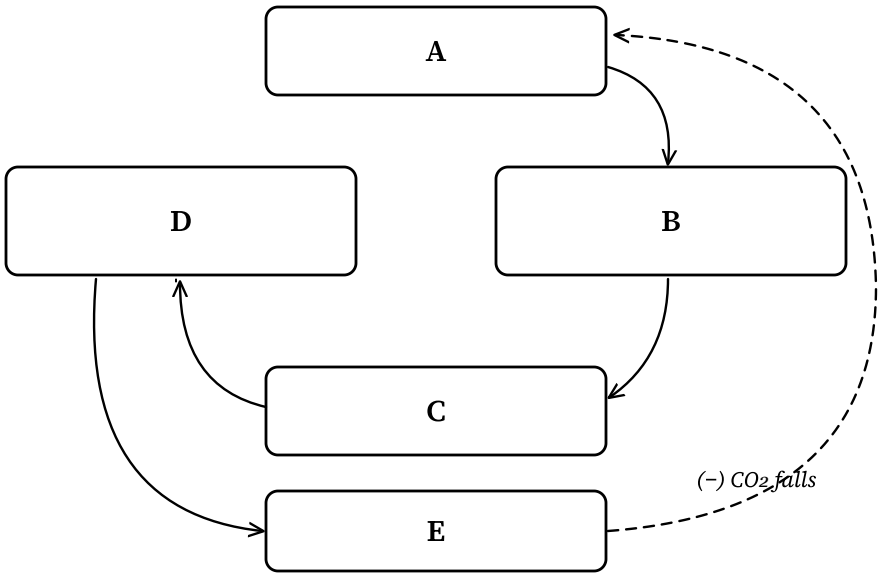
7. Medium List three changes, in order of how quickly they happen, when a lowlander moves to a high mountain town.

   Show answer

   Faster, deeper breathing (minutes); erythropoietin released by the kidneys (hours to days); more red cells and a higher hematocrit (weeks).

DIAGRAM AND DATA QUESTIONS

8. Medium Name the stages of the breathing-control loop lettered A to E.



Show answer

A stimulus: rising CO_2 and falling pH; B sensors: central and peripheral chemoreceptors; C control center: respiratory centers in medulla and pons; D effectors: phrenic and intercostal nerves to the diaphragm and rib muscles; E response: faster, deeper breathing that blows off CO_2.

WHEN IT GOES WRONG

9. Hard **Disorder as a broken mechanism.** A teenager takes many fast, deep breaths before swimming the length of a pool underwater, and partway across he blacks out. Using the control loop, explain why he never felt a strong urge to come up.

Show answer

Hyperventilating blew off CO_2, so blood CO_2 started far below normal. Underwater, oxygen fell steadily while CO_2 rose only back toward normal, so the chemoreceptors did not produce the usual urge to breathe until oxygen had fallen low enough to starve the brain. The normal CO_2 alarm was switched off in advance.

10. Hard Explain how emphysema reduces gas exchange, using what you know about the alveoli's surface area (Lesson 8.1).

Show answer

The walls between alveoli are destroyed and many small sacs merge into fewer large spaces, so the total surface area for diffusion falls sharply; the lungs also lose elastic recoil, so air is trapped and exhaling becomes hard work.

11. Challenge At very high altitude a climber breathes very fast and deep. His blood CO_2 falls far below normal, yet he keeps breathing hard. Explain which sensors are winning and why his blood pH rises.

Show answer

The peripheral chemoreceptors sense the very low $P(O_2)$ and keep driving breathing even though low CO_2 is telling the central chemoreceptors to slow down. Blowing off so much CO_2 removes carbonic acid, so H^+ falls and blood pH rises (respiratory alkalosis); over days the kidneys excrete bicarbonate to bring pH back toward normal.

COMMON MISTAKES

- Saying low oxygen is the main driver of breathing at sea level; it is carbon dioxide.
- Thinking the percent of oxygen in air is lower on mountains; the percent is the same, the total pressure is lower.
- Believing hyperventilating "stores up" oxygen; hemoglobin is already nearly full, and the main effect is to lower CO_2.
- Thinking the damage from smoking appears only after decades; cilia and airways are harmed from the start.

> **Make it a game · Breath Control Board.** Make a board with three dials drawn on paper: CO_2 (low–normal–high), O_2 (low–normal–high) and breathing (slow–normal–fast). The parent reads a situation (sprinting up stairs, sleeping, arriving at a ski resort, holding your breath, smoking for twenty years). The student sets the CO_2 and O_2 dials first, then the breathing dial, and names which sensor and which brain region did the work. A wrong order (breathing before the gases) costs a point.

> **Scripture.** “Let every thing that hath breath praise the LORD. Praise ye the LORD.” (Psalm 150:6, KJV)
>
> Every breath is timed by the brainstem without our thinking, and every one is a gift. The last verse of the Psalms asks us to use that breath to praise its Giver.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

UNIT 8

Respiration

This unit follows a breath from the nose to the mitochondria. Students trace the airway to the alveoli, explain breathing with Boyle's law from Chemistry, follow oxygen and carbon dioxide across the respiratory membrane and through the blood, and learn how the brainstem keeps the whole system in balance. The history runs from Boyle's J-tube (1662) and Laennec's chest sounds (1819) to Hutchinson's spirometer (1846), Bohr and Krogh's blood-gas measurements and Haldane's discovery that carbon dioxide drives breathing (1905).

Labs are simple and safe: measuring breathing rate and tidal volume with a bottle, a homemade bell-jar lung, a balloon estimate of vital capacity, a pulse oximeter, and bromothymol blue to show the carbon dioxide in breath. No lab involves breath-holding or hyperventilating, and Lesson 8.4 explains why those are dangerous. The unit connects to cellular respiration in Biology 4.3, to the gas laws in Chemistry 7.1 and 7.4, and to blood, hemoglobin and the heart in Unit 7.

PREREQUISITES

- Unit 7 (blood, hemoglobin and cardiac output)
- Chemistry 7.1 and 7.4 (Boyle's law and Dalton's partial pressures)
- Biology 4.3 (cellular respiration: why cells need oxygen and make carbon dioxide)

MASTERY CHECKLIST

- ☐ I can trace air from the nose to the alveoli, explain the job of each structure, and calculate minute and alveolar ventilation.
- ☐ I can explain inhaling and exhaling with Boyle's law, name the muscles involved, and read and calculate lung volumes and the FEV_1/FVC ratio.
- ☐ I can use partial pressures to predict gas diffusion, read the oxygen–hemoglobin curve, explain the Bohr effect, and calculate oxygen content and delivery.
- ☐ I can describe the breathing-control loop, explain the body's response to altitude, and explain how smoking damages the lungs.

LESSONS IN THIS UNIT

8.1 The Airway and Lungs: Laennec Listens to the Chest (1819)

3 sessions of 45 minutes

8.2 How Breathing Works: Boyle's Law (1662) and Hutchinson's Spirometer (1846)

4 sessions of 45 minutes

8.3 Gas Exchange and Transport: Dalton's Partial Pressures and Bohr's Shift (1904)

3 sessions of 45 minutes

8.4 Control of Breathing, Altitude and Smoking: Haldane's Carbon Dioxide (1905) and Paul Bert's Mountains

3 sessions of 45 minutes

Unit 8 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. (7 pts) **Lesson 8.1**

   List the conducting-zone structures in order and give one job of the nose, the epiglottis and the cilia.

2. (8 pts) **Lesson 8.1**

   A person breathes 15 times a minute with a tidal volume of 400 mL and 150 mL of dead space. Find the minute ventilation and alveolar ventilation.

3. (8 pts) **Lesson 8.1**

   Explain how surfactant and the thinness of the respiratory membrane each help gas exchange.

4. (9 pts) **Lesson 8.2**

   Explain one quiet inhalation and exhalation in terms of muscles, volume, pressure and air flow.

5. **8 pts** **Lesson 8.2**

   Lungs holding 2.5 L at 760 mmHg are squeezed to 2.45 L before any air leaves. Find the new pressure and the direction of air flow.

6. **8 pts** **Lesson 8.2**

   A spirogram shows TV 500 mL, IRV 2,800 mL, ERV 1,200 mL and RV 1,300 mL. Find VC and TLC. If the FEV_1 is 2.4 L and FVC equals the VC, find the FEV_1/FVC ratio and interpret it.

7. **8 pts** **Lesson 8.3**

   Air is 21% oxygen. Find $P(O_2)$ in the airways at sea level (760 mmHg, minus 47 mmHg water vapor), and explain why oxygen moves from alveolus to blood.

8. **9 pts** **Lesson 8.3**

   Blood has 14 g/dL hemoglobin, 97% saturation and $P(O_2)$ 100 mmHg. Find the oxygen content, and the oxygen delivered per minute at a cardiac output of 5.0 L/min (50 dL/min).

9. **8 pts** **Lesson 8.3**

   Describe the Bohr effect and explain why it is useful during exercise.

10. **7 pts** **Lesson 8.4**

    Draw or describe the breathing-control loop, naming the stimulus, sensors, control center, effectors and response.

11. **8 pts** **Lesson 8.4**

    A town is at 2,400 m where air pressure is about 570 mmHg. Find the humidified $P(O_2)$ in the airways, and describe two ways the body adjusts over the first weeks.

SHORT ESSAY

12. **12 pts** **Lesson 8.1–8.4**

    Choose one: (a) pneumothorax, (b) carbon monoxide poisoning, (c) emphysema, (d) shallow-water blackout. Explain it as a broken mechanism: the normal mechanism, the part that fails, and how the symptoms follow.

ANSWER KEY

1. Nasal cavity, pharynx, larynx, trachea, bronchi, bronchioles (to terminal bronchioles). Nose: warms, moistens and filters air. Epiglottis: covers the larynx in swallowing. Cilia: sweep mucus up to the throat.
2. 6.0 L/min; 3.75 L/min
3. Surfactant lowers surface tension so alveoli stay open and are easy to inflate; a membrane about half a micrometer thick gives gases a very short distance to diffuse.
4. Inhale: diaphragm and external intercostals contract, chest volume rises, intrapulmonary pressure falls below atmospheric (Boyle's law), air flows in. Exhale: muscles relax, lungs recoil, volume falls, pressure rises above atmospheric, air flows out.
5. About 776 mmHg; above atmospheric, so air flows out.
6. VC 4,500 mL; TLC 5,800 mL; ratio 2.4/4.5 ≈ 53%, an obstructive pattern.
7. 0.21 × 713 ≈ 150 mmHg in the airways (alveolar air about 104); blood arrives at about 40 mmHg, so O_2 diffuses down its partial-pressure gradient into the blood.
8. 1.34 × 14 × 0.97 + 0.3 ≈ 18.2 + 0.3 = 18.5 mL/dL; 18.5 × 50 ≈ 925 mL O_2/min
9. More CO_2, acid and heat lower hemoglobin's affinity for oxygen, shifting the curve right; working muscles produce all three, so hemoglobin releases more oxygen exactly where it is needed.
10. Rising CO_2/falling pH → central (medulla) and peripheral (carotid and aortic bodies) chemoreceptors → respiratory centers in medulla and pons → phrenic and intercostal nerves to diaphragm and rib muscles → faster, deeper breathing lowers CO_2 (negative feedback).
11. 0.21 × (570 − 47) ≈ 110 mmHg. Faster, deeper breathing; kidney erythropoietin raises red-cell production and hematocrit (also more of the chemical that helps red cells release oxygen).
12. Look for: the correct normal mechanism (pleural seal and pressure; hemoglobin oxygen binding; alveolar surface area and recoil; the CO_2-driven urge to breathe), the specific failure, and a clear chain from failure to symptoms, with correct use of pressures or the control loop.

UNIT 9

Digestion, Metabolism and the Kidneys

This unit follows a meal through the body and out again. Lessons 9.1 and 9.2 trace the digestive tract and its accessory organs, from Cannon's X-ray pictures of a churning stomach (1897) to Bayliss and Starling's discovery of secretin (1902), the first hormone. Lesson 9.3 follows the fuel into the cells: anabolism and catabolism, the fed and fasting states, vitamins, and how to estimate basal metabolic rate. Lessons 9.4 and 9.5 turn to the kidneys, which filter about 180 liters a day and return 99% of it, and to the balance of water, salt and acid that the kidneys and lungs keep together, ending with how a nurse reads a blood gas.

Each lesson has worked examples with real clinical numbers (filtration rates, clearance, energy needs, blood pH), a labeled diagram to learn, a "disorder as a broken mechanism" question, and TEAS-style test-prep items. The lab work uses kitchen materials: a stocking for peristalsis, soap and oil for bile, lactase and milk, a coffee-filter kidney and red-cabbage indicator for acid and base.

PREREQUISITES

- Unit 2 (membrane transport: osmosis, active transport and cotransport)
- Unit 6 (hormones: insulin, glucagon, ADH, aldosterone and thyroid hormone)
- Unit 8 (breathing and carbon dioxide)
- Biology 4.3 (cellular respiration) and Chemistry (pH and logarithms)

MASTERY CHECKLIST

- ☐ I can trace food through the digestive tract, name the four layers of its wall, and explain peristalsis, segmentation and the stomach's self-protection.
- ☐ I can describe the jobs of the liver, gallbladder and pancreas, the hormones secretin and CCK, and how each kind of nutrient is absorbed.
- ☐ I can explain the fed and fasting states, estimate BMR and daily energy needs, and compute energy from grams of nutrients.
- ☐ I can label a nephron, explain filtration, reabsorption and secretion, and calculate GFR, net filtration pressure and clearance.
- ☐ I can describe the body's fluid compartments and the hormones that control water and salt.
- ☐ I can calculate blood pH with the Henderson–Hasselbalch equation and classify an acid–base disturbance.

LESSONS IN THIS UNIT

9.1 The Digestive Tract: Cannon's X-Ray Pictures of a Working Stomach (1897)

4 sessions of 45 minutes

9.2 Liver, Pancreas and Absorption: Bayliss and Starling Find the First Hormone (1902)

4 sessions of 45 minutes

9.3 Metabolism and Nutrition: From Lavoisier's Guinea Pig to the Harris–Benedict Equation (1918–1919)

4 sessions of 45 minutes

9.4 The Kidney and the Nephron: From Bowman's Capsule to Kolff's Artificial Kidney

4 sessions of 45 minutes

9.5 Fluids, Electrolytes and Acid–Base Balance: Henderson and Hasselbalch's Equation (1908–1916)

4 sessions of 45 minutes

Unit 9 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **6 pts** **Lesson 9.1**

   Name the four layers of the wall of the digestive tract, from the inside out, and say which layer moves the food.

2. **6 pts** **Lesson 9.1**

   Give two ways the stomach protects itself from its own acid, and name the bacterium that most often breaks this protection.

3. **7 pts** **Lesson 9.2**

   Explain how the experiment of Bayliss and Starling showed that secretin is a hormone.

4. **7 pts** **Lesson 9.2**

   Compare the absorption of glucose and of fat: what carries each into the absorbing cell, and which vessel does each enter?

5. **7 pts** **Lesson 9.3**

   A 16-year-old young man is 175 cm tall and weighs 64 kg. Estimate his BMR with the Mifflin–St Jeor equation and his daily needs if he is very active (factor 1.725).

6. **6 pts** **Lesson 9.3**

   A sandwich has 45 g of carbohydrate, 20 g of protein and 14 g of fat. How many kilocalories does it supply?

7. **7 pts** **Lesson 9.3**

   Describe what the liver does with glucose (a) an hour after a meal and (b) after an overnight fast, naming each process and the hormone in charge.

8. **8 pts** **Lesson 9.4**

   The kidneys filter 120 mL of plasma per minute and the person makes 1.5 L of urine a day. Find the filtrate formed per day and the percent reabsorbed.

9. **7 pts** **Lesson 9.4**

   Glomerular blood pressure is 50 mmHg, capsular pressure 15 mmHg and the blood's colloid osmotic pressure 28 mmHg. Find the net filtration pressure. What happens to the GFR if the blood pressure in the glomerulus falls?

10. **7 pts** **Lesson 9.4**

    A patient's urine creatinine is 120 mg/dL, urine flow 1.0 mL/min and plasma creatinine 1.5 mg/dL. Estimate the GFR. Is it normal for a young adult?

11. **7 pts** **Lesson 9.5**

    A man loses a lot of blood. Trace the renin–angiotensin–aldosterone response and say how it restores blood volume and pressure.

LAB AND DATA

12. **10 pts** **Lesson 9.5**

    A blood gas shows bicarbonate 12 mEq/L and P_{CO_2} 28 mmHg. (a) Calculate the pH. (b) Classify the disturbance. (c) What are the lungs doing, and why?

SHORT ESSAY

13. **15 pts** **Lesson 9.1–9.5**

Short essay. Choose one disorder from this unit (an ulcer, celiac disease, PKU, diabetes in the kidney, diabetes insipidus or ketoacidosis). Describe the normal mechanism, the step that fails, the signs that follow from the failure, and how treatment repairs or works around it. Close with one sentence on what the disorder shows about the design of the healthy body.

ANSWER KEY

1. Mucosa, submucosa, muscularis, serosa; the muscularis (circular and longitudinal smooth muscle) moves food by peristalsis and segmentation.
2. A thick alkaline mucus layer, tight junctions between cells, and rapid replacement of the lining (any two); *Helicobacter pylori*.
3. With the nerves to the intestine cut, acid still made the pancreas secrete; an extract of the intestinal lining injected into the blood did the same. So a chemical messenger carried in the blood, not a nerve, switched on the pancreas.
4. Glucose enters with sodium on a cotransporter and passes into the capillaries (to the hepatic portal vein). Fatty acids are carried by bile-salt micelles, rebuilt into triglycerides, packaged as chylomicrons and released into the lacteal (lymph).
5. BMR ≈ 640 + 1093.75 − 80 + 5 = 1658.75, about 1,660 kcal/day; daily ≈ 1658.75 × 1.725 = 2861, about 2,860 kcal/day.
6. 180 + 80 + 126 = 386 kcal.
7. (a) Insulin is high: the liver stores glucose as glycogen (glycogenesis). (b) Glucagon is high: the liver breaks down glycogen (glycogenolysis) and makes new glucose from amino acids and glycerol (gluconeogenesis).
8. 120 × 1440 = 172,800 mL ≈ 172.8 L/day; 1.5 ÷ 172.8 = 0.87% excreted, so about 99.1% reabsorbed.
9. NFP = 50 − (15 + 28) = 7 mmHg. If glomerular blood pressure falls, NFP and GFR fall.
10. (120 × 1.0) ÷ 1.5 = 80 mL/min; lower than the normal of about 100–125 mL/min, suggesting reduced kidney function.
11. Low pressure makes the kidney release renin; renin leads to angiotensin II, which narrows vessels, triggers thirst and ADH, and calls out aldosterone from the adrenal cortex. Aldosterone saves sodium and water follows; ADH saves water; drinking adds more. Volume and pressure rise.
12. (a) 0.03 × 28 = 0.84; 12 ÷ 0.84 = 14.3; log 14.3 = 1.155; pH ≈ 7.25. (b) Metabolic acidosis (pH and bicarbonate both low). (c) Breathing deep and fast to blow off CO_2, a partial respiratory compensation.
13. Answers vary. A full answer (1) describes the normal mechanism accurately, (2) names the failed step, (3) links each sign to the failure, (4) explains the treatment, and (5) reflects thoughtfully on the body's design.

9.1 The Digestive Tract: Cannon's X-Ray Pictures of a Working Stomach (1897)

Mark up this lesson

OBJECTIVES

- Trace food through the organs of the digestive tract and name the job of each.
- Describe the four layers of the tract wall and how peristalsis and segmentation move food.
- Explain how the stomach protects itself from its own acid, and what happens when that protection fails.

> **Warm-up.** Swallow a sip of water while standing on your head (or lying flat with your feet up on the couch, with a parent watching). Did the water still reach your stomach? What does that tell you about how the esophagus moves food?

WATCH

Digestive System, Part 1: Crash Course Anatomy & Physiology #33

CrashCourse · 11:05

https://www.youtube.com/watch?v=yIoTRGfcMqM

> **WHEN TO WATCH**
> After the core ideas, as an overview of the whole tract.

BACKUP VIDEO

GCSE Biology - Digestive System

Cognito · 6:02

https://www.youtube.com/watch?v=vMI46qGQMDw

A shorter tour of the organs, if you want a second pass.

KEY TERMS

alimentary canal

The continuous tube from mouth to anus: mouth, pharynx, esophagus, stomach, small intestine and large intestine.

accessory organs

Organs that help digestion without food passing through them: teeth, tongue, salivary glands, liver, gallbladder and pancreas.

peristalsis

Waves of muscle contraction that push food along the tract in one direction.

segmentation

Back-and-forth contractions of rings of muscle in the small intestine that mix chyme with juices without moving it far.

sphincter

A ring of muscle that closes an opening, such as the lower esophageal sphincter and the pyloric sphincter.

chyme

The soupy mixture of partly digested food and gastric juice that leaves the stomach.

mucosa

The innermost layer of the tract wall; it secretes mucus, enzymes and acid and absorbs nutrients.

gastric pits

Openings in the stomach lining where parietal cells (acid) and chief cells (pepsinogen) release their secretions.

CORE IDEAS

The story. In December 1896 Walter Cannon, a first-year medical student at Harvard, was given a new tool: the X-ray, discovered by Röntgen only a year earlier. Cannon fed animals food mixed with bismuth salts, which block X-rays, and watched the shadow on a fluorescent screen. He watched a pearl button slide down a dog's esophagus, then studied swallowing in geese and watched the stomachs of cats churn their meals in rhythmic waves. He noticed that when a cat was frightened or angry the waves stopped completely. Beaumont had seen the same thing through Alexis St. Martin's stomach seventy years before (Biology 10.3, Beaumont and Digestion). Cannon spent the rest of his career studying how the nervous system and the emotions steer the organs, and he later gave us the word *homeostasis* (Lesson 1.3).

One long tube with helpers. The alimentary canal runs from mouth to anus, a tube several meters long. Food passes through the mouth, pharynx, esophagus, stomach, small intestine and large intestine. The accessory organs (teeth, tongue, salivary glands, liver, gallbladder and pancreas) never hold food, but pour in saliva, bile and enzymes. Every part does some of six jobs: ingestion (taking food in), propulsion (moving it), mechanical digestion (chewing and churning), chemical digestion (enzymes splitting molecules), absorption (moving nutrients into blood and lymph) and defecation (removing what is left).

The wall has four layers. From the inside out: the **mucosa**, a lining of epithelium that secretes and absorbs; the **submucosa**, connective tissue full of blood vessels, lymph vessels and a nerve net; the **muscularis**, an inner circular layer and an outer longitudinal layer of smooth muscle; and the **serosa**, a slippery outer covering. The tract has its own nervous system, the enteric nervous system, with millions of neurons in the wall. It can run peristalsis by itself, while the parasympathetic nerves speed digestion and the sympathetic nerves slow it (Lesson 5.5). That is why a frightened cat's stomach stood still.

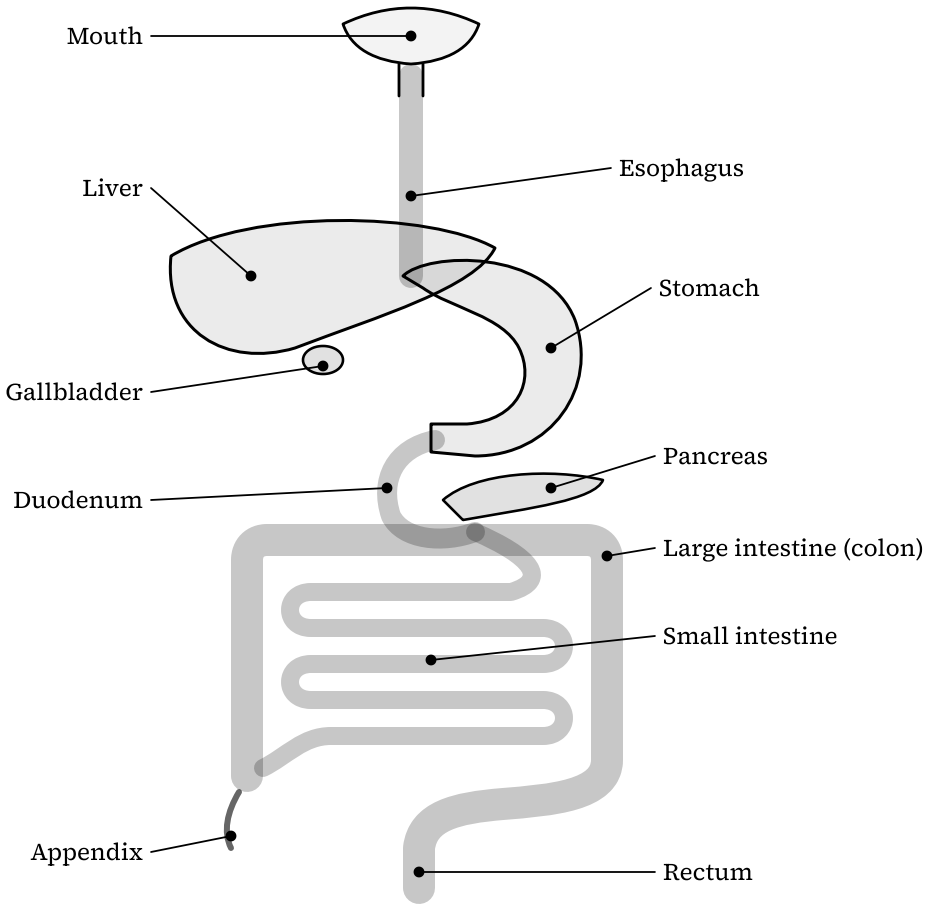
Mouth, pharynx and esophagus. Chewing breaks food into a soft ball, the bolus, and salivary amylase begins splitting starch. Swallowing starts as a voluntary push of the tongue, then becomes a reflex: the soft palate closes off the nose, the larynx rises and the epiglottis folds over it so food does not enter the airway (Lesson 8.1). The esophagus, about 25 cm long, carries the bolus down by peristalsis in a few seconds, even upside down. The lower esophageal sphincter then closes to keep stomach acid out of the esophagus.

The stomach. The stomach is a J-shaped bag that stretches from about 50 mL empty to more than a liter after a meal; folds called rugae flatten as it fills. It has a third, oblique layer of muscle for churning. Gastric pits in its lining hold parietal cells, which secrete hydrochloric acid (pH about 1.5 to 3.5) and intrinsic factor, and chief cells, which secrete pepsinogen; the acid turns pepsinogen into pepsin, which starts protein digestion. G cells release the hormone gastrin, which speeds acid secretion. Over two to four hours the food becomes chyme, and the pyloric sphincter lets a few milliliters at a time squirt into the small intestine.

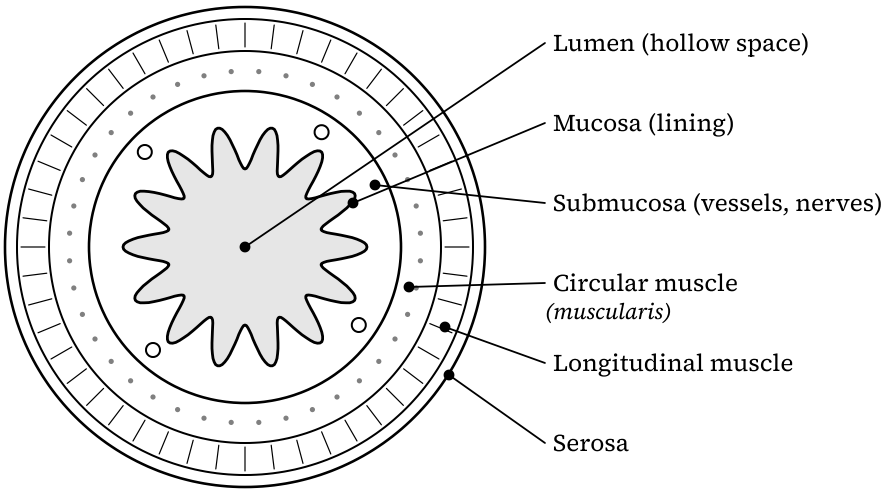
The intestines. The small intestine, about 3 meters long in a living person, has three parts: the duodenum (about 25 cm, where bile and pancreatic juice enter), the

jejunum and the ileum. Most chemical digestion and nearly all absorption happen here (Lesson 9.2). Segmentation mixes the chyme, and slow peristalsis moves it on over three to five hours. The large intestine (cecum with the appendix, ascending, transverse, descending and sigmoid colon, then rectum) is about 1.5 meters long. It absorbs most of the remaining water and salts, and its helpful bacteria ferment fiber and make vitamin K. Its contents move slowly, often for a day or more.

When it goes wrong. The stomach does not digest itself because a thick layer of alkaline mucus covers its lining, tight junctions seal the cells together, and the lining replaces itself every few days. In 1982 the Australian doctors Barry Marshall and Robin Warren showed that most peptic ulcers are caused by the bacterium *Helicobacter pylori*, which weakens that mucus barrier. Marshall even drank a culture of the bacteria to prove it, and the two won the Nobel Prize in 2005; ulcers that once needed surgery are now cured with antibiotics. In reflux disease the lower esophageal sphincter does not close well, so acid splashes up and burns the esophagus, which has no mucus shield like the stomach's.



The digestive tract runs from mouth to rectum; the liver, gallbladder and pancreas are accessory organs that pour juices into the duodenum.



The same four layers line the whole tube, from the esophagus to the rectum; the stomach adds a third (oblique) muscle layer.

> **Safety first.** Do the upside-down swallow only lying on a couch or bed with your feet raised, never in a headstand, and only a small sip. Wash hands before handling the food in the stomach model, and throw it away afterward.

LAB

Peristalsis in a Stocking and a Stomach in a Bag

You will model peristalsis, then compare how fast mechanical and chemical action break down food.

You will need

- An old nylon stocking or a long, thin sock; a tennis ball or a small orange
- Two zip bags, two crackers, water, and a little vinegar or lemon juice
- A timer and your sketchbook

Steps

1. Push the ball through the stocking by squeezing only the stocking behind it. Then try to move it by squeezing the stocking in front of it. Which works? That is peristalsis: the muscle behind the bolus contracts while the muscle ahead relaxes.
2. Put one cracker and 50 mL of water in bag A. Put the other cracker with 50 mL of water and a spoon of vinegar in bag B. Squeeze each bag gently for 2 minutes (churning), then let them rest.
3. Every 2 minutes for 10 minutes, note how broken down each cracker looks.
4. Draw the stocking model and label where the circular muscle contracts and where it relaxes.

Check your work

- ☐ Why can you swallow lying down or even upside down?
- ☐ What does squeezing the bag model, and what does the vinegar model? What important ingredient of real gastric juice is missing from your bag?
- ☐ Why would a weak lower esophageal sphincter cause heartburn when lying down after a big meal?

LAB NOTEBOOK

1. A labeled drawing of the digestive tract tracing a bite of food, with the time spent in each part.
2. A cross-section of the tract wall with its four layers, labeled from the inside out.

From history. Cannon later found that the stomach stops churning during fear and rage because the sympathetic nerves take over, and in 1915 he wrote a whole book on the body's changes in pain, hunger, fear and rage. His phrase "fight or flight" is still used in every physiology course. He first reported the bismuth X-ray studies in 1897 and 1898, while still a student.

Practice habit. When you study any organ, say aloud its three facts in the same order: what goes in, what it does to it, and what comes out. Do it for each organ of the tract until you can tour the whole canal without notes.

WORKED EXAMPLES

Example 1. Stomach juice has a pH of about 2. Pancreatic juice, which neutralizes the chyme in the duodenum, has a pH of about 8. How many times greater is the hydrogen-ion concentration of the stomach juice?

Show solution

1. Each step of 1 on the pH scale is a factor of 10 in hydrogen-ion concentration.
2. The difference is $8 - 2 = 6$ pH units, so the factor is 10^6.

Answer: About 1,000,000 times greater; that is why the duodenum needs so much bicarbonate.

Example 2. About 9.0 liters of fluid enter the digestive tract each day (about 2 L from food and drink and about 7 L of saliva, gastric juice, bile, pancreatic juice and intestinal juice). The small intestine absorbs about 7.5 L and the large intestine about 1.4 L. How much leaves in the feces, and what percent of the total does the small intestine absorb?

Show solution

1. Left over: $9.0 - 7.5 - 1.4 = 0.1$ L.
2. Small intestine: $7.5 \div 9.0 = 0.833$, about 83%.

Answer: About 0.1 L (100 mL) leaves in the feces; the small intestine absorbs about 83% of the fluid.

Example 3. One meal spends about 3 hours in the stomach, 5 hours in the small intestine and 30 hours in the large intestine. What is the total time from swallowing to the end of the tract, and what fraction of it is spent in the large intestine?

Show solution

1. Total: 3 + 5 + 30 = 38 hours.
2. Large intestine: 30 ÷ 38 = 0.79.

Answer: About 38 hours; nearly 80% of the time is in the large intestine, where water is slowly absorbed.

PRACTICE

CONCEPT CHECKS

1. Easy List the organs of the alimentary canal in order from mouth to anus.

   Show answer

   Mouth, pharynx, esophagus, stomach, small intestine (duodenum, jejunum, ileum), large intestine (cecum, colon, rectum), anus.

2. Easy Name the four layers of the wall of the digestive tract, from the inside out.

   Show answer

   Mucosa, submucosa, muscularis (circular then longitudinal muscle) and serosa.

3. Easy What is the difference between peristalsis and segmentation?

   Show answer

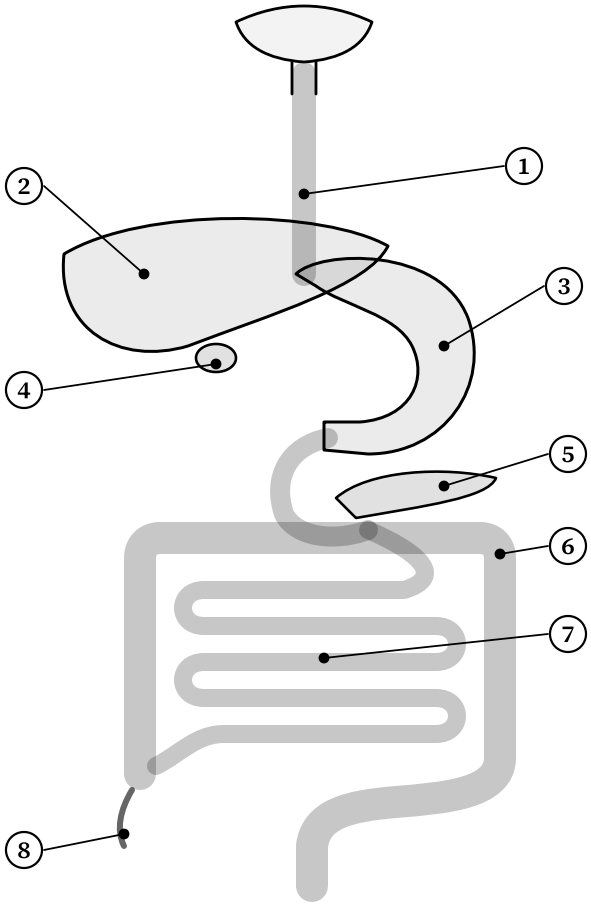
   Peristalsis is a traveling wave that pushes food forward; segmentation is back-and-forth squeezing by rings of muscle that mixes chyme with juices without moving it far.

4. Medium Which cells of the stomach secrete hydrochloric acid, and which secrete pepsinogen? Why is pepsin released as an inactive form?

   Show answer

   Parietal cells secrete acid (and intrinsic factor); chief cells secrete pepsinogen. Released inactive, it cannot digest the cells that make it; acid turns it into pepsin only in the stomach's lumen.

5. **Medium** Name the parts numbered 1 to 8 in the diagram.



Show answer

1 esophagus, 2 liver, 3 stomach, 4 gallbladder, 5 pancreas, 6 large intestine (colon), 7 small intestine, 8 appendix.

6. **Medium** A cracker you chew for two minutes tastes sweeter. Which enzyme is at work, and what is it doing?

Show answer

Salivary amylase is splitting starch into maltose and other sugars.

7. **Medium** A man's small intestine absorbs 7.2 L of fluid a day out of 9.0 L that enters the tract. What percent is that?

Show answer

7.2 ÷ 9.0 = 0.80, so 80%.

8. Hard **Disorder as a broken mechanism.** Explain how an *H. pylori* infection leads to a stomach ulcer. Which protective mechanism has failed, and why do antibiotics cure it?

Show answer

The bacteria live in the mucus and weaken the alkaline mucus barrier, so acid and pepsin reach the lining and digest it, making an open sore. Killing the bacteria lets the barrier and lining repair themselves.

9. Hard Predict the effect: a frightened student tries to eat a big lunch just before a performance. Why might the food sit heavily in his stomach?

Show answer

Fear activates the sympathetic nervous system, which slows peristalsis and gastric secretion, as Cannon saw in frightened cats; the stomach empties slowly.

TEST PREP

10. Medium Test prep. Which structure keeps food from entering the larynx during swallowing? (A) uvula (B) epiglottis (C) pyloric sphincter (D) lower esophageal sphincter

Show answer

(B) the epiglottis.

11. Medium Test prep (select all that apply). Which happen mainly in the large intestine? (A) absorption of water (B) digestion of protein by pepsin (C) bacterial fermentation of fiber (D) production of vitamin K by bacteria (E) emulsification of fat by bile

Show answer

A, C and D.

COMMON MISTAKES

- Thinking the stomach absorbs most nutrients; it absorbs only a little (water, alcohol, some drugs). The small intestine absorbs nearly everything.
- Calling the liver, pancreas and gallbladder part of the alimentary canal; food never passes through them. They are accessory organs.
- Thinking gravity moves food down the esophagus; peristalsis does, which is why astronauts and upside-down swallowers can still eat.

- Mixing up the two sphincters: the lower esophageal sphincter is at the top of the stomach, the pyloric sphincter at the bottom.
- Thinking stomach acid digests food by itself; the acid mainly unfolds proteins, kills germs and activates pepsin, the enzyme that does the cutting.

Make it a game · Bolus Relay. Tape eight paper signs around the house for the organs from mouth to rectum. The student carries a rolled-up sock (the bolus) from sign to sign; at each one the parent asks one question (What happens here? Which juice? Which sphincter comes next?). A right answer moves the bolus on; a wrong answer sends it back one organ, the way reflux sends acid backward. Time the whole trip and try to beat it next time.

Scripture. "He causeth the grass to grow for the cattle, and herb for the service of man: that he may bring forth food out of the earth." (Psalm 104:14, KJV)

God brings food out of the earth and also made the long, careful tube that turns it into the stuff of our own bodies. Both are gifts.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

9.2 Liver, Pancreas and Absorption: Bayliss and Starling Find the First Hormone (1902)

Mark up this lesson

OBJECTIVES

- Describe the jobs of the liver, gallbladder and pancreas in digestion and the ducts that carry their juices.
- Explain how carbohydrates, proteins and fats are finished off and absorbed through the villi.
- Explain how secretin and cholecystokinin coordinate the juices, and how lactose intolerance, celiac disease and gallstones break the system.

> **Warm-up.** Shake a little cooking oil with water in a jar and watch it separate. Now add a drop of dish soap and shake again. What changed? Which juice in your body do you think does the soap's job?

WATCH

Digestive System, Part 3: Crash Course Anatomy & Physiology #35

CrashCourse · 10:24

https://www.youtube.com/watch?v=jGme7BRkpuQ

> **WHEN TO WATCH**
> After the core ideas on the liver and pancreas.

BACKUP VIDEO

GCSE Biology - Digestive Enzymes (2027/28 exams)

Cognito · 4:24

https://www.youtube.com/watch?v=G2y6_VShnwc

A short review of amylase, protease, lipase and bile.

KEY TERMS

hepatic portal vein

The vein that carries blood from the stomach and intestines to the liver before it returns to the heart, so absorbed nutrients pass through the liver first.

bile

A greenish fluid made by the liver and stored in the gallbladder; its bile salts break fat into tiny droplets (emulsification).

pancreatic juice

The pancreas's digestive fluid: bicarbonate to neutralize acid, plus amylase, lipase, nucleases and protein-splitting enzymes such as trypsin.

secretin

A hormone from the duodenum, released when acid chyme arrives, that tells the pancreas to pour out bicarbonate; the first hormone discovered.

cholecystokinin (CCK)

A hormone from the duodenum, released when fat and protein arrive, that makes the gallbladder contract and the pancreas release enzymes.

villi and microvilli

Finger-like folds of the intestinal lining (villi) covered with cells whose surfaces carry tiny projections (microvilli, the brush border).

lacteal

A lymph capillary in the center of each villus that absorbs fats packaged as chylomicrons.

brush-border enzymes

Enzymes fixed in the microvilli, such as lactase, sucrase, maltase and peptidases, that finish digestion right at the absorbing surface.

CORE IDEAS

The story. In the 1890s the great Russian physiologist Ivan Pavlov taught that the pancreas was switched on by nerves. On January 16, 1902, at University College London, William Bayliss and his brother-in-law Ernest Starling cut every nerve to a loop of a dog's intestine and put a little acid into it. The pancreas still poured out its juice. So the signal must travel in the blood. They scraped the lining of the intestine, ground it with acid, filtered it and injected the extract into a vein: the pancreas responded within minutes. They named the chemical messenger *secretin*. In 1905

Starling coined the word *hormone*, from a Greek word meaning "I set in motion," and the whole science of endocrinology (Unit 6) began with a gut hormone.

The liver. The liver, about 1.5 kg, is the largest internal organ. Its millions of cells (hepatocytes) sit in lobules between two blood supplies: the hepatic artery brings oxygen, and the **hepatic portal vein** brings everything absorbed from the stomach and intestines. So nutrients, drugs and toxins pass through the liver before reaching the rest of the body. The liver makes up to about a liter of bile a day; stores glucose as glycogen and releases it between meals; makes plasma proteins such as albumin and clotting factors; turns the ammonia from protein breakdown into urea; stores iron and vitamins A, D and B_{12}; and breaks down alcohol, drugs and old hormones.

Bile and the gallbladder. Bile contains bile salts, cholesterol and bilirubin, a yellow pigment from worn-out red blood cells. Between meals bile backs up into the gallbladder, which stores and concentrates it. When fatty chyme enters the duodenum, the duodenum releases **CCK**, the gallbladder squeezes, and bile flows down the common bile duct. Bile salts have one end that likes water and one that likes fat, like the dish soap in the warm-up. They break big fat globules into tiny droplets so that lipase has far more surface to work on. Bile emulsifies; it does not digest.

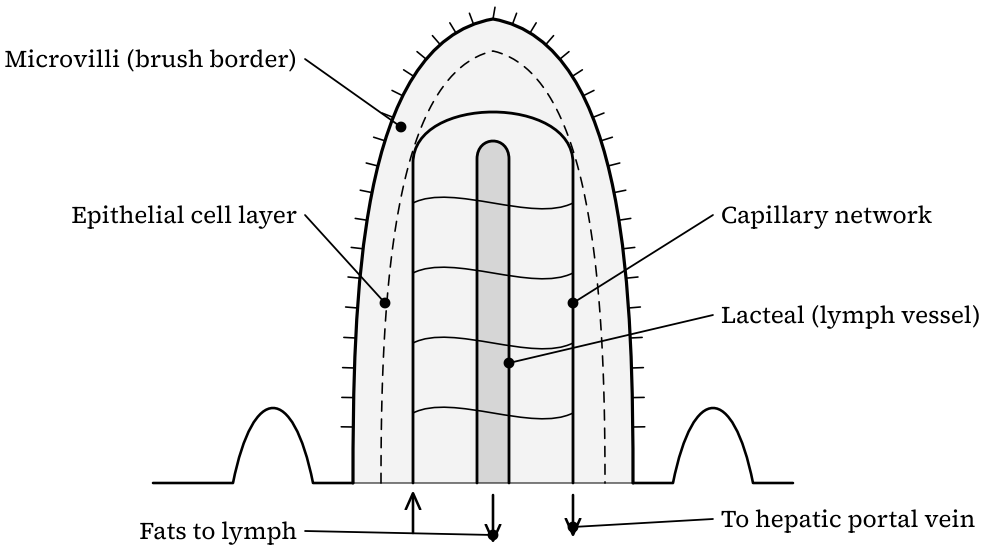
The pancreas. The pancreas is two organs in one. Its islets make insulin and glucagon (Lesson 6.4); its acinar cells make about 1.2 to 1.5 liters of pancreatic juice a day. **Secretin**, released when acid reaches the duodenum, calls out bicarbonate, which raises the pH so the intestinal enzymes can work. CCK calls out the enzymes: pancreatic amylase for starch, lipase for fats, nucleases for DNA and RNA, and trypsinogen, which an intestinal enzyme (enteropeptidase) turns into trypsin; trypsin then activates the other protein-splitting enzymes. The pancreatic duct joins the common bile duct, and both empty into the duodenum.

Finishing the job at the brush border. The small intestine's lining is folded three times over: circular folds, then villi about a millimeter tall, then microvilli on every absorbing cell. Enzymes fixed in the microvilli finish digestion: maltase, sucrase and lactase split double sugars into glucose, fructose and galactose, and peptidases split short peptides into amino acids. Glucose and galactose enter the cells by riding in with sodium (sodium–glucose cotransport, an active process, Lesson 2.2); amino

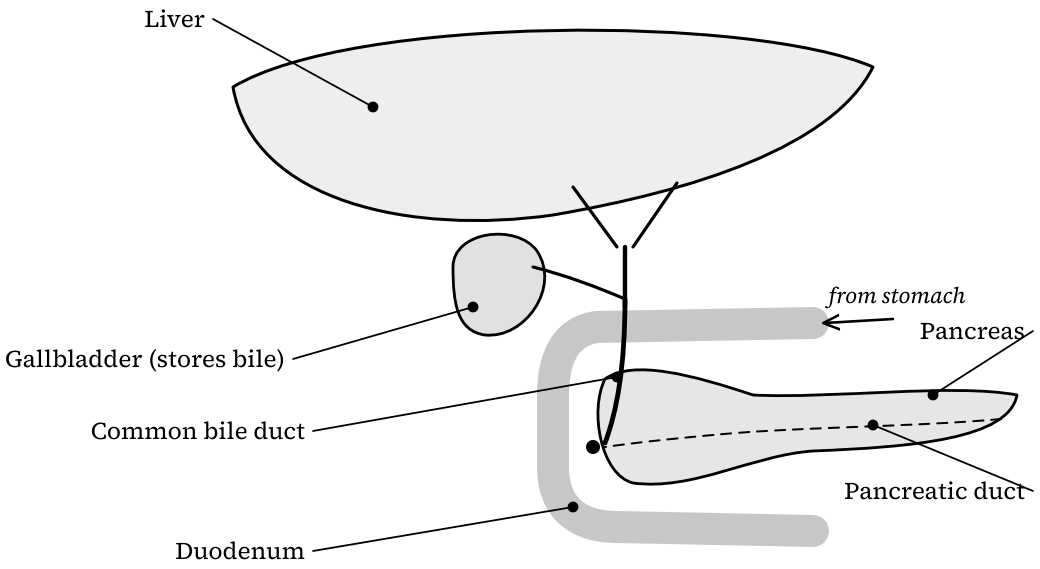
acids use similar sodium carriers; fructose moves by facilitated diffusion. Water follows the absorbed solutes by osmosis.

Two roads out of the villus. Sugars, amino acids, water-soluble vitamins and minerals enter the **capillaries** of the villus and travel by the hepatic portal vein to the liver. Fats take a different road: bile salts ferry fatty acids and monoglycerides to the cells in tiny clusters (micelles); inside, the cells rebuild triglycerides, wrap them in protein as **chylomicrons**, and release them into the **lacteal**. The lymph carries them up the thoracic duct into a vein near the heart (Lesson 7.4), bypassing the liver at first. Vitamin B_{12} is a special case: it must bind intrinsic factor from the stomach and is absorbed only in the last part of the ileum.

When it goes wrong. In **lactose intolerance**, the brush border makes little lactase, so milk sugar passes undigested into the colon, where it draws water by osmosis and bacteria ferment it into gas. In **celiac disease**, the immune system reacts to gluten in wheat, barley and rye and flattens the villi, so the surface area collapses and nutrients are lost. A **gallstone** stuck in the common bile duct stops bile: fat is poorly digested, and bilirubin backs up into the blood and turns the skin and eyes yellow (jaundice). Newborns often have mild jaundice because their livers are still learning to clear bilirubin; blue-light therapy breaks it down in the skin.



Each villus sends sugars and amino acids into its capillaries, bound for the liver, and fats into its central lacteal, bound for the lymph.



Bile from the liver and gallbladder and juice from the pancreas meet and enter the duodenum together.

> **Safety first.** Lactase drops or tablets are a food supplement, but use them only with a parent's permission and do not drink the test milk afterward. Iodine stains and is poisonous; an adult handles it.

LAB

Bile in a Jar and Lactase in a Cup

You will model emulsification and see a brush-border enzyme at work.

You will need

- Two jars with lids, cooking oil, water, dish soap (the bile model)
- Milk, lactase drops or a crushed lactase tablet, glucose test strips (sold for urine testing at a pharmacy)
- Two small cups, a dropper, a timer

Steps

1. Put 100 mL of water and 2 spoons of oil in each jar. Add 3 drops of dish soap to jar B only. Shake both for 20 seconds and time how long until the oil forms a layer again.
2. Put 50 mL of milk in each of two cups. Add lactase to cup B only, stir, and leave both for 20 minutes at room temperature.
3. Dip a glucose test strip in each cup and compare the color with the chart on the bottle.
4. Record your results in a table.

Check your work

- ☐ Which jar stayed cloudy longer, and why would tiny droplets help lipase?
- ☐ Why does only cup B show glucose? Which sugar did the enzyme split, and into which two sugars?
- ☐ Explain why a person without enough lactase feels bloated after a milkshake.

LAB NOTEBOOK

1. A labeled villus showing microvilli, capillaries and the lacteal, with arrows for the two roads nutrients take.
2. A flow chart of the hormones: acid → secretin → bicarbonate; fat and protein → CCK → bile and enzymes.

From history. Starling and Bayliss worked as a team for years at University College London. Starling also described the forces that move fluid across capillary walls (Lesson 9.4) and the rule that a heart stretched by more returning blood pumps harder (Lesson 7.2). Bayliss wrote one of the great textbooks of his day, *Principles of General Physiology* (1915).

Practice habit. For each digestive juice, write a three-part card: who makes it, what calls it out, and what it does. Read the stack once a day this week, shuffling the order.

WORKED EXAMPLES

Example 1. Bile breaks one fat droplet 1 mm across into droplets 1 μm across (1 mm = 1000 μm). How many small droplets are made, and how many times greater is their total surface area?

Show solution

1. Volume scales with the cube of the diameter: $(1000 \div 1)^3 = 10^9$ small droplets.
2. Each small droplet has $(1/1000)^2$ of the big droplet's area, so total area = $10^9 \times 10^{-6} = 10^3$ times as much.
3. In general, splitting into droplets of diameter d multiplies the area by D ÷ d.

Answer: About a billion droplets with 1,000 times the surface area for lipase to attack.

Example 2. The World Health Organization's oral rehydration salts make 1 liter with 13.5 g of glucose (molar mass 180 g/mol) and 2.6 g of sodium chloride (58.4 g/mol), plus potassium chloride and sodium citrate. How many millimoles of glucose and of sodium from the salt are in a liter? Why is the glucose there?

Show solution

1. Glucose: 13.5 ÷ 180 = 0.075 mol = 75 mmol.
2. Sodium from NaCl: 2.6 ÷ 58.4 = 0.0445 mol, about 45 mmol (the citrate adds about 30 more, for about 75 mmol of sodium in all).
3. The intestine absorbs glucose and sodium together on the same carrier, and water follows them by osmosis.

Answer: About 75 mmol of glucose and 45 mmol of sodium from the salt. The glucose drags sodium, and with it water, into the body even during diarrhea, which is why this simple drink has saved millions of children.

Example 3. The liver receives about 1.5 L of blood per minute when the heart pumps 5.6 L per minute. What percent of the cardiac output is that, and how many liters pass through the liver in a day?

Show solution

1. 1.5 ÷ 5.6 = 0.268, about 27%.
2. 1.5 L/min × 1440 min = 2160 L.

Answer: About 27% of the cardiac output, roughly 2,200 liters a day.

PRACTICE

CONCEPT CHECKS

1. Easy What does bile do, and what does it not do?

Show answer

It emulsifies fat into small droplets; it contains no digestive enzymes, so it does not split fat molecules itself.

2. **Easy** Name the hormone that tells the pancreas to release bicarbonate, and the hormone that makes the gallbladder contract.

Show answer

Secretin (bicarbonate); cholecystokinin, CCK (gallbladder and enzymes).

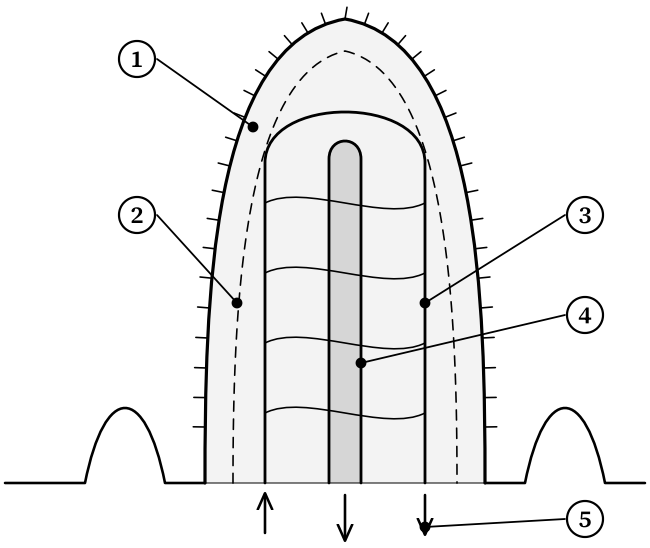
3. **Easy** Why does blood from the intestines go to the liver before the heart?

Show answer

The hepatic portal vein carries absorbed nutrients and toxins to the liver first, so it can store glucose, process nutrients and remove toxins and drugs before the blood reaches the rest of the body.

DIAGRAM AND DATA QUESTIONS

4. **Medium** Name the parts numbered 1 to 5 in the diagram of a villus, and say which kind of nutrient enters part 4.



Show answer

1 microvilli (brush border), 2 epithelial cell layer, 3 capillary network, 4 lacteal, 5 the vessel leading to the hepatic portal vein (venule). Fats, as chylomicrons, enter the lacteal.

5. Medium How did Bayliss and Starling show that the pancreas could be switched on without nerves?

Show answer

They cut all the nerves to a loop of intestine and the pancreas still responded to acid; then an extract of the intestinal lining injected into the blood also made the pancreas secrete, so the messenger traveled in the blood.

6. Medium A fat droplet 0.5 mm across is emulsified into droplets 5 µm across. By what factor does the surface area increase?

Show answer

D ÷ d = 500 µm ÷ 5 µm = 100 times.

7. Medium Trace a molecule of starch from a slice of bread to glucose in the blood, naming each enzyme.

Show answer

Salivary amylase (mouth) and pancreatic amylase (duodenum) split starch into maltose; maltase in the brush border splits maltose into glucose; glucose enters the cells with sodium and passes into the capillaries.

8. Hard **Disorder as a broken mechanism.** In celiac disease, why does a person lose weight and become short of iron and vitamins even while eating well?

Show answer

The immune reaction to gluten flattens the villi and microvilli, so the absorbing surface and the brush-border enzymes are greatly reduced; food passes through without being fully digested or absorbed.

9. Hard Predict the effect: a gallstone blocks the common bile duct. What happens to (a) fat digestion, (b) the color of the skin and eyes, (c) the color of the stool?

Show answer

(a) Fat is poorly emulsified and digested, so fatty stools appear. (b) Bilirubin backs up into the blood, causing jaundice. (c) Stools become pale because the bile pigment no longer reaches the intestine.

TEST PREP

10. **Medium** Test prep. Which enzyme is secreted in an inactive form and activated in the small intestine? (A) salivary amylase (B) lactase (C) trypsinogen (D) bile

Show answer

(C) trypsinogen, activated to trypsin by enteropeptidase.

11. **Medium** Test prep. In which part of the small intestine is vitamin B_{12} absorbed, and what must it bind first?

Show answer

In the ileum, bound to intrinsic factor from the stomach's parietal cells.

COMMON MISTAKES

- Saying the gallbladder makes bile; the liver makes it, the gallbladder only stores and concentrates it.
- Calling bile an enzyme; it is a detergent-like emulsifier.
- Forgetting that fats go into the lymph (lacteals) while sugars and amino acids go into the blood capillaries.
- Thinking all digestion is finished in the lumen; the last steps happen in the brush border of the absorbing cells.
- Mixing up secretin (bicarbonate, triggered by acid) and CCK (bile and enzymes, triggered by fat and protein).

Make it a game · Who Am I? Gut Edition. Write each of these on a card: liver, gallbladder, pancreas, bile, secretin, CCK, trypsin, lactase, lacteal, hepatic portal vein. The parent draws a card and gives clues one at a time ("I am made in the duodenum… I answer acid…"). The student guesses; one point for a guess after one clue, half a point after two. Then switch: the student gives the clues and the parent guesses.

Scripture. "Be not wise in thine own eyes: fear the LORD, and depart from evil. It shall be health to thy navel, and marrow to thy bones." (Proverbs 3:7–8, KJV)

Bayliss and Starling overturned the teaching of the most famous physiologist of their day by careful testing rather than by trusting their own cleverness. Humility before the facts, and before God, is the posture of good science.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

9.3 Metabolism and Nutrition: From Lavoisier's Guinea Pig to the Harris–Benedict Equation (1918–1919)

Mark up this lesson

OBJECTIVES

- Distinguish anabolism and catabolism, and describe what the body does with fuel in the fed and fasting states.
- Estimate basal metabolic rate with a prediction equation and total daily energy use with an activity factor.
- Name the energy content of carbohydrate, protein and fat, the fat- and water-soluble vitamins, and explain how a missing enzyme or vitamin breaks metabolism.

> **Warm-up.** Hold your hand an inch from a family member's arm without touching. Can you feel warmth? Where does that heat come from, and why does it keep coming even while the person sleeps?

WATCH

Metabolism & Nutrition, Part 1: Crash Course Anatomy & Physiology #36

CrashCourse · 10:32

https://www.youtube.com/watch?v=fR3NxCR9z2U

> **WHEN TO WATCH**
> After the core ideas on anabolism, catabolism and nutrients.

BACKUP VIDEO

Hormone control of hunger

khanacademymedicine · 3:37

https://www.youtube.com/watch?v=EVkFPeP5sFI

With the fed and fasting states: how hormones signal hunger and fullness.

KEY TERMS

metabolism

All the chemical reactions in the body: catabolism (breaking molecules down, releasing energy) plus anabolism (building molecules up, using energy).

basal metabolic rate (BMR)

The energy the body uses at complete rest, awake, in a warm room and fasting, just to keep its cells and organs running.

kilocalorie (kcal)

The food Calorie: the energy that warms 1 kg of water by 1 °C, equal to 4.184 kJ.

glycogenesis and glycogenolysis

Building glycogen from glucose (after a meal) and breaking glycogen back into glucose (between meals).

gluconeogenesis

Making new glucose in the liver from non-carbohydrate sources such as amino acids, lactate and glycerol.

ketone bodies

Small acids the liver makes from fatty acids when insulin is low; the brain can burn them, but too many acidify the blood.

vitamins

Organic molecules needed in small amounts, many as helpers (coenzymes) for enzymes: fat-soluble A, D, E and K and water-soluble B group and C.

thermic effect of food

The energy used to digest, absorb and process a meal, roughly a tenth of daily energy use.

CORE IDEAS

The story. In the winter of 1782–1783 Antoine Lavoisier and Pierre-Simon Laplace put a guinea pig in a cage packed in ice and measured how much ice it melted in ten hours. They compared that heat with the carbon dioxide it breathed out and concluded that respiration is a slow combustion (PE 9 Lesson 3.1). A century later Wilbur Atwater built a room-sized calorimeter in Connecticut and measured the energy of foods (Food Science 10.1, Atwater's Calorimeter). His colleague Francis Benedict measured the resting breathing and heat output of 239 men and women, and of newborn babies, at the Carnegie Nutrition Laboratory in Boston, and with the statistician J. Arthur Harris published equations, in 1918 and 1919, that predict basal metabolism from weight, height and age. Doctors and dietitians still use their method today.

Building up and breaking down. Catabolism breaks large molecules into small ones and captures part of the energy in ATP; anabolism uses ATP to build proteins, glycogen, fat and new cells. Glucose is the main fuel: glycolysis, the Krebs cycle and the electron transport chain turn it into carbon dioxide, water and about 30 ATP (Biology 4.3). Fatty acids are cut into two-carbon pieces (acetyl CoA) that enter the same Krebs cycle. Amino acids are mostly used for building, but they can be burned after the liver removes their nitrogen as urea, which the kidneys excrete (Lesson 9.4). Only about 40% of food energy ends up in ATP; the rest becomes heat, which keeps you near 37 °C.

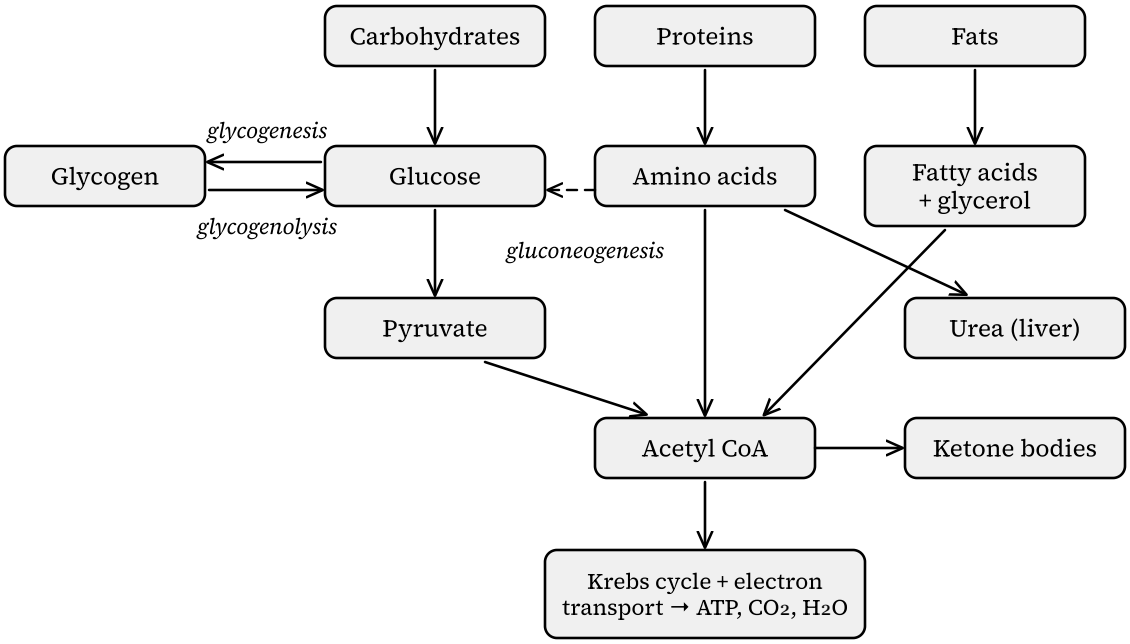
The fed state and the fasting state. For about four hours after a meal (the absorptive state), insulin is high. Cells take in glucose; the liver and muscles store it as glycogen (glycogenesis); fat cells store extra fuel as fat; and amino acids build proteins. Between meals and overnight (the post-absorptive state), insulin falls and glucagon rises (Lesson 6.4). The liver breaks glycogen into glucose (glycogenolysis) and, once its store of about 100 g is running low, makes new glucose from amino acids and glycerol (gluconeogenesis). Fat cells release fatty acids for the muscles. In a long fast the liver turns fatty acids into ketone bodies, which the brain can burn.

Nutrients. Carbohydrate and protein each supply about 4 kcal per gram and fat about 9 kcal per gram. Some amino acids and two fatty acids are *essential*: the body cannot make them, so food must supply them. Vitamins A, D, E and K dissolve in fat, are stored in the liver and fat tissue, and can build up to harmful levels if taken in excess; the B vitamins and vitamin C dissolve in water and must be eaten regularly. Minerals such as calcium, iron, sodium, potassium and iodine build bone, carry oxygen, run nerves and make thyroid hormone. Water, often forgotten, is the nutrient you would miss first. The Cooking and PE courses put this to work at the table (Culinary Arts 8.2, Macronutrients, Food Energy and Eating for Sport).

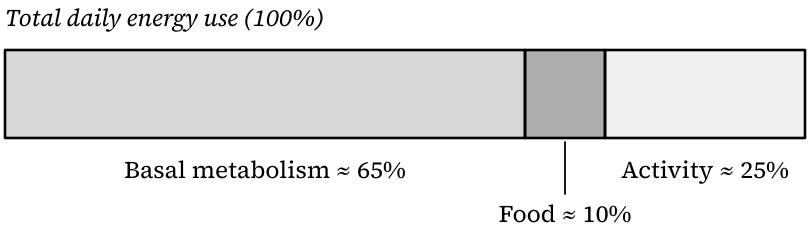
Where the energy goes. A moderately active person spends roughly 60–70% of a day's energy on basal metabolism (the brain, liver, heart, kidneys and muscles at rest), about 10% on processing food, and the rest on activity. BMR is higher in larger and more muscular people and in growing teenagers, and lower with age (Lesson 10.2). Thyroid hormone sets its pace (Lesson 6.3): too much speeds every cell, too little slows them. The hypothalamus balances heat made against heat lost by sweating, shivering and changing skin blood flow. Energy balance is a matter of

health and strength, not of looks; a growing body needs enough fuel, protein, calcium and iron.

When it goes wrong. Every step of metabolism is run by an enzyme, so a missing enzyme blocks a whole road. In **phenylketonuria (PKU)** the liver lacks the enzyme that turns the amino acid phenylalanine into tyrosine; phenylalanine builds up and harms the developing brain. In the early 1960s Robert Guthrie developed a simple blood test from a heel prick, and newborns are now screened; a special diet from birth lets children with PKU grow up healthy. Missing a vitamin breaks a step as well: without vitamin C, the enzymes that build collagen fail, and the gums bleed and wounds open in **scurvy**, as the naval surgeon James Lind showed in 1747 when oranges and lemons cured sick sailors.



All three fuels meet at acetyl CoA; the liver decides whether glucose is stored, released or newly made.



Most of a day's energy keeps the body running at rest; activity is the part that changes most from day to day.

LAB

A Day's Energy: Estimate, Log and Compare

You will estimate your own basal metabolic rate and daily needs, then compare them with a one-day food log, looking at nutrients rather than at weight.

You will need

- A bathroom scale and a tape measure, a calculator
- Nutrition Facts labels from your family's food, or the USDA FoodData Central website with a parent
- Your sketchbook for a food log

Steps

1. Measure your height in cm and weight in kg. Use the Mifflin–St Jeor equation to estimate your BMR, then multiply by an activity factor (1.375 lightly active, 1.55 moderately active, 1.725 very active).
2. Log everything you eat and drink for one ordinary day, with amounts.
3. For each food, find the grams of carbohydrate, protein and fat. Multiply by 4, 4 and 9 and total the kilocalories.
4. Make a bar chart of the percent of energy from carbohydrate, protein and fat, and list which foods supplied calcium, iron and vitamin C.

Check your work

- ☐ How close was your intake to your estimate? Why might one day's log be misleading?
- ☐ The equation was built from adult measurements. Why might it underestimate the needs of a growing teenager?
- ☐ Which nutrient would you most like to add more of, and which food would supply it?

LAB NOTEBOOK

1. The metabolic map: carbohydrates, proteins and fats meeting at acetyl CoA, with glycogen, gluconeogenesis, urea and ketones marked.
2. Your bar chart of where your day's energy came from.

KEY FORMULAS

$$\text{BMR (men)} \approx 10W + 6.25H - 5A + 5$$

$$\text{BMR (women)} \approx 10W + 6.25H - 5A - 161$$

W in kg, H in cm, A in years; BMR in kcal per day (Mifflin–St Jeor, 1990).

$$\text{daily energy} \approx \text{BMR} \times \text{activity factor } (1.2 \text{ to } 1.9)$$

Energy: carbohydrate 4 kcal/g, protein 4 kcal/g, fat 9 kcal/g.

From history. Benedict was so careful that he measured volunteers lying still for hours in the morning before breakfast, and kept them in a quiet room at a comfortable temperature; that is still the definition of "basal" conditions. The Harris–Benedict equations were revised in 1984, and the Mifflin–St Jeor equation of 1990, used in this lesson, fits modern adults a little better.

Practice habit. When you read a Nutrition Facts label, do the 4–4–9 multiplication in your head and check it against the calories listed. Do one label a day this week.

Career connection. A **registered dietitian** plans meals for hospital patients, athletes, children with PKU or diabetes and older adults, using exactly these equations and food tables. The path is a bachelor's degree in nutrition, supervised practice and a national exam; the TEAS-style science in this unit is the foundation.

WORKED EXAMPLES

Example 1. Estimate the basal metabolic rate of a 17-year-old young man who is 178 cm tall and weighs 68 kg, then his daily energy needs if he is moderately active (factor 1.55).

Show solution

1. BMR ≈ 10(68) + 6.25(178) − 5(17) + 5 = 680 + 1112.5 − 85 + 5 = 1712.5 kcal/day.
2. Daily needs ≈ 1712.5 × 1.55 = 2654 kcal/day.
3. Because he is still growing, his real needs may be somewhat higher.

Answer: BMR about 1,710 kcal per day; daily needs about 2,650 kcal per day.

Example 2. A granola bar has 30 g of carbohydrate, 8 g of protein and 10 g of fat. How many kilocalories does it supply, and what percent comes from fat?

Show solution

1. Carbohydrate 30 × 4 = 120 kcal; protein 8 × 4 = 32 kcal; fat 10 × 9 = 90 kcal.
2. Total 120 + 32 + 90 = 242 kcal.
3. Fat share: 90 ÷ 242 = 0.372.

Answer: 242 kcal, about 37% of it from fat.

Example 3. The liver stores about 100 g of glycogen. The brain uses about 120 g of glucose a day. If the liver's glycogen alone had to feed the brain, how long would it last? What must the body do overnight and during a long fast?

Show solution

1. Brain use per hour: 120 g ÷ 24 h = 5 g/h.
2. 100 g ÷ 5 g/h = 20 hours (and the liver's glucose also goes to red blood cells and other tissues, so in practice less).
3. So the liver must also make new glucose from amino acids and glycerol (gluconeogenesis), and in a long fast it makes ketones the brain can burn.

Answer: Less than a day; gluconeogenesis and, later, ketone bodies keep the brain fueled.

PRACTICE

CONCEPT CHECKS

1. Easy Give the energy per gram of carbohydrate, protein and fat.

   Show answer

   4 kcal, 4 kcal and 9 kcal.

2. Easy Which vitamins are fat-soluble? Why can they build up to harmful levels?

   Show answer

   A, D, E and K. They are stored in the liver and fat tissue instead of being excreted in urine.

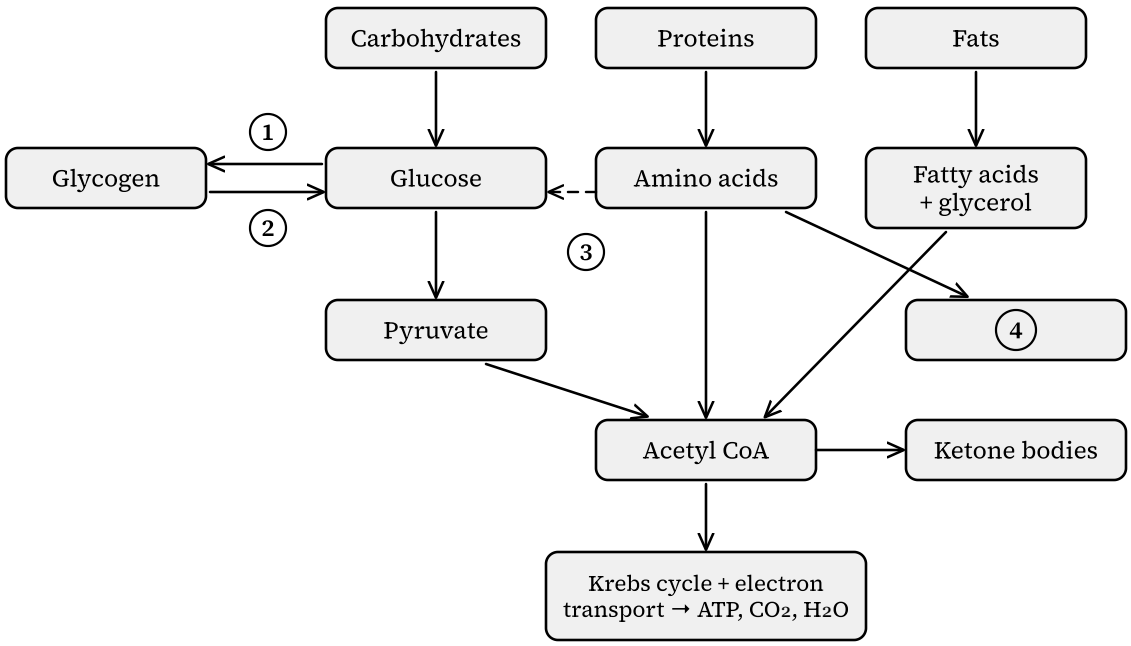
3. **Medium** Which hormone is high in the fed state and which in the fasting state? Name one thing the liver does in each.

Show answer

Fed: insulin high; the liver stores glucose as glycogen. Fasting: glucagon high; the liver breaks down glycogen and makes new glucose (gluconeogenesis).

DIAGRAM AND DATA QUESTIONS

4. **Medium** In the diagram, name the processes numbered 1, 2 and 3 and the waste product numbered 4.



Show answer

1 glycogenesis, 2 glycogenolysis, 3 gluconeogenesis, 4 urea.

5. **Medium** Estimate the BMR of a 15-year-old girl who is 160 cm tall and weighs 50 kg, and her daily needs if she is lightly active (factor 1.375).

Show answer

BMR ≈ 500 + 1000 − 75 − 161 = 1264 kcal/day; daily ≈ 1264 × 1.375 = 1738 kcal/day (likely a little more, since she is growing).

6. Medium A bowl of soup has 2 servings. Each serving has 12 g of fat, 25 g of carbohydrate and 4 g of protein. How many kilocalories are in the bowl?

Show answer

Per serving 108 + 100 + 16 = 224 kcal; the bowl has 448 kcal.

7. Medium Why does a person shiver when cold, and where does the heat come from?

Show answer

The hypothalamus senses a falling temperature and makes the skeletal muscles contract rapidly; the energy released by their metabolism is mostly heat, which warms the body.

8. Hard **Disorder as a broken mechanism.** Explain why a baby with PKU who drinks ordinary formula is harmed, and why a low-phenylalanine diet prevents the harm.

Show answer

The missing enzyme cannot convert phenylalanine to tyrosine, so phenylalanine from dietary protein builds up and damages the developing brain. Limiting phenylalanine in the diet keeps its level low, so the blocked road is never overloaded.

9. Hard Predict the effect: a man's thyroid gland makes too little hormone. What happens to his BMR, his body temperature and the way he feels?

Show answer

His BMR falls, he feels cold, tired and sluggish, and he may gain weight, because every cell runs its metabolism more slowly.

TEST PREP

10. Medium Test prep. Which process produces new glucose from amino acids? (A) glycolysis (B) glycogenesis (C) gluconeogenesis (D) lipolysis

Show answer

(C) gluconeogenesis.

11. **Medium** Test prep (select all that apply). Which are water-soluble vitamins? (A) vitamin C (B) vitamin D (C) folate (D) vitamin K (E) vitamin B_{12}

Show answer

A, C and E.

COMMON MISTAKES

- Thinking metabolism means only “how fast you burn food”; it is every reaction, building as well as breaking down.
- Mixing up glycogen (stored sugar), glucagon (the hormone that releases it), glycogenesis (making glycogen) and gluconeogenesis (making new glucose).
- Thinking fat cannot be made from sugar; extra glucose is readily turned into fat.
- Treating a prediction equation as exact; it estimates an average person and can be off by 10% or more for an individual.
- Thinking more vitamins are always better; too much vitamin A or D can poison.

Make it a game · Fed or Fasting?. The parent calls out an event: glycogenesis, glucagon high, ketones rising, insulin high, gluconeogenesis, fat being stored, glycogenolysis, fatty acids released. The student jumps to the kitchen side of the room for the fed state or to the bedroom side for the fasting state, and must say one sentence about why. Three right in a row earns a healthy snack.

Scripture. “For every creature of God is good, and nothing to be refused, if it be received with thanksgiving: for it is sanctified by the word of God and prayer.” (1 Timothy 4:4–5, KJV)

Food is a gift to be received with thanks, not feared. Knowing what it does inside us is one more reason to give thanks before a meal.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

9.4 The Kidney and the Nephron: From Bowman's Capsule to Kolff's Artificial Kidney

Mark up this lesson

OBJECTIVES

- Describe the parts of the urinary system and the structure of a nephron.
- Explain filtration, reabsorption and secretion, and calculate filtration rates, net filtration pressure and clearance.
- Explain how diabetes, kidney stones and kidney failure break the kidney's mechanism, and how dialysis replaces it.

> **Warm-up.** An adult makes about 1.5 liters of urine a day, but the kidneys filter about 180 liters of fluid from the blood each day. Before reading on, guess: where does the other 178 liters go?

WATCH

Urinary System, Part 1: Crash Course Anatomy & Physiology #38

CrashCourse · 10:18

https://www.youtube.com/watch?v=l128tW1H5a8

> **WHEN TO WATCH**
> After the core ideas on the nephron.

BACKUP VIDEO

Nephrons - Filtration and Reabsorption Basics

Siebert Science · 13:58

https://www.youtube.com/watch?v=OEzKQmqV2WQ

A slower walk along the nephron, segment by segment.

KEY TERMS

nephron

The working unit of the kidney (about a million per kidney): a glomerulus inside a glomerular capsule, plus a long tubule.

glomerulus

A tuft of capillaries where blood pressure pushes water and small solutes out of the blood into the glomerular capsule.

glomerular filtration rate (GFR)

The volume of filtrate formed by both kidneys per minute, about 125 mL/min in a healthy young man and a little less in women.

tubular reabsorption

Moving useful substances (water, glucose, amino acids, sodium, bicarbonate) from the tubule back into the blood.

tubular secretion

Moving substances (hydrogen ions, potassium, some drugs) from the blood into the tubule to be excreted.

nephron loop (loop of Henle)

The hairpin part of the tubule that dips into the medulla and makes the medulla salty, so the kidney can concentrate urine.

collecting duct

The tube that gathers urine from many nephrons; ADH opens water channels in it to save water (Lesson 9.5).

clearance

The volume of plasma cleared of a substance per minute; for creatinine it estimates the GFR.

CORE IDEAS

The story. In 1842 the young English surgeon William Bowman looked at kidneys under the microscope and described the cup around each tuft of capillaries that now bears his name. Two years later the German physiologist Carl Ludwig proposed that blood pressure simply filters fluid out of the tuft, and that the tubules then take most of it back. For eighty years no one could prove it. Then in 1924 Joseph Wearn and Alfred Newton Richards, at the University of Pennsylvania, slid a glass needle finer than a hair into a single capsule in a frog's kidney and drew out a drop of fluid. It was plasma without its proteins, with glucose in it; the urine had none. Filtration and reabsorption were both real.

The urinary system. Two bean-shaped kidneys, each about 11 cm long, lie against the back wall of the abdomen, behind the peritoneum, protected by the lower ribs and a cushion of fat. Each has an outer **cortex**, an inner **medulla** of cone-shaped renal pyramids, and a funnel, the **renal pelvis**, that collects urine into the **ureter**. The ureters carry urine by peristalsis to the bladder, which stores it until it leaves the body through the urethra. The renal arteries bring about 1.2 liters of blood a minute, roughly a fifth to a quarter of the heart's output, to organs that make up less than 1% of body weight.

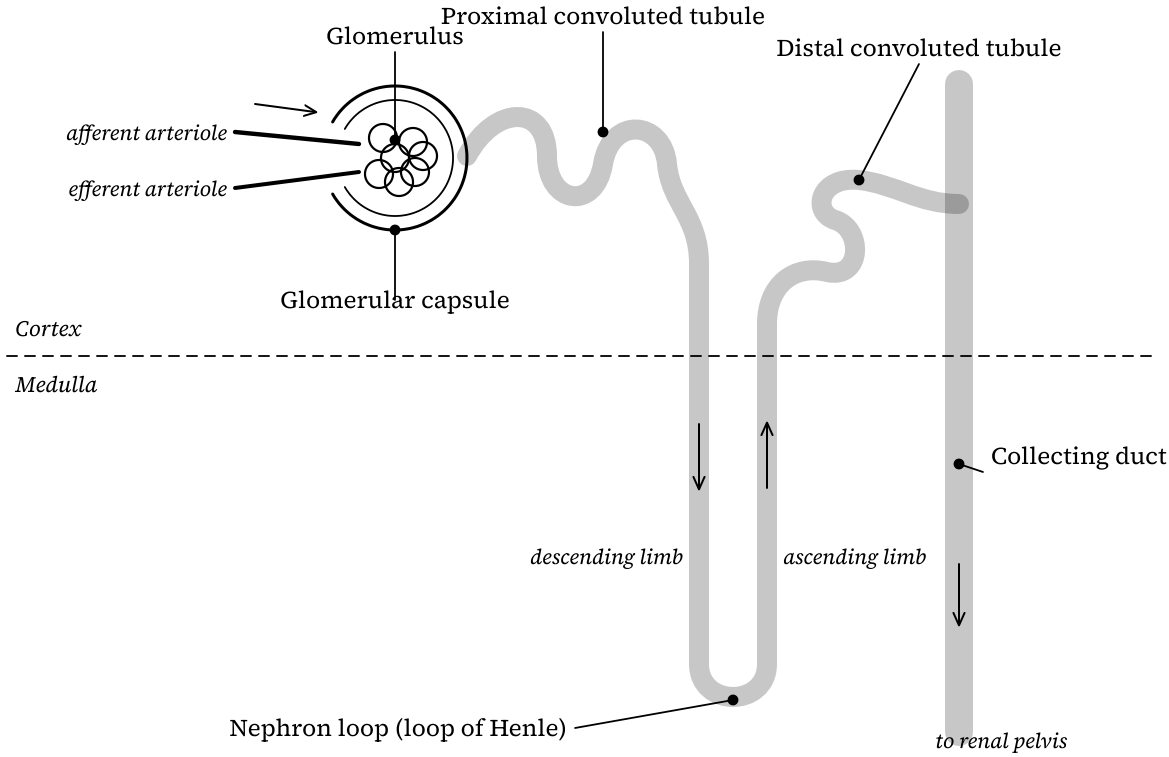
Filtration. In each glomerulus, blood pressure (about 55 mmHg) pushes fluid out through a three-layer filter of capillary wall, basement membrane and the foot-like cells of the capsule. Two forces push back: the fluid already in the capsule (about 15 mmHg) and the pull of the plasma proteins left behind (about 30 mmHg). These are the **Starling forces**, first described by Ernest Starling in 1896 (Lesson 9.2). The net filtration pressure is only about 10 mmHg, but the filter is so leaky to water and small solutes that the two kidneys make about 125 mL of filtrate a minute, 180 liters a day. Blood cells and most proteins stay in the blood.

Reabsorption and secretion. The **proximal convoluted tubule**, lined with cells carrying a brush border and many mitochondria, reabsorbs about two-thirds of the filtered sodium and water and normally all of the glucose and amino acids, using sodium-linked carriers as in the intestine (Lesson 9.2). The **nephron loop** pumps salt out of its ascending limb into the medulla, making the medulla saltier the deeper it goes; this lets the kidney save water later. The **distal convoluted tubule** and **collecting duct** fine-tune the urine under the control of hormones: aldosterone, ADH and parathyroid hormone (Lesson 9.5). Along the way the tubule *secretes* hydrogen ions, potassium and some drugs into the urine.

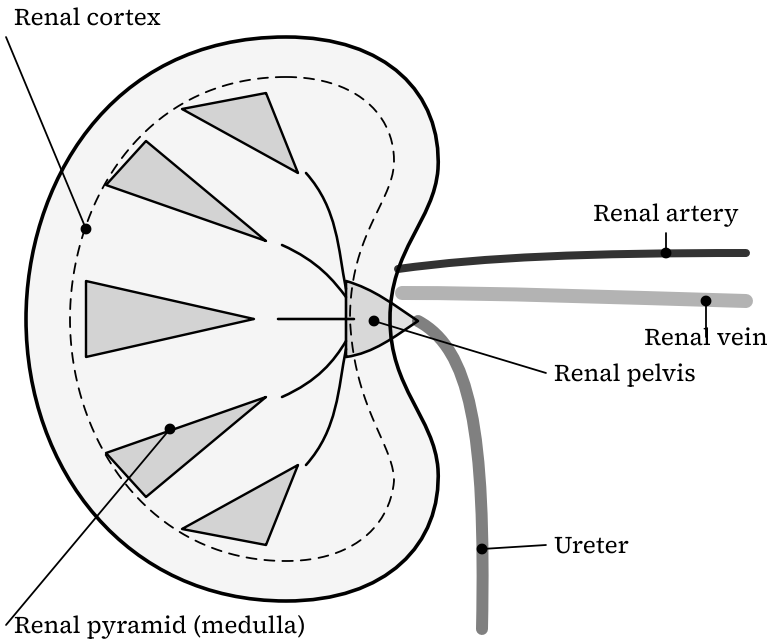
More than a filter. The kidneys also act as endocrine glands. Cells beside each glomerulus release **renin** when blood pressure falls, starting a hormone chain that raises it (Lesson 9.5). When oxygen in the blood is low, the kidneys release **erythropoietin**, which tells the bone marrow to make more red blood cells (Lesson 7.1). They also turn vitamin D into its active form, which helps the intestine absorb calcium. Doctors estimate kidney function by measuring creatinine, a waste from muscle that is filtered but hardly reabsorbed: its clearance is close to the GFR.

When it goes wrong. In untreated diabetes, blood glucose rises so high that the filtered glucose exceeds what the proximal tubule's carriers can carry back (about 375 mg per minute when every carrier is full). Glucose spills into the urine, and water follows it, so the person urinates often and becomes thirsty (Lesson 10.4). A **kidney stone** blocking a ureter raises the pressure in the capsule and can stop filtration in that kidney, as well as causing great pain. Long-standing diabetes and high blood pressure slowly scar the glomeruli; when the GFR falls below about 15 mL/min, the person needs dialysis or a transplant.

The artificial kidney. In 1943, in the occupied Netherlands, the young doctor Willem Kolff built the first working artificial kidney from sausage casing, orange-juice cans and a washing-machine part. Blood ran through the cellophane casing, which was wound on a drum turning in a bath of salt solution; urea and other wastes diffused out through the casing into the bath. Most of his first patients died, but in 1945 a woman in kidney failure woke from a coma and lived for years afterward. Today hundreds of thousands of people are kept alive by dialysis machines built on Kolff's principle, and many receive kidney transplants: the first successful one, between identical twins, was done in Boston in 1954.



Filtrate leaves the blood at the glomerulus and is reworked along the tubule: most is reabsorbed, a few substances are secreted, and what remains becomes urine.



Each renal pyramid holds the loops and collecting ducts of many nephrons; urine drains from their tips into the renal pelvis and ureter.

> **Safety first.** Do not taste or handle any real urine samples. In the filter model, food coloring stains; wear old clothes.

LAB

A Kidney in a Funnel and a Urine-Output Log

You will model glomerular filtration and then measure how your own kidneys respond to the water you drink.

You will need

- A funnel, coffee filter, a jar, water, a spoon of salt, a few drops of food coloring, a spoon of cornstarch, small dried beans (blood cells)
- A measuring cup, a notebook and a clock

Steps

1. Mix the “blood”: 250 mL of water with salt, food coloring, cornstarch and beans. Pour it through the coffee filter in the funnel.
2. Record what passes into the jar (the filtrate) and what stays behind. Taste nothing; compare by looking.
3. For one ordinary school day, record each drink (mL) and, privately, estimate each urine output with the measuring cup or by counting trips. Note the color of the urine each time.
4. Compare morning and afternoon, and a time after you drank a large glass of water.

Check your work

- ☐ Which parts of your model “blood” were too big to be filtered? Which real parts of blood stay behind in the glomerulus?
- ☐ Your model filter keeps the salt in the filtrate. What would the tubule have to do next?
- ☐ Why was your urine paler after a large drink of water?

LAB NOTEBOOK

1. A labeled nephron, with arrows for filtration, reabsorption and secretion.
2. A section of the kidney showing cortex, pyramids, pelvis and ureter.

KEY FORMULAS

$$\text{NFP} = P_{\text{glomerular blood}} - (P_{\text{capsule}} + \pi_{\text{plasma proteins}})$$

$$\text{clearance} = \frac{U \times V}{P}$$

U = concentration in urine, V = urine flow (mL/min), P = concentration in plasma.

$$\text{filtered load} = \text{GFR} \times \text{plasma concentration}$$

From history. Homer Smith, an American physiologist of the 1930s and 1940s, worked out how to measure the GFR of a living person by injecting inulin, a plant sugar that is filtered but neither reabsorbed nor secreted, and comparing its level in the blood and urine. The clearance method in this lesson is his.

Practice habit. Every time you meet a kidney problem, write the three words filter, reabsorb, secrete across the top of your page and decide which one the question is about before you start.

Career connection. A **dialysis technician** sets up and watches the machines that clean the blood of patients in kidney failure, usually three times a week for four hours each time. Many states let a high-school graduate train on the job and take a certification exam; a **nephrology nurse** leads the team. Both use this lesson every day: fluid removed, blood pressure, potassium and the clearance of urea.

WORKED EXAMPLES

Example 1. The kidneys filter 125 mL of plasma a minute and the person makes 1.8 L of urine a day. How much filtrate is formed in a day, and what percent is reabsorbed?

Show solution

1. 125 mL/min × 1440 min = 180,000 mL = 180 L per day.
2. Fraction excreted: 1.8 ÷ 180 = 0.01, so 99% is reabsorbed.

Answer: 180 L of filtrate a day; about 99% of it is returned to the blood.

Example 2. The blood pressure in the glomerulus is 55 mmHg, the pressure in the capsule is 15 mmHg and the protein (colloid osmotic) pressure of the blood is 30 mmHg. Find the net filtration pressure. Then find it if a kidney stone raises the capsule pressure to 30 mmHg.

Show solution

1. NFP = 55 − (15 + 30) = 10 mmHg.
2. With the stone: NFP = 55 − (30 + 30) = −5 mmHg.

Answer: Normally 10 mmHg outward; with the blockage the net pressure is negative, so filtration in that kidney stops.

Example 3. A man with untreated diabetes has a plasma glucose of 400 mg/dL and a GFR of 125 mL/min. His tubules can reabsorb at most about 375 mg of glucose a minute. How much glucose is filtered, and how much spills into the urine each minute?

Show solution

1. 400 mg/dL = 4 mg/mL.
2. Filtered load = 125 mL/min × 4 mg/mL = 500 mg/min.
3. Spill = 500 − 375 = 125 mg/min.

Answer: 500 mg is filtered and about 125 mg of glucose a minute is lost in the urine, drawing water with it.

PRACTICE

CONCEPT CHECKS

1. Easy List, in order, the parts of the nephron a drop of filtrate passes through.

Show answer

Glomerular capsule, proximal convoluted tubule, descending limb and ascending limb of the nephron loop, distal convoluted tubule, collecting duct.

2. **Easy** What are the three processes that form urine, and where does each mainly happen?

Show answer

Filtration (glomerulus), reabsorption (mostly the proximal tubule, fine-tuned in the distal tubule and collecting duct) and secretion (along the tubules).

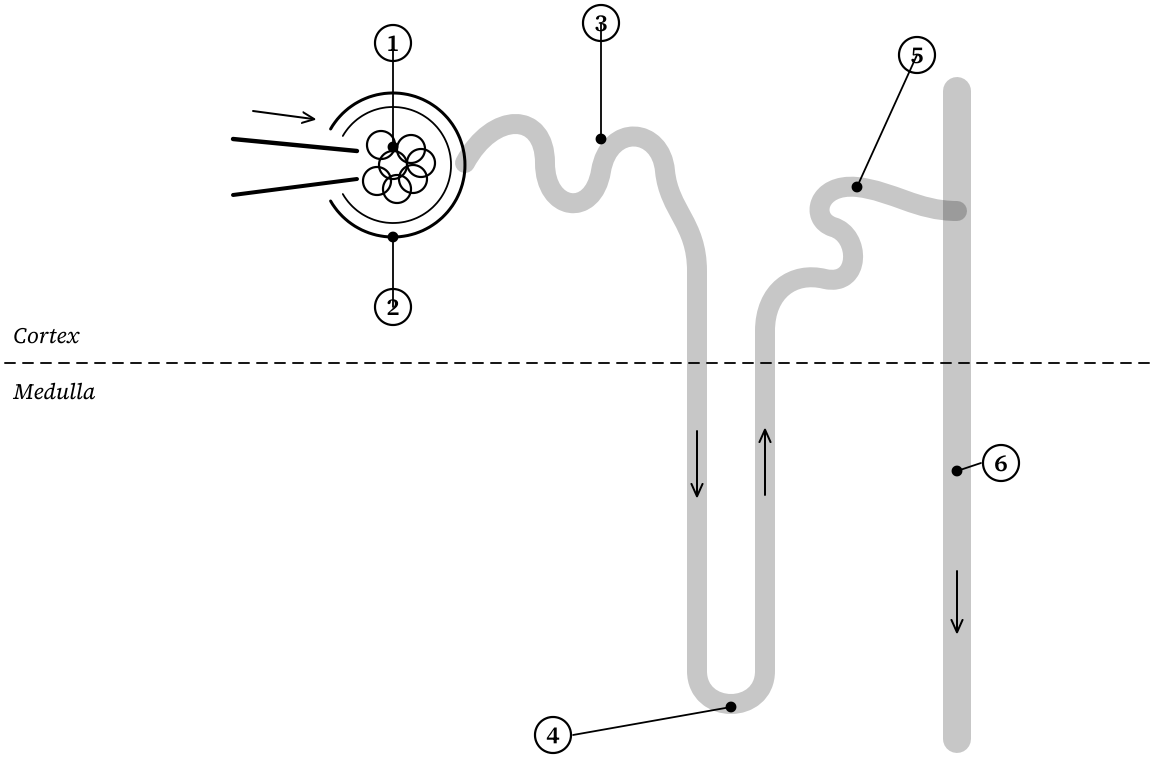
3. **Easy** Name three hormones or hormone-like jobs of the kidney besides making urine.

Show answer

Renin (raises blood pressure), erythropoietin (more red blood cells) and activating vitamin D (calcium absorption).

DIAGRAM AND DATA QUESTIONS

4. **Medium** Name the parts numbered 1 to 6 in the diagram.



Show answer

1 glomerulus, 2 glomerular capsule, 3 proximal convoluted tubule, 4 nephron loop (loop of Henle), 5 distal convoluted tubule, 6 collecting duct.

5. Medium A woman's urine creatinine is 90 mg/dL, her urine flow is 1.5 mL/min and her plasma creatinine is 1.2 mg/dL. Estimate her GFR.

Show answer

Clearance = (90 × 1.5) ÷ 1.2 = 112.5 mL/min, within the normal range.

6. Medium Plasma sodium is about 140 mmol/L. How much sodium is filtered in a day at a GFR of 180 L/day? If 150 mmol is excreted, what percent was reabsorbed?

Show answer

140 × 180 = 25,200 mmol filtered; 150 ÷ 25,200 = 0.6% excreted, so about 99.4% reabsorbed.

7. Medium Why are blood cells and albumin normally absent from urine? What might protein in the urine suggest?

Show answer

They are too large to pass the glomerular filter. Protein in the urine suggests the filter has been damaged, for example by diabetes or high blood pressure.

8. Hard **Disorder as a broken mechanism.** Explain why a person with untreated diabetes is always thirsty and urinating often, starting from the proximal tubule.

Show answer

Filtered glucose exceeds the transport maximum of the proximal tubule's carriers, so glucose stays in the tubule. It holds water there by osmosis, so more urine is made; the water loss makes the blood concentrated, which triggers thirst.

9. Hard Predict the effect: the blood pressure in the glomerulus falls sharply after heavy bleeding. What happens to the GFR and the urine output, and which hormone does the kidney release in response?

Show answer

Net filtration pressure falls, so GFR and urine output fall (urine may nearly stop). The kidney releases renin, starting the chain that raises blood pressure and saves sodium and water.

TEST PREP

10. **Medium** Test prep. Which part of the nephron reabsorbs most of the filtered water and all of the glucose? (A) glomerulus (B) proximal convoluted tubule (C) ascending limb (D) collecting duct

Show answer

(B) the proximal convoluted tubule.

11. **Medium** Test prep (ordered response). Put in order the path of urine: bladder, renal pelvis, collecting duct, urethra, ureter.

Show answer

Collecting duct → renal pelvis → ureter → bladder → urethra.

COMMON MISTAKES

- Thinking the kidney filters only the wastes; it filters almost everything small, then takes back what it needs.
- Confusing the ureter (kidney to bladder) with the urethra (bladder to outside).
- Forgetting that the net filtration pressure subtracts two opposing pressures from the glomerular blood pressure.
- Thinking glucose in the urine means the kidney is broken; usually the kidney is fine and the blood glucose is too high.
- Mixing up afferent (arriving) and efferent (exiting) arterioles.

Make it a game · Filter or Keep?. The parent names a substance: water, glucose, albumin, red blood cell, urea, sodium, hydrogen ion, penicillin, amino acid, creatinine. The student answers in two parts: is it filtered at the glomerulus (yes or no), and then is it mostly reabsorbed, secreted or excreted? One point for each correct part; a perfect round of ten earns a Kolff award (a paper medal).

Scripture. “I the LORD search the heart, I try the reins, even to give every man according to his ways, and according to the fruit of his doings.” (Jeremiah 17:10, KJV)

The King James “reins” are the kidneys, which the Hebrews counted among the inmost parts of a person. The kidneys sift every drop of blood forty or more times a day; the Lord searches deeper still.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up

👎 Thumbs down

Too hard

Too easy

Video problem

Found an error

Took too long

Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback

Mark up this lesson

9.5 Fluids, Electrolytes and Acid–Base Balance: Henderson and Hasselbalch's Equation (1908–1916)

Mark up this lesson

OBJECTIVES

- Describe the body's fluid compartments and how ADH, aldosterone, the renin–angiotensin system and ANP keep water and salt in balance.
- Explain how buffers, the lungs and the kidneys keep blood pH between 7.35 and 7.45, and calculate pH with the Henderson–Hasselbalch equation.
- Classify an acid–base disturbance as respiratory or metabolic, acidosis or alkalosis, from pH, carbon dioxide and bicarbonate values.

> **Warm-up.** Weigh yourself before and after an hour of hard exercise on a hot day, without drinking during it. Where did the lost weight go? (Do this only with a parent, and drink afterward.)

WATCH

Acidosis and Alkalosis MADE EASY

Dr Matt & Dr Mike · 5:28

https://www.youtube.com/watch?v=w3nsxx6AcdA

> **WHEN TO WATCH**
> After the core ideas on acid–base balance, before the worked examples.

BACKUP VIDEO

Urinary System, Part 2: Crash Course Anatomy & Physiology #39

CrashCourse · 9:51

https://www.youtube.com/watch?v=DlqyyyvTI3k

With the hormones that regulate the urine: ADH, aldosterone and the renin–angiotensin system.

KEY TERMS

intracellular and extracellular fluid

The fluid inside cells (about two-thirds of body water) and outside them: interstitial fluid around the cells and blood plasma.

electrolyte

A substance that forms ions in water; in the body chiefly sodium, potassium, chloride, calcium, bicarbonate and phosphate.

antidiuretic hormone (ADH)

A hypothalamic hormone released from the posterior pituitary when the blood is too concentrated; it opens water channels in the collecting ducts.

aldosterone

An adrenal-cortex hormone that makes the kidneys save sodium (and water with it) and excrete potassium.

renin–angiotensin–aldosterone system

A hormone chain started by renin from the kidney when blood pressure falls; angiotensin II narrows vessels and calls out aldosterone, ADH and thirst.

buffer

A pair of chemicals (a weak acid and its base) that takes up or releases hydrogen ions to resist a change in pH.

acidosis and alkalosis

Blood pH below 7.35 (acidosis) or above 7.45 (alkalosis).

compensation

A second system's correction of an acid–base disturbance: the lungs for a metabolic problem, the kidneys for a respiratory one.

CORE IDEAS

The story. In the 1860s the French physiologist Claude Bernard taught that the body's cells live in an inner sea, the *milieu intérieur*, kept steady while the world outside changes. In 1908 the Harvard chemist Lawrence Henderson worked out why blood resists acid so well: carbonic acid and bicarbonate act as a pair, and he wrote an equation linking the acidity to the ratio of the two. In 1909 the Danish chemist Søren Sørensen, studying proteins and enzymes at the Carlsberg Laboratory, invented the pH scale. In 1916 Karl Hasselbalch, also in Copenhagen, rewrote Henderson's equation in pH terms. Every intensive-care nurse who reads a blood-gas report uses the Henderson–Hasselbalch equation, whether she names it or not.

Where the water is. Water makes up about 60% of an adult man's body mass, somewhat less in women, about 75% in a newborn and less in old age. About two-thirds is **intracellular fluid**, rich in potassium; one-third is **extracellular fluid**, rich in sodium and chloride. Of the extracellular fluid, about three-quarters is interstitial fluid bathing the cells and one-quarter is blood plasma. Water moves freely between the compartments by osmosis, following the solutes. A typical adult takes in about 2.5 liters a day (drinks, food and the water made by metabolism) and loses the same amount (urine, breath and skin, sweat and feces). The PE course applies this to sport (PE 9 Lesson 2.1, Fluid Balance).

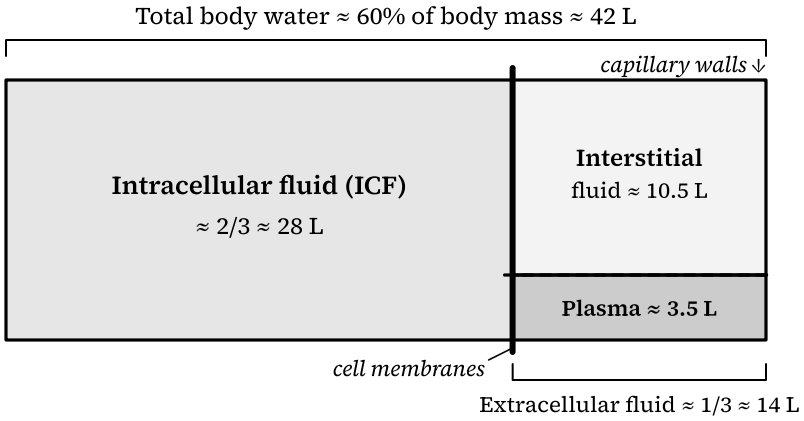
Water and salt hormones. When the blood becomes too concentrated, osmoreceptors in the hypothalamus make you thirsty and release **ADH** from the posterior pituitary (Lesson 6.2). ADH puts water channels (aquaporins) into the collecting ducts, and water is drawn out into the salty medulla, so the urine becomes small and concentrated. When blood pressure or volume falls, the kidney releases **renin**; renin starts the chain that makes **angiotensin II**, which narrows blood vessels, triggers thirst and ADH, and makes the adrenal cortex release **aldosterone**. Aldosterone makes the distal tubule and collecting duct reabsorb sodium, water follows, and potassium is excreted. When the heart's atria are overstretched, they release **atrial natriuretic peptide**, which does the opposite and lets salt and water go.

Electrolytes matter to every nerve and muscle. Normal plasma sodium is about 135–145 mEq/L and potassium about 3.5–5.0 mEq/L. Sodium mostly sets how much water the extracellular fluid holds. Potassium sets the resting voltage of every cell (Lesson 5.1), so a high or low potassium can make the heart beat dangerously; nurses watch it closely. Calcium (about 8.5–10.5 mg/dL) is needed for muscle contraction, nerve signals and clotting and is controlled by parathyroid hormone (Lesson 6.3). Bicarbonate (about 22–26 mEq/L) is the main buffer base.

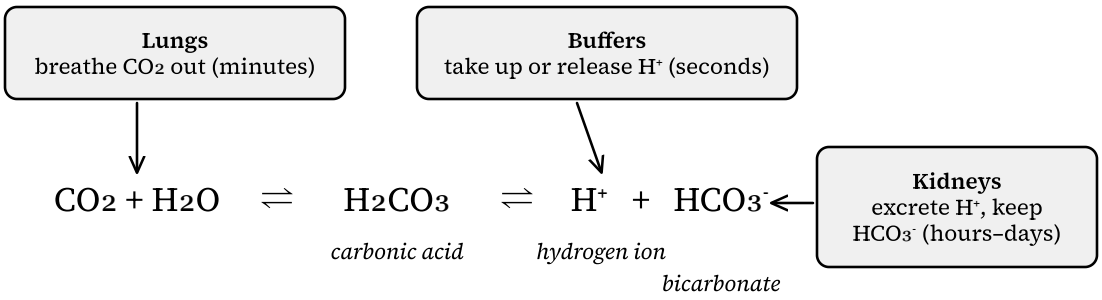
Acid–base balance: three lines of defense. Normal arterial blood pH is 7.35–7.45. Metabolism makes acids all day, above all carbon dioxide: $CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$. First, **buffers** (bicarbonate, phosphate and proteins such as hemoglobin) soak up or release hydrogen ions within seconds. Second, the **lungs** adjust breathing within minutes: breathing faster blows off CO_2 and raises the pH, breathing slower keeps CO_2 and lowers it (Lesson 8.4). Third, the **kidneys**, over hours to days, secrete hydrogen ions into the urine (carried by phosphate and ammonia) and reabsorb or make new bicarbonate.

Reading a blood gas. There are four basic disturbances. In **respiratory acidosis** the lungs fail to remove CO_2 (a severe asthma attack, an overdose that slows breathing), so CO_2 rises and pH falls. In **respiratory alkalosis** a person over-breathes (panic, high altitude), CO_2 falls and pH rises. In **metabolic acidosis** the body gains acid or loses bicarbonate (diabetic ketoacidosis, severe diarrhea), so bicarbonate falls. In **metabolic alkalosis** the body loses acid or gains base (repeated vomiting of stomach acid, too many antacids), so bicarbonate rises. A memory aid is ROME: in Respiratory problems pH and CO_2 move Opposite ways; in Metabolic problems pH and bicarbonate move Equally, the same way.

When it goes wrong. In **diabetes insipidus** the pituitary makes no ADH (or the kidney ignores it), so the collecting ducts stay closed to water and a person can pass many liters of dilute urine a day. In **exercise-associated hyponatremia**, a long-distance athlete who drinks far more plain water than he sweats out dilutes his plasma sodium; water moves into the brain cells by osmosis, causing headache, confusion and, rarely, seizures. In **diabetic ketoacidosis**, ketone acids pour into the blood, the bicarbonate is used up, and the lungs try to compensate with deep, rapid breathing (Lesson 10.4).



In a 70-kg adult about 42 L of water is divided between the cells (about 28 L) and the extracellular fluid (about 14 L), most of which bathes the cells rather than flowing in the blood.



More CO_2 → more H^+ → lower pH; less CO_2 → fewer H^+ → higher pH

Buffers act in seconds, the lungs in minutes and the kidneys over hours to days, all on the same carbonic acid–bicarbonate reaction.

> **Safety first.** In the breath lab, only breathe *out* through the straw; never suck the liquid up. Breathe normally between trials and stop if you feel dizzy. Do not hyperventilate on purpose. Red cabbage juice stains.

LAB

Breath, Cabbage and a Buffer

You will see carbon dioxide make water acidic and see a buffer resist a change in pH.

You will need

- Red cabbage indicator: chop a quarter of a red cabbage, cover with hot water for 15 minutes, strain (an adult handles the hot water)
- Three clear cups, drinking straws, a dropper, white vinegar, baking soda, distilled or tap water
- A timer

Steps

1. Cup A: 100 mL water with 20 mL indicator. Blow gently out through a straw into it for 1 minute, then 2. Note the color change (toward pink means more acidic).
2. Cup B: 100 mL water with 20 mL indicator. Cup C: the same, plus half a teaspoon of baking soda dissolved in it (a bicarbonate buffer).
3. Add vinegar drop by drop to cup B, stirring, and count the drops until the color clearly changes. Do the same with cup C.
4. Record the drops needed and make a bar chart.

Check your work

- ☐ What did your breath add to cup A, and why did the color change? Which equation shows it?
- ☐ How many more drops of acid did cup C take before its color changed? What did the bicarbonate do with the hydrogen ions?
- ☐ Which organ removes the acid your breath carried, and which organ removes the acid that bicarbonate cannot hold forever?

LAB NOTEBOOK

1. The body-water boxes for your own body mass, with liters in each compartment.
2. A four-box chart of the acid–base disturbances with an arrow up or down for pH, CO_2 and bicarbonate in each.

KEY FORMULAS

$$\mathrm{pH} = 6.1 + \log_{10} \frac{[\mathrm{HCO_3^-}]}{0.03 \times P_{\mathrm{CO_2}}}$$

$[\mathrm{HCO_3^-}]$ in mEq/L (mmol/L), $P_{\mathrm{CO_2}}$ in mmHg. Normal: 24 and 40, ratio 20 : 1, pH 7.40. Normal arterial values: pH 7.35–7.45; $P_{\mathrm{CO_2}}$ 35–45 mmHg; $\mathrm{HCO_3^-}$ 22–26 mEq/L.

From history. Walter Cannon, whom you met in Lesson 9.1, took Bernard's idea of the inner sea and named it *homeostasis* in 1926; his 1932 book *The Wisdom of the Body* described how the body keeps its water, salt, sugar, temperature and acidity steady. Henderson, Cannon's colleague at Harvard, later wrote a whole book on the chemistry of the inner sea, *Blood: A Study in General Physiology* (1928).

Practice habit. Before you classify any blood gas, write three arrows in a row (pH, CO_2, HCO_3^-) and decide up or down for each. Only then say respiratory or metabolic.

WORKED EXAMPLES

Example 1. A 60-kg woman's body water is 60% of her mass. How many liters are in each compartment, using two-thirds inside cells, and three-quarters of the rest interstitial?

Show solution

1. Total body water: 0.60 × 60 = 36 L.
2. Intracellular: 36 × 2/3 = 24 L; extracellular: 36 × 1/3 = 12 L.
3. Interstitial: 12 × 3/4 = 9 L; plasma: 12 × 1/4 = 3 L.

Answer: 36 L total: 24 L in cells, 9 L interstitial and 3 L of plasma.

Example 2. Normal blood has bicarbonate 24 mEq/L and P_{CO_2} 40 mmHg. Find the pH. Then a patient with a severe asthma attack has P_{CO_2} 60 mmHg and bicarbonate still 24. Find the pH and name the disturbance.

Show solution

1. Normal: 0.03 × 40 = 1.2; 24 ÷ 1.2 = 20; log 20 = 1.30; pH = 6.1 + 1.30 = 7.40.
2. Asthma: 0.03 × 60 = 1.8; 24 ÷ 1.8 = 13.3; log 13.3 = 1.12; pH = 6.1 + 1.12 = 7.22.
3. pH is low and CO_2 is high (opposite directions), so the cause is respiratory.

Answer: Normal pH 7.40; the asthma patient's pH is about 7.22, a respiratory acidosis.

Example 3. A child with severe diarrhea has bicarbonate 14 mEq/L and P_{CO_2} 30 mmHg. Find the pH and classify the disturbance. Is it compensated?

Show solution

1. 0.03 × 30 = 0.9; 14 ÷ 0.9 = 15.6; log 15.6 = 1.19; pH = 6.1 + 1.19 = 7.29.
2. pH is low and bicarbonate is low (same direction): metabolic acidosis, from bicarbonate lost in the stool.
3. The low CO_2 shows the lungs are breathing faster to compensate, but the pH is not yet back in the normal range.

Answer: pH about 7.29: metabolic acidosis with partial respiratory compensation.

PRACTICE

CONCEPT CHECKS

1. Easy What are the normal ranges of arterial pH, P_{CO_2} and bicarbonate?

   Show answer

   pH 7.35–7.45; P_{CO_2} 35–45 mmHg; bicarbonate 22–26 mEq/L.

2. Easy Which ion is the main cation inside cells, and which outside them?

   Show answer

   Potassium inside; sodium outside.

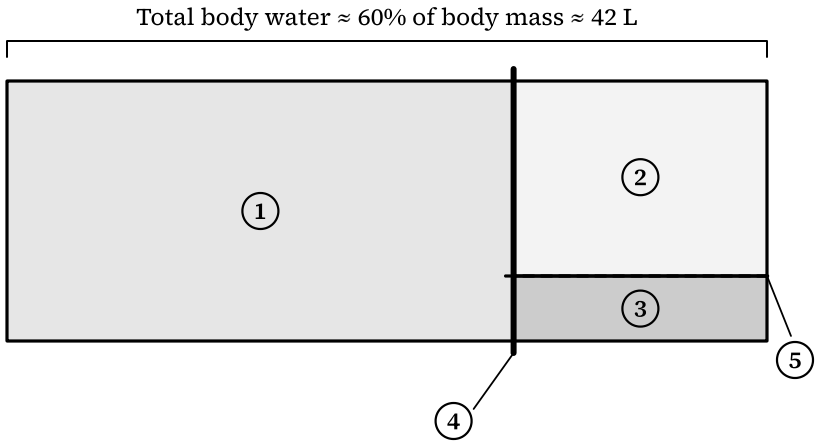
3. **Medium** Compare ADH and aldosterone: where each comes from, what triggers it, and what it makes the kidney save.

Show answer

ADH: made in the hypothalamus, released from the posterior pituitary when the blood is too concentrated; saves water. Aldosterone: from the adrenal cortex, triggered by angiotensin II (low blood pressure) or high potassium; saves sodium (water follows) and excretes potassium.

DIAGRAM AND DATA QUESTIONS

4. **Medium** In the diagram, name compartments 1, 2 and 3 and the barriers numbered 4 and 5.



Show answer

1 intracellular fluid, 2 interstitial fluid, 3 blood plasma; 4 cell membranes, 5 capillary walls.

5. **Medium** Find the body water, intracellular fluid and plasma volume of a 50-kg teenager, using 60% water.

Show answer

Total 30 L; intracellular 20 L; extracellular 10 L, of which plasma is about 2.5 L.

6. **Medium** A patient has pH 7.50, P_{CO_2} 40 mmHg, bicarbonate 30 mEq/L. Check the pH with the equation and classify.

Show answer

0.03 × 40 = 1.2; 30 ÷ 1.2 = 25; log 25 = 1.40; pH = 7.50. pH and bicarbonate both high: metabolic alkalosis (for example, from repeated vomiting).

7. Medium A climber at high altitude breathes fast and has P_{CO_2} 25 mmHg with bicarbonate 24 mEq/L. Find the pH and classify.

Show answer

$0.03 \times 25 = 0.75$; $24 \div 0.75 = 32$; $\log 32 = 1.51$; pH ≈ 7.61. Respiratory alkalosis (CO_2 down, pH up).

8. Hard **Disorder as a broken mechanism.** Explain why a person with diabetes insipidus makes huge volumes of dilute urine and is always thirsty, even though his blood glucose is normal.

Show answer

Without ADH (or without the kidney's response to it) the collecting ducts have no water channels, so water cannot be drawn back into the salty medulla; the dilute urine carries off liters of water, the blood becomes concentrated, and the hypothalamus makes him thirsty.

9. Hard Predict the effect: a marathon runner drinks a liter of plain water every 30 minutes but sweats only half that. What happens to his plasma sodium and to his brain cells, and why?

Show answer

His plasma sodium is diluted (hyponatremia). The extracellular fluid becomes less concentrated than the cells, so water moves into the brain cells by osmosis, causing swelling, headache and confusion.

TEST PREP

10. Medium Test prep. A patient has pH 7.30 and P_{CO_2} 55 mmHg. Which is most likely? (A) metabolic acidosis (B) metabolic alkalosis (C) respiratory acidosis (D) respiratory alkalosis

Show answer

(C) respiratory acidosis: pH low, CO_2 high.

11. Medium Test prep (select all that apply). Which raise blood pressure or volume? (A) angiotensin II (B) aldosterone (C) atrial natriuretic peptide (D) ADH (E) renin

Show answer

A, B, D and E (renin starts the chain).

COMMON MISTAKES

- Thinking most body water is in the blood; plasma is only about a twelfth of it.
- Mixing up ADH (saves water only) and aldosterone (saves sodium, with water following).
- Forgetting that CO_2 is an acid: more CO_2 means lower pH.
- Reading the direction backward: in a respiratory problem pH and CO_2 move in opposite directions; in a metabolic problem pH and bicarbonate move the same way (ROME).
- Using the natural log in the Henderson–Hasselbalch equation; it uses the base-10 logarithm.

Make it a game · ROME Was Not Built in a Day. Make twelve cards, each with a pH arrow and either a CO_2 arrow or a bicarbonate arrow (for example pH ↓, CO_2 ↑). The student sorts each card into one of four labeled bowls (respiratory acidosis, respiratory alkalosis, metabolic acidosis, metabolic alkalosis) and names one cause. Time the sort, then reshuffle and try to beat your time. Write < and > on the cards for "below normal" and "above normal" if you like.

Scripture. "Who hath measured the waters in the hollow of his hand, and meted out heaven with the span, and comprehended the dust of the earth in a measure, and weighed the mountains in scales, and the hills in a balance?" (Isaiah 40:12, KJV)

The God who measured the seas also measured the inner sea of every body, holding its salt and acid within a few hundredths of a pH unit.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

UNIT 9

Digestion, Metabolism and the Kidneys

This unit follows a meal through the body and out again. Lessons 9.1 and 9.2 trace the digestive tract and its accessory organs, from Cannon's X-ray pictures of a churning stomach (1897) to Bayliss and Starling's discovery of secretin (1902), the first hormone. Lesson 9.3 follows the fuel into the cells: anabolism and catabolism, the fed and fasting states, vitamins, and how to estimate basal metabolic rate. Lessons 9.4 and 9.5 turn to the kidneys, which filter about 180 liters a day and return 99% of it, and to the balance of water, salt and acid that the kidneys and lungs keep together, ending with how a nurse reads a blood gas.

Each lesson has worked examples with real clinical numbers (filtration rates, clearance, energy needs, blood pH), a labeled diagram to learn, a "disorder as a broken mechanism" question, and TEAS-style test-prep items. The lab work uses kitchen materials: a stocking for peristalsis, soap and oil for bile, lactase and milk, a coffee-filter kidney and red-cabbage indicator for acid and base.

PREREQUISITES

- Unit 2 (membrane transport: osmosis, active transport and cotransport)
- Unit 6 (hormones: insulin, glucagon, ADH, aldosterone and thyroid hormone)
- Unit 8 (breathing and carbon dioxide)
- Biology 4.3 (cellular respiration) and Chemistry (pH and logarithms)

MASTERY CHECKLIST

- ☐ I can trace food through the digestive tract, name the four layers of its wall, and explain peristalsis, segmentation and the stomach's self-protection.
- ☐ I can describe the jobs of the liver, gallbladder and pancreas, the hormones secretin and CCK, and how each kind of nutrient is absorbed.
- ☐ I can explain the fed and fasting states, estimate BMR and daily energy needs, and compute energy from grams of nutrients.
- ☐ I can label a nephron, explain filtration, reabsorption and secretion, and calculate GFR, net filtration pressure and clearance.
- ☐ I can describe the body's fluid compartments and the hormones that control water and salt.
- ☐ I can calculate blood pH with the Henderson–Hasselbalch equation and classify an acid–base disturbance.

LESSONS IN THIS UNIT

9.1 The Digestive Tract: Cannon's X-Ray Pictures of a Working Stomach (1897)

4 sessions of 45 minutes

9.2 Liver, Pancreas and Absorption: Bayliss and Starling Find the First Hormone (1902)

4 sessions of 45 minutes

9.3 Metabolism and Nutrition: From Lavoisier's Guinea Pig to the Harris–Benedict Equation (1918–1919)

4 sessions of 45 minutes

9.4 The Kidney and the Nephron: From Bowman's Capsule to Kolff's Artificial Kidney

4 sessions of 45 minutes

9.5 Fluids, Electrolytes and Acid–Base Balance: Henderson and Hasselbalch's Equation (1908–1916)

4 sessions of 45 minutes

Unit 9 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **6 pts** **Lesson 9.1**

   Name the four layers of the wall of the digestive tract, from the inside out, and say which layer moves the food.

2. **6 pts** **Lesson 9.1**

   Give two ways the stomach protects itself from its own acid, and name the bacterium that most often breaks this protection.

3. **7 pts** **Lesson 9.2**

   Explain how the experiment of Bayliss and Starling showed that secretin is a hormone.

4. **7 pts** **Lesson 9.2**

   Compare the absorption of glucose and of fat: what carries each into the absorbing cell, and which vessel does each enter?

5. **7 pts** **Lesson 9.3**

   A 16-year-old young man is 175 cm tall and weighs 64 kg. Estimate his BMR with the Mifflin–St Jeor equation and his daily needs if he is very active (factor 1.725).

6. **6 pts** **Lesson 9.3**

   A sandwich has 45 g of carbohydrate, 20 g of protein and 14 g of fat. How many kilocalories does it supply?

7. **7 pts** **Lesson 9.3**

   Describe what the liver does with glucose (a) an hour after a meal and (b) after an overnight fast, naming each process and the hormone in charge.

8. **8 pts** **Lesson 9.4**

   The kidneys filter 120 mL of plasma per minute and the person makes 1.5 L of urine a day. Find the filtrate formed per day and the percent reabsorbed.

9. **7 pts** **Lesson 9.4**

   Glomerular blood pressure is 50 mmHg, capsular pressure 15 mmHg and the blood's colloid osmotic pressure 28 mmHg. Find the net filtration pressure. What happens to the GFR if the blood pressure in the glomerulus falls?

10. **7 pts** **Lesson 9.4**

    A patient's urine creatinine is 120 mg/dL, urine flow 1.0 mL/min and plasma creatinine 1.5 mg/dL. Estimate the GFR. Is it normal for a young adult?

11. **7 pts** **Lesson 9.5**

    A man loses a lot of blood. Trace the renin–angiotensin–aldosterone response and say how it restores blood volume and pressure.

LAB AND DATA

12. **10 pts** **Lesson 9.5**

    A blood gas shows bicarbonate 12 mEq/L and P_{CO_2} 28 mmHg. (a) Calculate the pH. (b) Classify the disturbance. (c) What are the lungs doing, and why?

SHORT ESSAY

13. **15 pts** **Lesson 9.1–9.5**

Short essay. Choose one disorder from this unit (an ulcer, celiac disease, PKU, diabetes in the kidney, diabetes insipidus or ketoacidosis). Describe the normal mechanism, the step that fails, the signs that follow from the failure, and how treatment repairs or works around it. Close with one sentence on what the disorder shows about the design of the healthy body.

ANSWER KEY

1. Mucosa, submucosa, muscularis, serosa; the muscularis (circular and longitudinal smooth muscle) moves food by peristalsis and segmentation.
2. A thick alkaline mucus layer, tight junctions between cells, and rapid replacement of the lining (any two); *Helicobacter pylori*.
3. With the nerves to the intestine cut, acid still made the pancreas secrete; an extract of the intestinal lining injected into the blood did the same. So a chemical messenger carried in the blood, not a nerve, switched on the pancreas.
4. Glucose enters with sodium on a cotransporter and passes into the capillaries (to the hepatic portal vein). Fatty acids are carried by bile-salt micelles, rebuilt into triglycerides, packaged as chylomicrons and released into the lacteal (lymph).
5. BMR ≈ 640 + 1093.75 − 80 + 5 = 1658.75, about 1,660 kcal/day; daily ≈ 1658.75 × 1.725 = 2861, about 2,860 kcal/day.
6. 180 + 80 + 126 = 386 kcal.
7. (a) Insulin is high: the liver stores glucose as glycogen (glycogenesis). (b) Glucagon is high: the liver breaks down glycogen (glycogenolysis) and makes new glucose from amino acids and glycerol (gluconeogenesis).
8. 120 × 1440 = 172,800 mL ≈ 172.8 L/day; 1.5 ÷ 172.8 = 0.87% excreted, so about 99.1% reabsorbed.
9. NFP = 50 − (15 + 28) = 7 mmHg. If glomerular blood pressure falls, NFP and GFR fall.
10. (120 × 1.0) ÷ 1.5 = 80 mL/min; lower than the normal of about 100–125 mL/min, suggesting reduced kidney function.
11. Low pressure makes the kidney release renin; renin leads to angiotensin II, which narrows vessels, triggers thirst and ADH, and calls out aldosterone from the adrenal cortex. Aldosterone saves sodium and water follows; ADH saves water; drinking adds more. Volume and pressure rise.
12. (a) 0.03 × 28 = 0.84; 12 ÷ 0.84 = 14.3; log 14.3 = 1.155; pH ≈ 7.25. (b) Metabolic acidosis (pH and bicarbonate both low). (c) Breathing deep and fast to blow off CO_2, a partial respiratory compensation.
13. Answers vary. A full answer (1) describes the normal mechanism accurately, (2) names the failed step, (3) links each sign to the failure, (4) explains the treatment, and (5) reflects thoughtfully on the body's design.

UNIT 10

Life, Growth and Care

The last unit follows the body through a whole life. Lesson 10.1 shows how genes become proteins and proteins become traits, from Garrod's inborn errors (1902) and Pauling's molecular disease (1949) to newborn screening. Lesson 10.2 follows growth and aging, from Montbeillard's first growth chart to the telomeres of aging cells, and how exercise and nutrition build a lifetime's bone and muscle. Lesson 10.3 is a **parent-led lesson**: it treats the testes and ovaries only as endocrine glands, links them to meiosis, and traces the child's development before birth week by week alongside Psalm 139, with schematic diagrams of glands and a timeline only. Lesson 10.4 is the capstone: one patient's case traced through every system of the course, and a review in the formats of nursing entrance exams.

Parents: please read Lesson 10.3 before your student and read it together. It contains no external anatomy and no discussion of sexual activity, contraception or abortion; it describes the hormone axis, the menstrual cycle in one clinical sentence, fertilization, and development to birth.

PREREQUISITES

- Units 6–9 of this course (hormones, blood and heart, breathing, digestion and the kidneys)
- Biology Unit 5 (Mendel, Punnett squares and meiosis)
- Unit 3 (bone tissue and growth)

MASTERY CHECKLIST

- ☐ I can explain how a gene becomes a trait and predict recessive, dominant, X-linked and codominant inheritance with Punnett squares and pedigrees.
- ☐ I can explain how long bones grow at the growth plates and which hormones drive and end growth.
- ☐ I can describe how the body systems change with age and how exercise and nutrition slow those changes.
- ☐ I can describe the gonads as endocrine glands, the feedback loop that controls them, and how sperm and egg formation differ in meiosis.
- ☐ I can trace development from fertilization to birth and explain the placenta and the newborn's first breath.
- ☐ I can reason through a clinical case system by system and answer exam items of every format.

LESSONS IN THIS UNIT

10.1 Inheritance in the Body: Garrod's Inborn Errors (1902) and Pauling's Molecular Disease (1949)

4 sessions of 45 minutes

10.2 Growth and Aging Across the Lifespan: Montbeillard's Growth Chart (1759–1777)

4 sessions of 45 minutes

10.3 Reproduction and Development: The Gonads as Glands and Psalm 139

3 sessions of 45 minutes

10.4 Capstone: A Body-Systems Case Study and TEAS-Style Review

4 sessions of 45 minutes

Unit 10 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **7 pts** **Lesson 10.1**

   Two parents are both carriers of sickle cell disease. Give the chance that a child (a) has the disease, (b) is a carrier, (c) has two copies of the usual allele. (d) What is the chance that two of their children both have the disease?

2. **7 pts** **Lesson 10.1**

   A woman who carries red–green color blindness and a color-blind man have children. What are the chances for sons and for daughters?

3. **6 pts** **Lesson 10.1**

   Explain how one changed DNA letter causes the signs of sickle cell disease.

4. **7 pts** **Lesson 10.2**

   Describe how a long bone grows in length and why growth stops after the teen years. Name two hormones involved.

5. **6 pts** **Lesson 10.2**

   A man's GFR is 120 mL/min at 40 and falls 0.8 mL/min a year. Estimate it at 75, and give one reason this matters for his medicines.

6. **7 pts** **Lesson 10.2**

   Explain why the teen years matter most for preventing osteoporosis.

7. **8 pts** **Lesson 10.3**

   Draw or describe the hypothalamus–pituitary–testis loop, naming each hormone. Predict the effect of an anabolic steroid on LH and on the young man's own testosterone.

8. **6 pts** **Lesson 10.3**

   Name the one positive-feedback event in the ovarian cycle and the positive-feedback loop of birth.

9. **7 pts** **Lesson 10.3**

   Put in order, with approximate times after fertilization: neural tube closes, heart begins to beat, implantation begins, all major organs begun, full term.

10. **6 pts** **Lesson 10.3**

    Explain how the foramen ovale and ductus arteriosus close at birth.

CASE AND DATA

11. **10 pts** **Lesson 10.4**

    A patient has bicarbonate 14 mEq/L and P_{CO_2} 28 mmHg. (a) Calculate the pH. (b) Classify the disturbance. (c) Name one disorder from this course that could cause it, and explain the breathing you would expect to see.

12. **8 pts** **Lesson 10.4**

    Select all that apply. A patient with untreated type 1 diabetes is likely to have: (A) glucose in the urine (B) low urine output (C) a fast pulse (D) ketones in the blood (E) a high blood pH

SHORT ESSAY

13. **15 pts** **Lesson 10.1–10.4**

    Short essay. Choose one patient from this unit (Sam, a child with cystic fibrosis, an older adult with osteoporosis, or a newborn born early without enough surfactant). Explain the failed mechanism, trace its effects through at least three body systems, describe the care that helps, and close with a paragraph on what the course has taught you about the body as “fearfully and wonderfully made.”

ANSWER KEY

1. (a) 1/4 (b) 1/2 (c) 1/4 (d) 1/4 × 1/4 = 1/16.
2. Sons: 1/2 color-blind, 1/2 normal (they receive the mother's X). Daughters: 1/2 color-blind (X^cX^c), 1/2 carriers (X^CX^c).
3. The change alters one amino acid of beta-globin (glutamic acid to valine); hemoglobin S clumps into fibers when it gives up oxygen, bending red cells into stiff sickles that block small vessels and break down early, causing pain, organ damage and anemia.
4. Cartilage cells in the growth plate divide and enlarge and are replaced by bone, so the shaft lengthens; growth hormone (through IGF-1) and thyroid hormone drive it. At the end of puberty estrogen closes the plate, which becomes an epiphyseal line, and the bone can no longer lengthen.
5. 120 − 0.8 × 35 = 120 − 28 = 92 mL/min. Drugs cleared by the kidneys stay in his blood longer, so doses may need to be lowered.
6. Bone mass peaks around 30; most of it is built in the teen years with weight-bearing exercise, calcium, vitamin D and protein. A higher peak means that the slow loss of later life (when breakdown outpaces building) takes longer to reach the level where bones break easily.
7. Hypothalamus (GnRH) → anterior pituitary (FSH, LH) → testis: LH → interstitial cells → testosterone; FSH → sustentacular cells (sperm production, inhibin). Testosterone and inhibin feed back negatively. A steroid suppresses GnRH and LH, so his own testosterone and sperm production fall.
8. Sustained high estrogen triggers the LH surge (which releases an egg); in labor, stretching releases oxytocin, which strengthens contractions, which stretch further.
9. Implantation begins (end of week 1), heart begins to beat (about day 22), neural tube closes (week 4), all major organs begun (week 8), full term (about week 38).
10. When the lungs fill with air, resistance in the lungs falls and more blood returns to the left atrium; the higher left-atrial pressure pushes the flap of the foramen ovale shut. The ductus arteriosus constricts within days as oxygen levels rise.
11. (a) 0.03 × 28 = 0.84; 14 ÷ 0.84 = 16.7; log 16.7 = 1.22; pH ≈ 7.32. (b) Metabolic acidosis with partial respiratory compensation. (c) Diabetic ketoacidosis (or severe diarrhea); deep, rapid (Kussmaul) breathing to blow off CO_2.
12. A, C and D.

13. Answers vary. A full answer (1) states the failed mechanism accurately, (2) traces it correctly through at least three systems, (3) describes appropriate care, and (4) reflects thoughtfully on the body's design and on caring for patients.

10.1 Inheritance in the Body: Garrod's Inborn Errors (1902) and Pauling's Molecular Disease (1949)

Mark up this lesson

OBJECTIVES

- Explain how a gene's instructions become a protein and a protein becomes a trait of the body.
- Predict the inheritance of autosomal recessive, autosomal dominant, X-linked, codominant and polygenic traits with Punnett squares and pedigrees.
- Explain sickle cell disease, cystic fibrosis and hemophilia as single broken proteins, and describe newborn screening and genetic counseling.

> **Warm-up.** Look at a family photo with three generations. List three traits that seem to run in the family, and one trait that seems to depend on how people live (what they eat, how much they work outdoors). Which traits do you think come from one gene and which from many?

WATCH

Multiple Alleles (ABO Blood Types) and Punnett Squares

Amoeba Sisters · 7:05

https://www.youtube.com/watch?v=9O5JQqlngFY

> **WHEN TO WATCH**
> Before Example 3, as a review of codominance and blood types.

BACKUP VIDEO

Polygenetic Inheritance | Genetics | Biology

greatpacificmedia · 3:04

https://www.youtube.com/watch?v=gouqTq5p168

With the core idea on traits controlled by many genes.

KEY TERMS

genotype and phenotype

The alleles a person carries (genotype) and the trait that results in the body (phenotype).

autosomal recessive

A trait that appears only when both copies of a gene on a non-sex chromosome are the altered allele; carriers have one copy and are usually healthy.

autosomal dominant

A trait that appears when even one copy of the altered allele is present; an affected parent has a one-in-two chance of passing it on.

X-linked recessive

A trait carried on the X chromosome; it shows far more often in males, who have only one X.

codominance

Both alleles show fully in a heterozygote, as A and B antigens both appear on type AB red cells.

polygenic trait

A trait shaped by many genes plus the environment, such as height or skin tone, which varies smoothly rather than in a few classes.

carrier

A person with one copy of a recessive allele who does not show the trait but can pass it on.

newborn screening

Testing a few drops of blood from every newborn for treatable inherited conditions such as PKU, sickle cell disease and cystic fibrosis.

CORE IDEAS

The story. In 1902 the London physician Archibald Garrod studied families with alkaptonuria, a harmless but striking condition in which the urine turns black on standing. He noticed that the affected children were often born to parents who were first cousins, and with the geneticist William Bateson he recognized the pattern Mendel had described (Biology 5.1): a recessive trait. Garrod proposed that the patients lacked one enzyme, so one step of metabolism was blocked, and in 1908 he called such conditions “inborn errors of metabolism.” Almost no one listened; the link between genes and enzymes was rediscovered decades later. In 1949 Linus Pauling and his colleagues showed that the hemoglobin of people with sickle cell

anemia moves differently in an electric field, and called it the first “molecular disease.” In 1956 Vernon Ingram found the difference: one amino acid out of 146 in each beta chain.

From gene to trait. A gene is a stretch of DNA that codes for a protein. The cell copies the gene into messenger RNA, and ribosomes read it three letters (one codon) at a time to string amino acids together (Biology 6.3). The protein’s shape decides its work: an enzyme (Lesson 9.3), a channel, a receptor, a hormone, a structural fiber or a carrier such as hemoglobin. Change one letter and you may change one amino acid; change the right amino acid and the protein folds or works differently, and the body shows it. Most traits, though, involve many proteins at once, and many alleles cause no harm at all; they simply make people different.

Recessive and dominant conditions. In an **autosomal recessive** condition, one working copy of the gene makes enough protein, so carriers are healthy; only a child who inherits the altered allele from both parents is affected. When both parents are carriers, each child has a 1 in 4 chance of being affected, 1 in 2 of being a carrier and 1 in 4 of inheriting two working copies. Cystic fibrosis (a broken chloride channel, CFTR, that leaves mucus thick and sticky in the lungs and pancreas), sickle cell disease and PKU (Lesson 9.3) follow this pattern. In an **autosomal dominant** condition one altered copy is enough. In familial hypercholesterolemia, for example, half the usual number of LDL receptors in the liver lets cholesterol build up in the blood from childhood, and each child of an affected parent has a 1 in 2 chance of inheriting it.

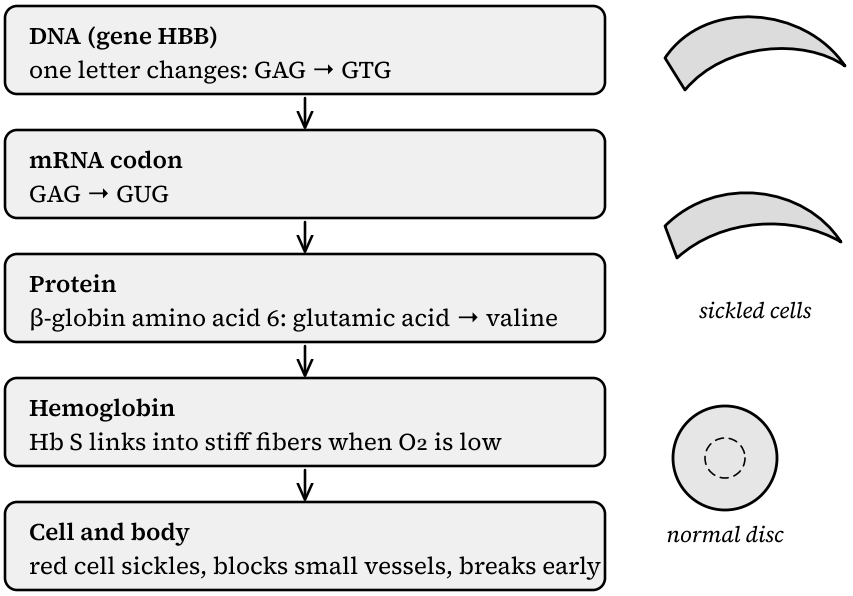
X-linked traits. A woman has two X chromosomes; a man has one X and one Y (Biology 5.4). Genes on the X that have no partner on the Y show up in a man whenever he carries the altered allele. Red–green color blindness affects about 1 in 12 men of European descent but only about 1 in 200 women. Hemophilia A, a lack of clotting factor VIII (Lesson 7.1), ran through the royal families of Europe from Queen Victoria, a carrier: her son Leopold had it, and through two of her daughters it reached the royal families of Spain and Russia. A carrier mother passes the allele to half her sons, who are affected, and half her daughters, who become carriers. An affected father passes his X to every daughter (all carriers) and to no son.

Codominance, many genes and the environment. The ABO blood groups show both codominance and multiple alleles: A and B are codominant, and O is recessive to

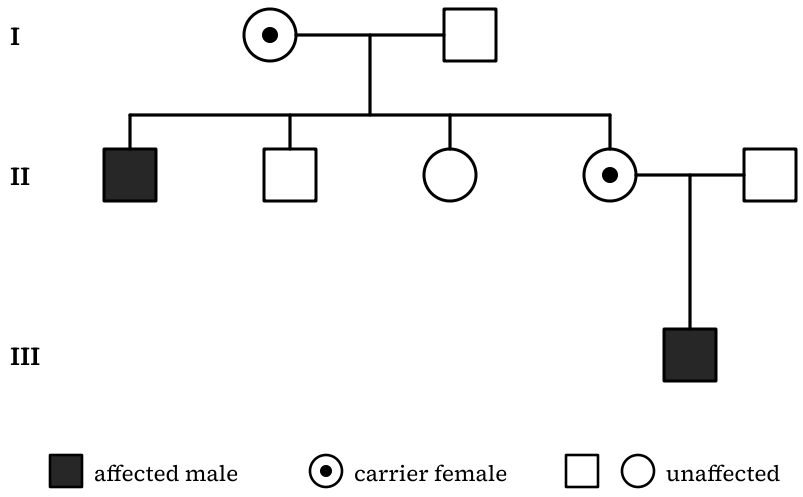
both, so a child of an AO parent and a BO parent may have any of the four types (Lesson 7.1, Biology 5.3). Height, on the other hand, is shaped by hundreds of genes, each with a small effect, and also by nutrition, sleep and health: children in many countries are taller than their great-grandparents were, though their genes have hardly changed. Mitochondria have a little DNA of their own, and because a baby's mitochondria all come from the egg, mitochondrial genes are inherited only from the mother. Whole-chromosome changes, such as the extra chromosome 21 of Down syndrome, come from errors when chromosomes separate in meiosis (Lesson 10.3).

Caring for families. Every newborn in the United States has a few drops of blood taken from the heel for screening, so that conditions such as PKU, sickle cell disease and cystic fibrosis are found and treated before harm is done. Genetic counselors help families read pedigrees and understand their chances. Knowing one's carrier status is a medical fact, not a measure of a person's worth: a child with a genetic condition is as fully made in God's image as any other, and many such children grow up to serve and lead with great courage.

When it goes wrong. In **sickle cell disease** one DNA letter in the beta-globin gene changes, so the sixth amino acid changes from glutamic acid to valine. The altered hemoglobin S sticks to its neighbors when it gives up oxygen and forms stiff fibers that bend the red cell into a sickle. Sickled cells block small vessels, causing pain and damage to organs, and they break down early, causing anemia. Carriers (sickle cell trait) are usually healthy and have some protection against severe malaria, which is why the allele is common where malaria is. Treatments now include medicines that raise fetal hemoglobin, and, for some patients, bone-marrow transplants and newly approved gene therapies.



One changed DNA letter becomes one changed amino acid, a hemoglobin that clumps, and a stiff sickled cell: the whole disease follows from the shape of one protein.



An X-linked recessive trait skips through carrier daughters and shows in sons.

LAB

A Family Trait Survey and a Blood-Type Puzzle

You will collect real family data on simple traits and solve inheritance puzzles with Punnett squares.

You will need

- Your family members, by phone or in person; a notebook
- Index cards for a blood-type puzzle (each card with a parent pair, such as AO × BO)

Steps

1. Survey at least eight relatives over two or three generations for two traits: attached or free earlobes and the ability to roll the tongue. (These are often taught as single-gene traits, but they are actually influenced by more than one gene; treat your results as a test of that claim.)
2. Draw a pedigree for one trait with standard symbols: squares for males, circles for females, shaded for the trait.
3. If any family members know their blood types (from donor cards), add them to the pedigree and check whether they are consistent with Mendel's rules.
4. Solve ten blood-type cards: for each parent pair, make a Punnett square and list the possible types and their chances.

Check your work

- ☐ Did your earlobe or tongue-rolling pedigree fit a simple dominant–recessive pattern? Why might it not?
- ☐ Which parent pairs can have a type O child? Which can have a type AB child?
- ☐ Why does a pedigree with many generations tell you more than a single family?

LAB NOTEBOOK

1. The gene-to-trait chain for sickle cell disease, drawn in your own words.
2. Punnett squares for the three patterns: recessive, dominant and X-linked, each with its probabilities written beside it.

From history. Garrod was right about one gene, one enzyme forty years before George Beadle and Edward Tatum proved it in bread mold (1941). When they received the Nobel Prize in 1958, Beadle gave Garrod the credit for having seen it first.

Practice habit. Draw the Punnett square every time, even for problems you think you can do in your head; label the parents' gametes on the edges before filling in the boxes.

WORKED EXAMPLES

Example 1. Two parents are both carriers of cystic fibrosis (Ff × Ff). What are the chances that a child is affected, is a carrier, or has two working copies? If a child is healthy, what is the chance that he or she is a carrier?

Show solution

1. Punnett square: FF, Ff, fF, ff.
2. Affected (ff): 1/4. Carrier (Ff): 2/4 = 1/2. Two working copies (FF): 1/4.
3. Among the three healthy outcomes (FF, Ff, fF), two are carriers: 2/3.

Answer: 1/4 affected, 1/2 carrier, 1/4 non-carrier; a healthy child has a 2/3 chance of being a carrier.

Example 2. A woman who carries hemophilia A ($X^{H}X^{h}$) and an unaffected man ($X^{H}Y$) have children. What are the chances for a son and for a daughter?

Show solution

1. Her eggs: X^{H} or X^{h}, each 1/2. His sperm: X^{H} or Y, each 1/2.
2. Sons get Y from the father and one X from the mother: 1/2 $X^{H}Y$ (unaffected), 1/2 $X^{h}Y$ (affected).
3. Daughters get X^{H} from the father: 1/2 $X^{H}X^{H}$, 1/2 $X^{H}X^{h}$ (carriers); none affected.

Answer: Each son has a 1/2 chance of hemophilia; each daughter has a 1/2 chance of being a carrier and almost no chance of being affected.

Example 3. A type A parent with genotype I^Ai and a type B parent with genotype I^Bi have a child. List the possible blood types and their chances.

Show solution

1. Gametes: I^A or i from one parent; I^B or i from the other.
2. Square: I^AI^B (AB), I^Ai (A), I^Bi (B), ii (O).

Answer: Types AB, A, B and O, each with a chance of 1/4.

PRACTICE

CONCEPT CHECKS

1. Easy Define genotype and phenotype, using blood type as the example.

   Show answer

   Genotype is the pair of alleles, such as I^Ai; phenotype is the trait that shows, type A blood.

2. Easy Why do X-linked recessive traits show up more often in males?

   Show answer

   Males have one X; whatever allele is on it shows, because the Y has no matching gene to cover it. Females need the allele on both X chromosomes.

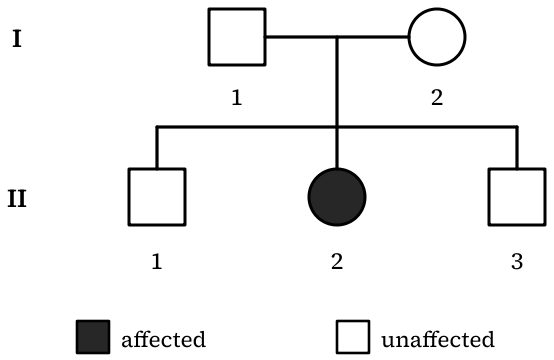
3. Easy Why are mitochondrial traits passed only from the mother?

   Show answer

   A baby's mitochondria all come from the egg; the sperm's mitochondria do not survive in the embryo.

DIAGRAM AND DATA QUESTIONS

4. **Medium** In the pedigree, persons I-1 and I-2 are unaffected and their daughter II-2 is affected. (a) Is the trait dominant or recessive? (b) Label the genotypes of I-1, I-2 and II-2. (c) What is the chance that II-3 is a carrier?



Show answer

(a) Recessive, because two unaffected parents had an affected child. (b) I-1 Aa, I-2 Aa, II-2 aa. (c) II-3 is unaffected, so he is AA or Aa: a 2/3 chance of being a carrier.

5. **Medium** Two carrier parents plan a family of four children. What is the chance that none of the four has the recessive condition?

Show answer

$(3/4)^4 = 81/256 \approx 0.32$, about 32%; so about a 68% chance that at least one child is affected. Each child's chance stays 1/4 regardless of the others.

6. **Medium** A man with hemophilia A and a woman who is not a carrier have children. What are the chances for their sons and daughters?

Show answer

All sons get his Y and her normal X: unaffected. All daughters get his X^h: every daughter is a carrier, none affected.

7. **Medium** Can a type AB mother and a type O father have a type O child? Explain.

Show answer

No. The father gives i and the mother gives I^A or I^B, so every child is type A or type B.

8. Hard **Disorder as a broken mechanism.** Explain cystic fibrosis as one broken protein: what does CFTR normally do, and how does its failure lead to lung infections and poor digestion?

Show answer

CFTR is a chloride channel in the membranes of lining cells. When it fails, chloride (and water following it) does not move into the mucus, which becomes thick and sticky. In the lungs it traps bacteria and blocks airways; in the pancreas it plugs the ducts so enzymes cannot reach the intestine, and food is poorly digested.

9. Hard Predict: why are children growing up today, on average, taller than their great-great-grandparents, if genes hardly change in a century?

Show answer

Height is polygenic and also depends on the environment; better nutrition, cleaner water and fewer childhood illnesses let more children reach the height their genes allow.

TEST PREP

10. Medium Test prep. Which inheritance pattern fits a trait that appears in every generation and that an affected parent passes to about half of the children, sons and daughters alike? (A) autosomal recessive (B) autosomal dominant (C) X-linked recessive (D) mitochondrial

Show answer

(B) autosomal dominant.

11. Medium Test prep. A change of one DNA letter in a gene alters one amino acid of a protein. This is called (A) a point mutation (B) nondisjunction (C) crossing over (D) codominance

Show answer

(A) a point mutation.

COMMON MISTAKES

- Thinking a 1 in 4 chance means that if the first child is affected the next three will not be; each child's chance is independent.
- Saying a recessive allele is weaker or rarer; recessive describes how it shows, not how common it is.

- Giving a father's X-linked allele to his sons; fathers pass the X only to daughters.
- Treating every trait as one gene; most body traits, such as height, are polygenic and shaped by the environment too.
- Confusing carriers (one copy, usually healthy) with affected people (two copies, for a recessive trait).

Make it a game · Punnett Speed Round. Write twelve parent pairs on cards: Aa × Aa, Aa × aa, $X^{H}X^{h} \times X^{H}Y$, $I^{A}i \times I^{B}i$ and so on. Set a 60-second timer. The parent flips a card and asks one question ("chance of an affected son?", "chance of type O?"). The student answers as a fraction. Count correct answers in a minute, then play again next day to beat the score.

Scripture. "And his disciples asked him, saying, Master, who did sin, this man, or his parents, that he was born blind? Jesus answered, Neither hath this man sinned, nor his parents: but that the works of God should be made manifest in him." (John 9:2–3, KJV)

An inherited condition is not a punishment and not a person's identity. Jesus turned the disciples' question about blame into a call to see God's works, and to serve.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error

Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

10.2 Growth and Aging Across the Lifespan: Montbeillard's Growth Chart (1759–1777)

Mark up this lesson

OBJECTIVES

- Describe the stages of the human lifespan and the hormones that drive growth, including growth at the growth plates.
- Describe how the major body systems change with age, and calculate simple measures of growth and aging.
- Explain how exercise, nutrition and sleep slow the losses of aging, and explain osteoporosis as a broken balance.

> **Warm-up.** Find the marks on a door frame (or a growth chart) where your height was measured as a child, or ask a parent for your height at ages 2, 6 and 10. In which years did you grow fastest?

WATCH

Why do our bodies age? - Monica Menesini

TED-Ed · 5:09

https://www.youtube.com/watch?v=GASaqPv0t0g

> **WHEN TO WATCH**
> After the core idea on aging cells.

BACKUP VIDEO

Bone elongation - processes at the epiphyseal plate

Homework Clinic · 2:03

https://www.youtube.com/watch?v=V9knxKdDf9A

With the core idea on growth plates.

KEY TERMS

growth plate (epiphyseal plate)
A disc of cartilage near each end of a growing long bone, where new cartilage is made and turned into bone, lengthening the bone.

epiphyseal line
The thin line of bone left when a growth plate closes after the teen years; the bone can no longer grow longer.

growth hormone
An anterior pituitary hormone that drives growth, largely by making the liver release insulin-like growth factor 1 (IGF-1).

peak bone mass
The greatest amount of bone a person builds, reached around the late twenties to about thirty.

sarcopenia
The gradual loss of muscle mass and strength with age, slowed by strength training and enough protein.

Hayflick limit
The limited number of times (often about 40 to 60) that most human body cells can divide in culture before they stop.

telomere
A protective repeated DNA cap at the end of each chromosome that shortens a little with each cell division.

presbyopia
Age-related stiffening of the eye's lens that makes close focusing hard, usually noticed in the forties.

CORE IDEAS

The story. In 1759 the French nobleman Philibert Guéneau de Montbeillard began measuring his newborn son's height every six months or so, and kept it up until the boy was eighteen. The great naturalist Buffon published the record in 1777. Plotted as a graph, it is the first known growth chart. It shows what every pediatrician's chart shows today: very fast growth in infancy, a steady slowing through childhood, a sudden spurt in the teen years, and then a stop. Doctors still plot a child's height and weight at every visit, because a curve that leaves its usual track can be the first sign of illness, poor nutrition or a hormone problem.

Stages of life. In the first year a baby's length grows by about half and the birth weight roughly triples. Through childhood growth slows to about 5 to 6 cm a year. In

adolescence the growth spurt can reach 8 to 10 cm a year, usually starting earlier in girls than in boys; muscles, heart and lungs grow, and the body's proportions change (a newborn's head is about a quarter of its length, an adult's about an eighth). Young adulthood is the peak of strength, speed, bone mass and organ reserve. Gradual changes begin after about thirty, and from late middle age they become more noticeable. Old age is not a disease; it is a stage, and the Bible honors it.

How bones grow longer. A long bone grows in length only at its growth plates (Lesson 3.3). On the side nearest the end, cartilage cells divide and stack up in columns; toward the shaft they enlarge and die, and bone-building cells replace the cartilage with bone. The plate stays the same thickness while the shaft lengthens behind it. **Growth hormone** (through IGF-1 from the liver) and thyroid hormone keep the plates working through childhood (Lesson 6.2). At puberty the sex hormones cause the growth spurt, and then estrogen, in both young women and young men, closes the plates: the cartilage is replaced completely, leaving an epiphyseal line. Most plates close by the late teens, and after that a person grows no taller.

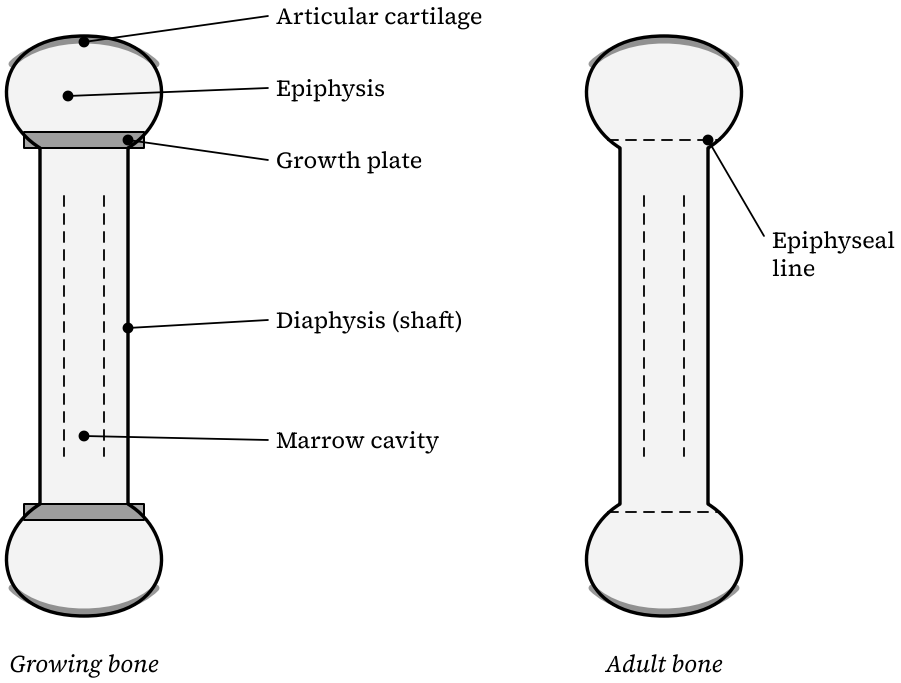
Aging of the systems. Skin thins and loses collagen and elastic fibers, so it wrinkles, bruises and heals more slowly, and fewer sweat glands make heat waves dangerous for the elderly (Lesson 3.1). Muscle mass falls by roughly 3 to 8% per decade after thirty, faster after sixty. Arteries stiffen and the maximum heart rate falls (roughly 220 minus age). The lungs lose elastic recoil. The kidneys' filtration rate falls by roughly 0.75 to 1 mL/min per year after about forty, so medicines are cleared more slowly (Lesson 9.4). The lens stiffens (presbyopia) and high-pitched hearing fades. The thymus shrinks after puberty, so fewer new T cells are made (Lesson 7.5). The brain processes new information more slowly, but vocabulary and knowledge, the fruit of a lifetime, can keep growing.

Why cells age. In 1961 Leonard Hayflick and Paul Moorhead found that normal human cells grown in a dish divide a limited number of times and then stop. Part of the reason is the **telomeres**: each division leaves the chromosome ends a little shorter, and very short telomeres signal the cell to stop dividing. (Elizabeth Blackburn, Carol Greider and Jack Szostak shared the 2009 Nobel Prize for discovering how telomeres and the enzyme telomerase protect chromosomes.) Damage also builds up over the years in DNA, proteins and mitochondria. No one of

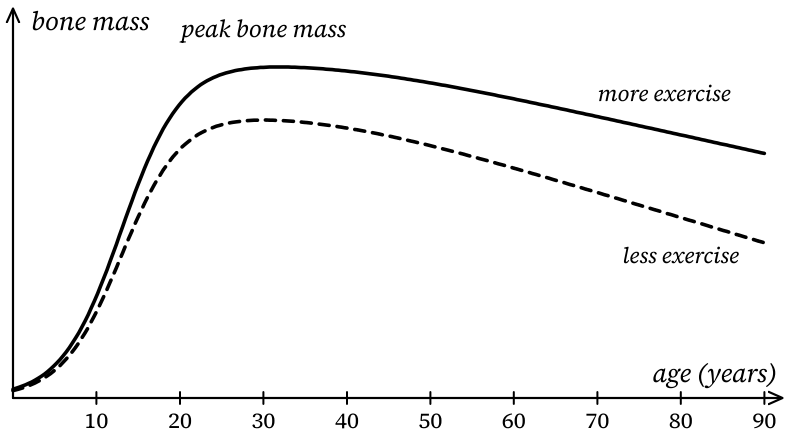
these explains all of aging; the body's repair systems simply wear, as Scripture says the outward man perishes.

Living well at every age. Much of the decline once blamed on age is really due to inactivity. Strength training builds muscle even in people in their eighties; weight-bearing exercise and enough calcium, vitamin D and protein build bone; aerobic exercise keeps the heart, lungs and vessels supple (PE 9 Lesson 5.1, The Cardiorespiratory System); and good sleep, purposeful work, friendships and learning help the brain. The teenage years are the best time to build the bone and muscle "savings account" that the rest of life will draw on.

When it goes wrong. Bone is broken down by osteoclasts and rebuilt by osteoblasts all through life. In **osteoporosis** breakdown outpaces building, so bone becomes thin and porous and can break from a minor fall; a broken hip is a serious injury for an older person. Risk rises when a person built a low peak bone mass in youth, after estrogen falls in women, and with little exercise, low calcium and vitamin D, smoking or certain medicines. Weight-bearing exercise and good nutrition in the teen years are the best prevention, and medicines can slow the breakdown in later life.



A long bone lengthens at its cartilage growth plates; when they close after puberty only a thin epiphyseal line remains.



A schematic, not measured data: bone mass peaks around age thirty and then slowly declines, more slowly in people who exercise and eat well.

> **Safety first.** For the balance test, the older person stands beside a wall or holds the back of a sturdy chair, with you standing close. Stop any test that causes pain or dizziness.

LAB

Three Generations: Reaction, Balance and Grip

You will measure simple signs of aging in willing family members of different ages, kindly and safely.

You will need

- A 30-cm ruler, a watch with a second hand, a sturdy chair, a notebook
- Volunteers of three generations if possible (a sibling, a parent, a grandparent)

Steps

1. Ruler drop: hold the ruler vertically with its 0 mark between the volunteer's open thumb and finger. Drop it without warning; record where it is caught. Do five trials and average. Convert distance to time with $t = \sqrt{(2d \div g)}$, using d in meters and $g = 9.8\ m/s^2$.
2. Balance: the volunteer stands on one foot beside a wall, eyes open, for up to 30 seconds; record the time.
3. Grip and strength (optional): count how many times each volunteer can rise from a chair without using the arms in 30 seconds.
4. Make a table and a bar chart by age.

Check your work

- ☐ Which measures changed most with age? Which changed little?
- ☐ Did the most active person of each age do best? What does that suggest?
- ☐ List two habits you could start now to build your "savings account" of bone and muscle.

LAB NOTEBOOK

1. A growing bone and an adult bone side by side, with the growth plates and epiphyseal lines labeled.
2. Your family results table and bar chart.

From history. Montbeillard's son grew up to be tall for his time. Modern growth charts used in American clinics are built from measurements of tens of thousands of children, but the shape of the curve is the same as the one a father drew by hand in the 1700s.

Practice habit. Do one weight-bearing or strength exercise every day this week (jumping, squats, push-ups or carrying loads), and write one line in your sketchbook about the bone or muscle it builds.

Career connection. A **physical therapist** or **occupational therapist** helps people of every age move and live well: a teenager after a sports injury, a grandmother after a hip fracture. Both need a graduate degree, and both use anatomy, aging and exercise science every day. A **physical therapist assistant** needs a two-year degree and a licensing exam.

WORKED EXAMPLES

Example 1. A girl was 152 cm tall at age 12 and 165 cm at age 14. What was her average growth rate? Is this consistent with a growth spurt?

Show solution

1. Growth: 165 − 152 = 13 cm in 2 years.
2. Rate: 13 ÷ 2 = 6.5 cm per year.

Answer: 6.5 cm per year, faster than the 5–6 cm of late childhood and typical of the teen growth spurt.

Example 2. Estimate the maximum heart rate of a 16-year-old and of a 70-year-old with the rule 220 − age. A newer formula is 208 − 0.7 × age; compare.

Show solution

1. 220 − 16 = 204 and 220 − 70 = 150 beats per minute.
2. 208 − 0.7(16) = 196.8 ≈ 197 and 208 − 0.7(70) = 159 beats per minute.

Answer: About 204 versus 150 by the old rule, and about 197 versus 159 by the newer one; both show a steady fall with age, and the newer formula fits older adults better.

Example 3. A man's GFR is 125 mL/min at age 40. If it falls by about 0.8 mL/min each year, what will it be at 80? Why would a doctor lower the dose of a drug the kidneys clear?

Show solution

1. Loss over 40 years: 0.8 × 40 = 32 mL/min.
2. GFR at 80: 125 − 32 = 93 mL/min.

Answer: About 93 mL/min. The kidneys clear the drug about a quarter more slowly, so the same dose would build up to a higher level in the blood.

PRACTICE

CONCEPT CHECKS

1. Easy Where does a long bone grow in length, and what tissue is there?

   Show answer

   At the growth plates near each end, which are made of cartilage.

2. Easy Which hormone finally closes the growth plates in both young women and young men?

   Show answer

   Estrogen (in young men it is made from testosterone).

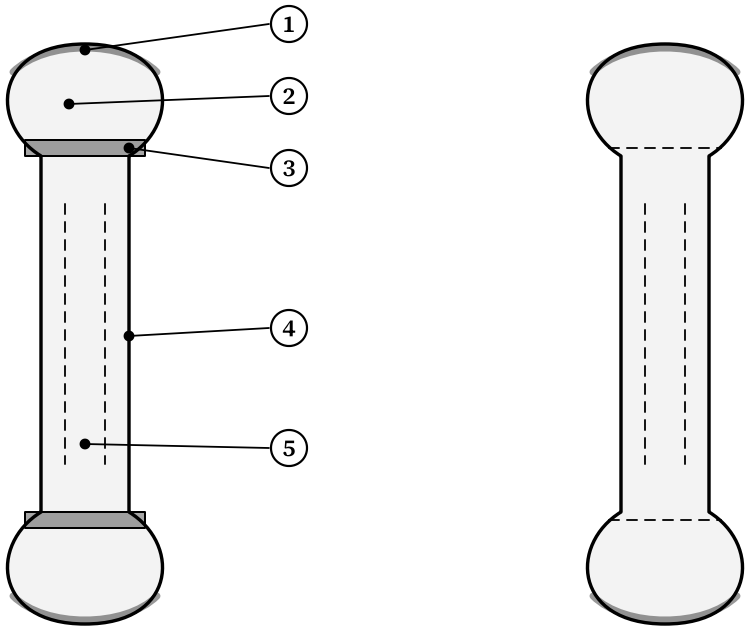
3. Easy Give three changes of aging, from three different body systems.

   Show answer

   Any three, such as thinner skin and fewer sweat glands, loss of muscle mass, stiffer arteries and lower maximum heart rate, lower GFR, a stiffer lens, a smaller thymus.

DIAGRAM AND DATA QUESTIONS

4. **Medium** Name the parts numbered 1 to 5 in the growing bone.



Growing bone *Adult bone*

Show answer

1 articular cartilage, 2 epiphysis, 3 growth plate (epiphyseal plate), 4 diaphysis (shaft), 5 marrow (medullary) cavity.

5. **Medium** In a ruler-drop test a 15-year-old catches the ruler after it falls 15 cm, and his grandfather after 20 cm. Find each reaction time with $t = \sqrt{(2d/g)}$.

Show answer

Student: $\sqrt{(2 \times 0.15 \div 9.8)} = 0.175$ s. Grandfather: $\sqrt{(2 \times 0.20 \div 9.8)} = 0.202$ s, about 0.03 s slower.

6. **Medium** A woman has 24 kg of skeletal muscle at age 30 and loses 5% per decade. About how much will she have at age 70 if she does no strength training?

Show answer

$24 \times 0.95^4 = 24 \times 0.8145 \approx 19.5$ kg.

7. Medium Using the Mifflin–St Jeor equation, by how much does predicted BMR fall between ages 20 and 60 for the same height and weight? Why might the real fall be larger?

Show answer

5 kcal per year × 40 years = 200 kcal/day. The real fall may be larger because most people also lose muscle, which burns more energy than fat.

8. Hard **Disorder as a broken mechanism.** Explain osteoporosis in terms of osteoclasts and osteoblasts, and explain why a teenager's exercise and diet matter for it fifty years later.

Show answer

Bone is constantly broken down by osteoclasts and rebuilt by osteoblasts; in osteoporosis breakdown outpaces building and bone thins. A person who builds a high peak bone mass in youth, through weight-bearing exercise, calcium and vitamin D, starts the slow decline from a higher level and reaches the fracture zone later, if ever.

9. Hard Predict: why are older adults more at risk during a heat wave? Use at least two body systems in your answer.

Show answer

Fewer and less active sweat glands (skin), a weaker thirst sense and kidneys that concentrate urine less well (fluid balance), and a heart and vessels less able to increase skin blood flow (circulation), so they cool less well and dehydrate more easily.

TEST PREP

10. Medium Test prep. A 45-year-old has trouble reading small print up close. This is most likely (A) myopia (B) presbyopia (C) cataract (D) glaucoma

Show answer

(B) presbyopia.

11. **Medium** Test prep (select all that apply). Which slow the loss of bone and muscle with age? (A) strength training (B) weight-bearing exercise (C) adequate calcium and vitamin D (D) smoking (E) enough protein

Show answer

A, B, C and E.

COMMON MISTAKES

- Thinking bones grow from the middle or from the ends' outer surfaces; they lengthen only at the growth plates.
- Thinking aging is the same as disease; many changes are normal and can be slowed by good habits.
- Treating 220 − age as exact; it is a rough estimate with an error of 10 or more beats per minute.
- Forgetting that estrogen closes growth plates in young men as well as young women.
- Thinking older people cannot build muscle; strength training works at every age.

Make it a game · Lifespan Line-Up. Write ten events on cards: birth weight triples, growth spurt, growth plates close, peak bone mass, presbyopia begins, thymus shrinks, maximum heart rate about 150, and so on. The student lays them along a hallway in age order and says one sentence about each. The parent then swaps two cards when the student is not looking; the student must spot and fix the swap.

Scripture. "And even to your old age I am he; and even to hoar hairs will I carry you: I have made, and I will bear; even I will carry, and will deliver you." (Isaiah 46:4, KJV)

The God who made each body at its beginning promises to carry it through its last years. Honoring the old (Leviticus 19:32) means helping them stay strong and serving them when they cannot.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

10.3 Reproduction and Development: The Gonads as Glands and Psalm 139

Mark up this lesson

OBJECTIVES

- Describe the testes and ovaries as endocrine glands, their hormones, and the hypothalamus–pituitary–gonad feedback loop.
- Explain the link between the gonads and meiosis, and compare how sperm and eggs are formed.
- Trace human development from fertilization to birth week by week, and describe the placenta and the newborn's first breath.

> **Warm-up.** With a parent, look at a photo or record of your own birth: your length and weight on the day you were born. Read Psalm 139:13–16 together. What does the psalmist say God saw before anyone else could?

WATCH

Hypothalamus-pituitary-gonadal axis

Mechanisms and Logic in Human Physiology · 4:35

https://www.youtube.com/watch?v=g2RKMNNIMBU

> **WHEN TO WATCH**
> Parent preview suggested. A whiteboard explanation of the hormone axis; watch after the core idea on feedback.

BACKUP VIDEO

Hypothalamic Pituitary Axis | Endocrine System

Dr Matt & Dr Mike · 4:24

https://www.youtube.com/watch?v=fqz4WOwfz4Q

Parent preview suggested. A general review of how the hypothalamus controls the pituitary (Lesson 6.2).

KEY TERMS

gonads

The testes in a man and the ovaries in a woman: glands that make gametes (sperm or eggs) by meiosis and also secrete sex hormones.

GnRH

Gonadotropin-releasing hormone, released by the hypothalamus in pulses; it tells the anterior pituitary to release FSH and LH.

FSH and LH

Follicle-stimulating hormone and luteinizing hormone, the pituitary's two gonadotropins, which act on the testes and ovaries.

testosterone

The main androgen, made by the interstitial cells of the testes; it supports sperm production and builds muscle, bone and a deeper voice.

estrogen and progesterone

The main ovarian hormones: estrogen from growing follicles and progesterone from the corpus luteum; in pregnancy the placenta makes both.

zygote, embryo and fetus

The single cell formed at fertilization; the developing child through week 8, while the organs form; and the developing child from week 9 until birth.

placenta

The organ, built from the embryo's and the mother's tissues, where oxygen, nutrients and wastes are exchanged without the two bloods mixing; it also makes hormones.

fetal shunts

The foramen ovale and ductus arteriosus, openings that send most blood past the unused lungs before birth and close soon after.

CORE IDEAS

Parent-led lesson: read this lesson with a parent. This lesson treats the testes and ovaries as endocrine glands, the way the TEAS and HESI nursing exams test them, and then follows the growth of a child before birth. It uses only schematic diagrams of glands and a timeline.

The story. For two thousand years no one had seen a mammal's egg. In 1827 the Estonian-born naturalist Karl Ernst von Baer, working in Königsberg, opened a small swelling on the ovary of a dog and found inside it a tiny yellowish sphere, barely visible to the eye. He had found the mammalian egg, and he went on to describe how

every vertebrate embryo builds itself in layers. A century later embryologists had traced the development of the human child week by week. In 1958 the Scottish obstetrician Ian Donald published the first ultrasound pictures from inside the womb, and parents could see what the psalmist had only known: a whole person being knit together.

The gonads are glands. The hypothalamus releases **GnRH** in pulses; GnRH tells the anterior pituitary to release **FSH** and **LH** (Lesson 6.2). In the testes, LH makes the interstitial cells secrete **testosterone**, and FSH, with testosterone, acts on the sustentacular (Sertoli) cells that nourish developing sperm; those cells also make **inhibin**. In the ovaries, FSH makes follicles grow, and the follicle cells secrete **estrogen**; after an egg is released, the empty follicle becomes the corpus luteum, which secretes **progesterone** and estrogen. All of these hormones act on many tissues besides the gonads: bone, muscle, skin, the brain and the growth plates (Lesson 10.2).

Feedback keeps the levels steady. Testosterone, estrogen, progesterone and inhibin travel back to the hypothalamus and pituitary and slow the release of GnRH, FSH and LH, a classic negative-feedback loop (Lesson 1.3). If testosterone falls, LH rises; if a man takes extra testosterone or an anabolic steroid, his LH and FSH are suppressed, and his own testes make less hormone and fewer sperm. The ovary adds one famous exception: when estrogen stays high for about two days, it switches to *positive* feedback and triggers a surge of LH, which releases a mature egg. If no pregnancy begins, the corpus luteum fades after about two weeks, its hormones fall, the uterine lining is shed and the roughly monthly cycle starts again. Puberty begins when the hypothalamus increases its GnRH pulses, bringing the growth spurt, the closing of the growth plates and adult strength.

The link to meiosis. The gonads are the only places where meiosis happens (Biology 5.4). In a man, sperm are made continually from puberty on: each primary spermatocyte divides by meiosis into four sperm, each with 23 chromosomes, a process that takes about two months from start to finish. In a woman, every egg cell began meiosis before she was born and paused partway through meiosis I. A baby girl has one to two million such cells; only about four hundred will ever be released. Each month one resumes meiosis, and the division is lopsided: one large egg keeps nearly all the cytoplasm and the other products are tiny polar bodies. The egg completes meiosis II only at fertilization. Errors in separating chromosomes, more

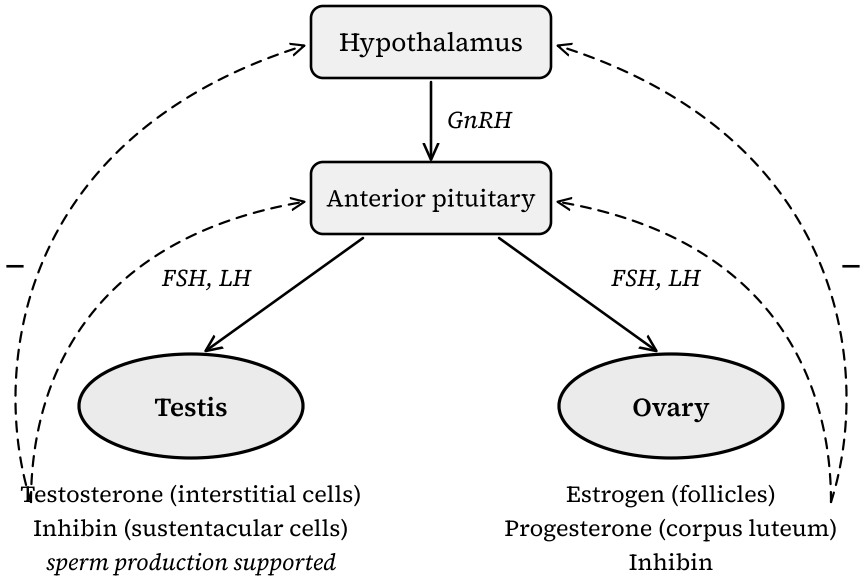
common as a mother ages, can give a child an extra chromosome, as in Down syndrome (Lesson 10.1).

Week by week. At fertilization sperm and egg unite to form a **zygote**, one new cell with 46 chromosomes and its own unique DNA; its sex is already set by the X or Y the sperm carried. Dividing as it travels, it becomes a hollow ball (blastocyst) that begins to implant in the uterine wall at the end of the first week and soon releases hCG, the hormone a pregnancy test detects; hCG keeps the corpus luteum making progesterone. In week 3 the three germ layers form, and around day 22 the heart begins to beat. In week 4 the neural tube closes and the arm and leg buds appear. By the end of week 8 every major organ has begun and the embryo is about 3 cm long; from week 9 the child is called a fetus, and the organs grow and mature. The kidneys begin making urine in weeks 10 to 12; the mother often first feels movement in weeks 14 to 18; the lungs begin making surfactant in weeks 20 to 24 (Lesson 8.3). Full term is about 38 weeks after fertilization, which doctors count as 40 weeks of "gestational age" from two weeks earlier. A typical newborn is about 50 cm long and weighs about 3.4 kg.

The placenta and the first breath. The placenta lets the child's blood and the mother's blood come within a hair's breadth of each other without mixing; oxygen, glucose and antibodies cross one way and carbon dioxide and urea the other. Fetal hemoglobin holds oxygen more tightly than adult hemoglobin, so it can take oxygen from the mother's blood (Lesson 8.3). Because the lungs are filled with fluid, two shunts send most blood past them: the **foramen ovale** between the atria and the **ductus arteriosus** from the pulmonary trunk to the aorta (Lesson 7.2). In labor, stretching triggers oxytocin, which strengthens contractions, which cause more stretching: a positive-feedback loop that ends with birth. With the first breaths the lungs fill with air, the pressure in the left atrium rises and pushes the foramen ovale shut, and within days the ductus arteriosus closes. Every system has to switch over in minutes, and in nearly every birth it does.

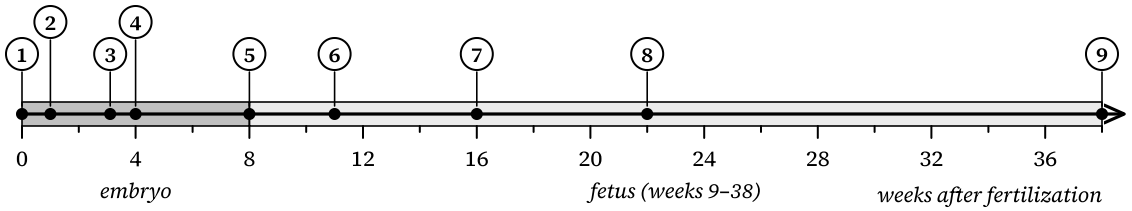
When it goes wrong. The neural tube closes in the fourth week after fertilization, often before a mother knows she is expecting. If it fails to close, the result is a **neural tube defect** such as spina bifida, in which part of the spinal cord is left exposed. The vitamin folate is needed for the rapid cell division of that week; since grain products were fortified with folic acid and women who may become mothers were advised to take it daily, these defects have become much less common. A baby born very early

may not yet make enough surfactant, so its air sacs collapse with each breath; doctors can now give surfactant directly into the newborn's lungs.



Dashed arrows: negative feedback (−).
Exception: a high, sustained estrogen level triggers the LH surge (+).

The hypothalamus and pituitary drive the gonads, and the gonads' hormones feed back to slow them; a sustained high estrogen level is the exception that triggers the LH surge.



1. Day 1: fertilization; one new cell with 46 chromosomes
2. End of week 1: the embryo begins to implant
3. About day 22: the heart begins to beat
4. Week 4: neural tube closes; arm and leg buds appear
5. Week 8: every major organ begun; about 3 cm long
6. Weeks 10–12: the kidneys begin to make urine
7. Weeks 14–18: the mother often first feels movement
8. Weeks 20–24: the lungs begin to make surfactant
9. About week 38: full term; about 50 cm and 3.4 kg

Doctors count gestational age from two weeks earlier, so add 2 to these weeks.

Every organ is begun in the first eight weeks; the rest of the pregnancy is growth and maturing. Psalm 139:16: "in thy book all my members were written, which in continuance were fashioned."

LAB

A Psalm 139 Timeline

With a parent, you will make a timeline of development before birth and set Psalm 139:13–16 beside it.

You will need

- A long strip of paper (about 1 meter), a ruler, pencils or markers
- Your own birth length and weight from a family record, if available

Steps

1. Mark 0 to 38 weeks along the strip, 2.5 cm for each week. Shade weeks 1–8 (embryo) differently from weeks 9–38 (fetus).
2. Mark the milestones from the lesson: fertilization, implantation, heartbeat, neural tube, all organs begun, kidneys working, movements felt, surfactant, full term.
3. Above the strip, copy Psalm 139:13–16, placing each phrase over the part of the timeline it fits best.
4. Beside week 38, write your own birth length and weight and compare them with the typical values.

Check your work

- ☐ In which weeks is every major organ begun? Why is that the most sensitive time for the child's health?
- ☐ Which hormone does a pregnancy test detect, and what does it do for the pregnancy?
- ☐ Which phrase of the psalm fits the first eight weeks best, and why?

LAB NOTEBOOK

1. The hormone axis: hypothalamus, pituitary and the two gonads, with + and − on each arrow.
2. Side-by-side diagrams of meiosis in sperm formation (four equal cells) and egg formation (one egg and polar bodies).

From history. Von Baer also described the notochord and the germ layers, and he argued that embryos of different animals look most alike early on and become distinct as they develop. He believed that nature shows purpose and saw development as the orderly unfolding of a plan toward a goal.

Practice habit. Before you answer any hormone question, sketch the three levels (hypothalamus, pituitary, gland) and mark each arrow with + or −; then follow the arrows.

WORKED EXAMPLES

Example 1. A young athlete secretly takes an anabolic steroid (a synthetic testosterone). Predict what happens to his GnRH, LH and FSH, to his own testosterone production, and to his growth plates.

Show solution

1. The steroid acts like high testosterone, so negative feedback suppresses GnRH, LH and FSH.
2. Without LH, his interstitial cells make less of his own testosterone; without FSH and local testosterone, sperm production falls and the testes shrink.
3. Some of the steroid is converted to estrogen, which can close his growth plates early (Lesson 10.2).

Answer: GnRH, LH and FSH fall; his own testosterone and sperm production fall; and he may stop growing taller sooner. It is a clear case of the body's feedback working against the drug.

Example 2. The heart begins to beat about day 22 after fertilization. What is that in weeks after fertilization, and in a doctor's gestational weeks?

Show solution

1. 22 ÷ 7 = 3.1 weeks after fertilization.
2. Gestational age adds 2 weeks: 3.1 + 2 = 5.1 weeks.

Answer: About 3 weeks after fertilization, which a doctor calls about 5 weeks of gestation.

Example 3. If a zygote's cells simply doubled again and again, how many doublings would make about one trillion (10^{12}) cells? Why is real development more than doubling?

Show solution

1. $2^n = 10^{12}$, so $n = \log_2(10^{12}) = 12 \div \log_{10}2 = 12 \div 0.301 \approx 39.9$.
2. About 40 doublings.

Answer: About 40 doublings. But cells also move, specialize into more than 200 kinds and die in planned places (such as between the fingers), all on schedule; development is ordered construction, not just multiplication.

PRACTICE

CONCEPT CHECKS

1. Easy Which cells of the testes make testosterone, and which pituitary hormone stimulates them?

   Show answer

   The interstitial (Leydig) cells, stimulated by LH.

2. Easy Name the two main ovarian hormones and the structure that makes each after an egg is released.

   Show answer

   Estrogen (from the follicles) and progesterone (from the corpus luteum).

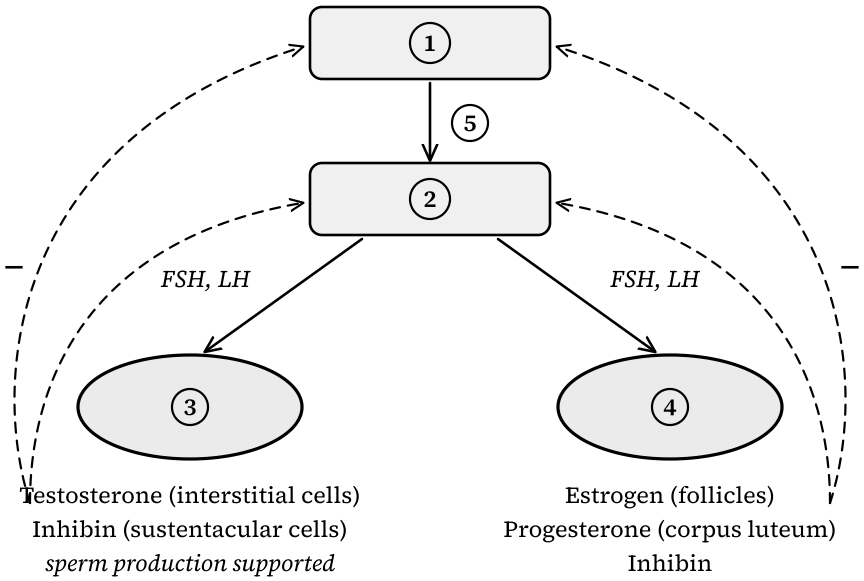
3. Easy Name the two shunts in the heart and vessels before birth, and say why they exist.

   Show answer

   The foramen ovale and the ductus arteriosus; they send most blood past the fluid-filled lungs, which cannot yet exchange gas.

DIAGRAM AND DATA QUESTIONS

4. **Medium** Name the structures numbered 1 to 4 and the hormone numbered 5 in the diagram.



Dashed arrows: negative feedback (−).
Exception: a high, sustained estrogen level triggers the LH surge (+).

Show answer

1 hypothalamus, 2 anterior pituitary, 3 testis, 4 ovary, 5 GnRH.

5. **Medium** Compare meiosis in the testes and in the ovaries: how many gametes come from each cell that begins meiosis, and when does each process happen?

Show answer

Testes: four sperm from each primary spermatocyte, continually from puberty on. Ovaries: one egg (plus polar bodies) from each, begun before birth, paused in meiosis I, resumed one at a time each month, and finished only at fertilization.

6. **Medium** Ordered response. Put these in order: heart begins to beat, kidneys make urine, implantation begins, all major organs begun, neural tube closes, lungs begin to make surfactant.

Show answer

Implantation begins (end of week 1) → heart begins to beat (about day 22) → neural tube closes (week 4) → all major organs begun (week 8) → kidneys make urine (weeks 10–12) → surfactant (weeks 20–24).

7. Medium An embryo is about 3 cm long at 8 weeks and a newborn about 50 cm. By what factor does length increase?

Show answer

50 ÷ 3 ≈ 16.7, about 17 times.

8. Hard **Disorder as a broken mechanism.** Explain how a lack of folate can cause spina bifida, and why the vitamin must already be present before a mother knows she is expecting.

Show answer

Folate is needed to make DNA for the very rapid cell division that folds and closes the neural tube in the fourth week after fertilization. Without enough, the tube may fail to close and the spinal cord is left exposed. Because this happens so early, often before pregnancy is known, folate must already be in the mother's diet.

9. Hard Predict: what happens to LH and FSH in a woman whose ovaries stop making estrogen and inhibin? Explain with feedback.

Show answer

With no estrogen and inhibin to slow them, the hypothalamus and pituitary release much more GnRH, FSH and LH: removing negative feedback lets the signals rise.

TEST PREP

10. Medium Test prep. Which hormone is detected by a pregnancy test and keeps the corpus luteum making progesterone in early pregnancy? (A) FSH (B) LH (C) hCG (D) oxytocin

Show answer

(C) hCG.

11. Medium Test prep. Labor contractions strengthen because oxytocin causes contractions that cause more oxytocin release. This is an example of (A) negative feedback (B) positive feedback (C) a reflex arc only (D) homeostasis restoring a set point

Show answer

(B) positive feedback.

COMMON MISTAKES

- Thinking the pituitary makes testosterone or estrogen; it makes FSH and LH, which tell the gonads to make them.
- Thinking all hormone feedback is negative; the LH surge and labor are the two classic positive-feedback loops.
- Mixing up weeks after fertilization and gestational weeks, which differ by two.
- Thinking the mother's and child's blood mix in the placenta; they exchange across a thin barrier but stay separate.
- Thinking the egg finishes meiosis before fertilization; it completes meiosis II only when a sperm enters.

Make it a game · Feedback Freeze. The parent calls out a change ("testosterone injected", "estrogen high for two days", "inhibin falls", "GnRH pulses increase at puberty"). The student freezes in a pose (arms up for "rises", arms down for "falls") for each of GnRH, LH and FSH in turn, then explains. Then play Timeline Shuffle: lay the nine milestone cards face down, flip one at a time, and place each in order on the floor.

Scripture. "For thou hast possessed my reins: thou hast covered me in my mother's womb. I will praise thee; for I am fearfully and wonderfully made: marvellous are thy works; and that my soul knoweth right well. My substance was not hid from thee, when I was made in secret, and curiously wrought in the lowest parts of the earth. Thine eyes did see my substance, yet being unperfect; and in thy book all my members were written, which in continuance were fashioned, when as yet there was none of them." (Psalm 139:13–16, KJV)

"Curiously wrought" means skillfully embroidered, and "in continuance were fashioned" describes exactly what the timeline shows: every member begun in order, day by day, before any could be seen. The "reins" are the kidneys of Unit 9, already making urine by the third month.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback **Mark up this lesson**

10.4 Capstone: A Body-Systems Case Study and TEAS-Style Review

Mark up this lesson

OBJECTIVES

- Reason through a clinical case by tracing one failed mechanism through several body systems.
- Read vital signs and laboratory values against normal ranges, and calculate blood pH, fluid loss and energy lost in urine.
- Practice the item formats of nursing entrance exams (multiple choice, select-all, ordered response, hot spot and fill-in) across the whole course.

> **Warm-up.** Take your own resting pulse for 30 seconds and double it; then count your breaths for a full minute without changing how you breathe (have someone else count if you can). Write both numbers down. You will use them as your own normal values in the lab.

WATCH

TEAS 7 Science Most Common Questions 2026 | Anatomy & Physiology Review

Nurse Cheung · 29:20

https://www.youtube.com/watch?v=v7QSeCqr6Dg

> **WHEN TO WATCH**
> After the practice set: pause before each answer and answer it yourself first.

BACKUP VIDEO

ATI TEAS 7 l PRACTICE QUESTIONS (30 Anatomy + Physiology Q) I Part 1 l

TheTutorGeek · 25:14

https://www.youtube.com/watch?v=wsvHXO5VQ9U

A second set of exam-style questions for review.

KEY TERMS

vital signs

Pulse, breathing rate, blood pressure, temperature and oxygen saturation: the first numbers a nurse or EMT measures.

diabetic ketoacidosis (DKA)

A dangerous state of untreated type 1 diabetes: very high blood glucose, dehydration and a metabolic acidosis from ketone acids.

Kussmaul breathing

Deep, rapid breathing that blows off carbon dioxide to compensate for a metabolic acidosis.

osmotic diuresis

Large urine output caused by a solute, such as glucose, left in the kidney tubule and holding water there.

differential diagnosis

The list of conditions that could explain a patient's signs, narrowed by tests and reasoning.

ABCs

Airway, breathing, circulation: the order of priorities in any emergency.

hot-spot item

An exam question answered by clicking a location on a diagram.

ordered-response item

An exam question answered by putting steps or structures in the correct sequence.

CORE IDEAS

The story. When the Johns Hopkins Hospital opened in Baltimore in 1889, its first chief of medicine was a Canadian, William Osler. He believed medicine had to be learned at the bedside, not only in the lecture hall. He brought students onto the wards, had them take each patient's history, examine the patient themselves, run the simple laboratory tests and present the case to him on rounds. That method, the clinical clerkship, and the idea of residents living and training in the hospital, spread to every medical and nursing school. His 1892 textbook, *The Principles and Practice of Medicine*, taught a generation to reason from the patient's signs to the mechanism behind them. This lesson asks you to do the same.

How to reason through a case. First, the ABCs: is the airway open, is the person breathing, is the blood circulating? Then gather the history (what happened, how long, what has changed) and the vital signs. For an adult at rest, a pulse of 60–100

beats a minute, 12–20 breaths a minute, blood pressure below about 120/80 mmHg, a temperature near 37 °C (98.6 °F) and an oxygen saturation of 95–100% are typical. Compare every laboratory value with its normal range. Then ask the question this whole course has trained: which mechanism has failed, and how would that failure spread from one system to the next? Finally, check that your explanation accounts for every sign.

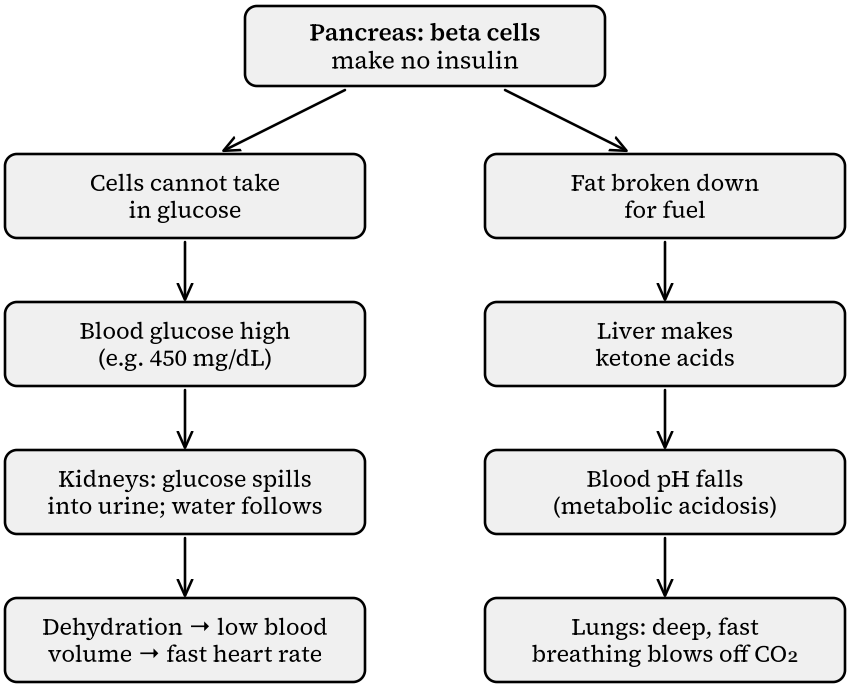
The case. Sam, a 16-year-old, has been unusually thirsty for three weeks, getting up at night to urinate, eating a lot and yet losing weight; he is tired at practice. Today he has been vomiting, and his mother brings him to the emergency room. He is drowsy, breathing deeply at 28 breaths a minute, and his breath smells fruity. His pulse is 118, blood pressure 100/62 and temperature 37.0 °C. He weighs 56 kg, down from 58 kg a week ago. His blood glucose is 450 mg/dL (normal fasting about 70–99), his urine contains glucose and ketones, and his arterial blood gas shows pH 7.22, bicarbonate 10 mEq/L and P_{CO_2} 25 mmHg.

Tracing the mechanism. The beta cells of Sam's pancreatic islets have been destroyed by his own immune system (Lessons 6.4 and 7.5), so he makes no insulin. Without insulin his muscle and fat cells cannot take in glucose, and the liver keeps making more: blood glucose climbs. The filtered glucose overwhelms the proximal tubules, so glucose spills into the urine and drags water with it (Lesson 9.4); he loses water and salt, his blood volume falls, his heart speeds up to keep up the cardiac output, and the concentrated blood makes him thirsty (Lesson 9.5). Meanwhile, starving for glucose inside, his cells break down fat; the liver turns the fatty acids into ketone acids (Lesson 9.3), which use up his bicarbonate. His pH falls. The chemoreceptors of his brainstem respond (Lesson 8.4): deep, rapid breathing blows off CO_2, partly compensating. The fruity smell is acetone, a ketone, on his breath. Every sign follows from one missing hormone.

Treatment and the long road. In the hospital Sam receives fluids by vein to restore his blood volume, insulin to let glucose into his cells and stop ketone production, and careful replacement of potassium, because as insulin drives potassium back into the cells the blood level can fall dangerously (Lesson 9.5). Within a day or two his blood chemistry is normal. Before 1922 he would have died within months; since Banting and Best's insulin (Lesson 6.4) he can expect a full life, checking his glucose

and taking insulin every day. Nurses, dietitians and diabetes educators will teach him and his family to manage it.

Thinking like an exam. The ATI TEAS, used by many nursing schools for admission, includes a science section in which human anatomy and physiology is the largest part: 18 of the 44 scored science questions. Besides ordinary multiple choice it uses select-all-that-apply, ordered-response, hot-spot (click the place on a diagram) and fill-in items. The HESI A2 exam covers similar material. The best preparation is what this course has done: learn each structure with its job, draw it, trace each pathway in order, and explain each disorder as a broken mechanism. The site's Nursing Entrance Exam quick reference summarizes the normal values and systems on a few pages.



One missing hormone, many systems: the case of untreated type 1 diabetes traced from the pancreas to the kidneys, heart, liver and lungs.

> **Safety first.** For the vital-signs lab, exercise only at a level that is comfortable, and stop if anyone feels dizzy, short of breath or has chest pain. Clean a shared thermometer with alcohol between people. This is a learning exercise, not a medical check-up; an unusual reading should be taken to a doctor.

LAB

Home Vital-Signs Lab and a Case Write-Up

You will measure vital signs like a nurse, then write up the case of Sam in the order a nurse would report it.

You will need

- A watch with a second hand, a thermometer, a home blood-pressure cuff and a fingertip pulse oximeter if your family has them
- A volunteer, your sketchbook

Steps

1. At rest: measure pulse (30 seconds × 2), breathing rate (a full minute, without the person noticing), temperature, and blood pressure and oxygen saturation if you have the instruments. Record each with its normal range beside it.
2. After two minutes of brisk stepping on a stair: measure pulse and breathing again, then every minute until they return to within 10% of the resting values. Record the recovery time.
3. Write Sam's case in four parts: what the patient reports; what was measured (vitals and labs, each marked high, low or normal); your explanation of the mechanism, system by system; and the plan (fluids, insulin, potassium, teaching).
4. Draw a one-page diagram linking the systems in Sam's case.

Check your work

- ☐ Which vital signs changed most with exercise, and which system caused each change?
- ☐ Which of Sam's vital signs were abnormal, and which mechanism explains each?
- ☐ Why does Sam's deep breathing help, and why can it not fix the problem by itself?

LAB NOTEBOOK

1. Your vital-signs table with normal ranges.
2. The body-systems web for Sam's case, drawn from memory.

From history. In 1905 Osler left Baltimore to become Regius Professor of Medicine at Oxford, the highest medical chair in Britain. His textbook was revised again and again for decades after his death in 1919. Many nursing and medical students keep a "case log" of the patients they learn from; your sketchbook from this course can be the start of one.

Practice habit. For every practice question this week, say aloud which body system it belongs to and which mechanism it tests before choosing an answer. On a missed question, write the mechanism on a card for review.

Career connection. A **registered nurse** (two-year associate degree or four-year bachelor's degree, then the NCLEX-RN exam), a **licensed practical nurse** (about a year of training) and an **EMT** (a course of a few months and a certification exam) all assess patients exactly as in this lesson. Many nursing programs require the TEAS or HESI A2 for admission; a **certified nursing assistant** course, often open to high-school students, is a good first step into patient care.

WORKED EXAMPLES

Example 1. Check Sam's blood pH from his bicarbonate (10 mEq/L) and P_{CO_2} (25 mmHg), and classify his acid–base state.

Show solution

1. $0.03 \times 25 = 0.75$; $10 \div 0.75 = 13.3$.
2. $\log 13.3 = 1.12$; $pH = 6.1 + 1.12 = 7.22$.
3. pH and bicarbonate are both low (same direction): metabolic acidosis. The low CO_2 shows partial respiratory compensation.

Answer: pH 7.22: metabolic acidosis with partial respiratory compensation, matching the lab report.

Example 2. Sam lost 2 kg in a week, almost all of it water. How many liters of fluid is that, and what percent of his former body mass of 58 kg?

Show solution

1. 1 kg of water is about 1 L, so about 2 L.
2. 2 ÷ 58 = 0.034, about 3.4%.

Answer: About 2 liters, 3.4% of his body mass: moderate dehydration, enough to raise his pulse and lower his blood pressure.

Example 3. At his worst, Sam was losing about 100 g of glucose a day in his urine. How many kilocalories is that? Why was he losing weight while eating a lot?

Show solution

1. 100 g × 4 kcal/g = 400 kcal a day.
2. Without insulin his cells could not use the glucose he ate, so it was wasted in the urine while his body broke down fat and muscle for fuel.

Answer: About 400 kcal a day lost in the urine; together with fat and muscle breakdown, this explains the weight loss.

PRACTICE

CASE QUESTIONS

1. Medium List three of Sam's signs that come from dehydration and explain the mechanism of each.

   Show answer

   Thirst (concentrated blood stimulates the hypothalamus), fast pulse (low blood volume, so the heart beats faster to keep up output), lower blood pressure and weight loss (water lost in the urine by osmotic diuresis).

2. Medium Why does Sam breathe deeply and quickly even though his lungs are healthy?

   Show answer

   Ketone acids lower his blood pH; brainstem chemoreceptors drive deeper, faster breathing to blow off CO_2 and raise the pH (respiratory compensation).

3. Medium Why must the nurses watch Sam's potassium closely once insulin is started?

Show answer

Insulin moves potassium into the cells along with glucose, so the blood potassium can fall dangerously, affecting the heart's rhythm.

4. Hard **Disorder as a broken mechanism.** A second patient, an older woman, has vomited for three days and has bicarbonate 34 mEq/L and P_{CO_2} 48 mmHg.

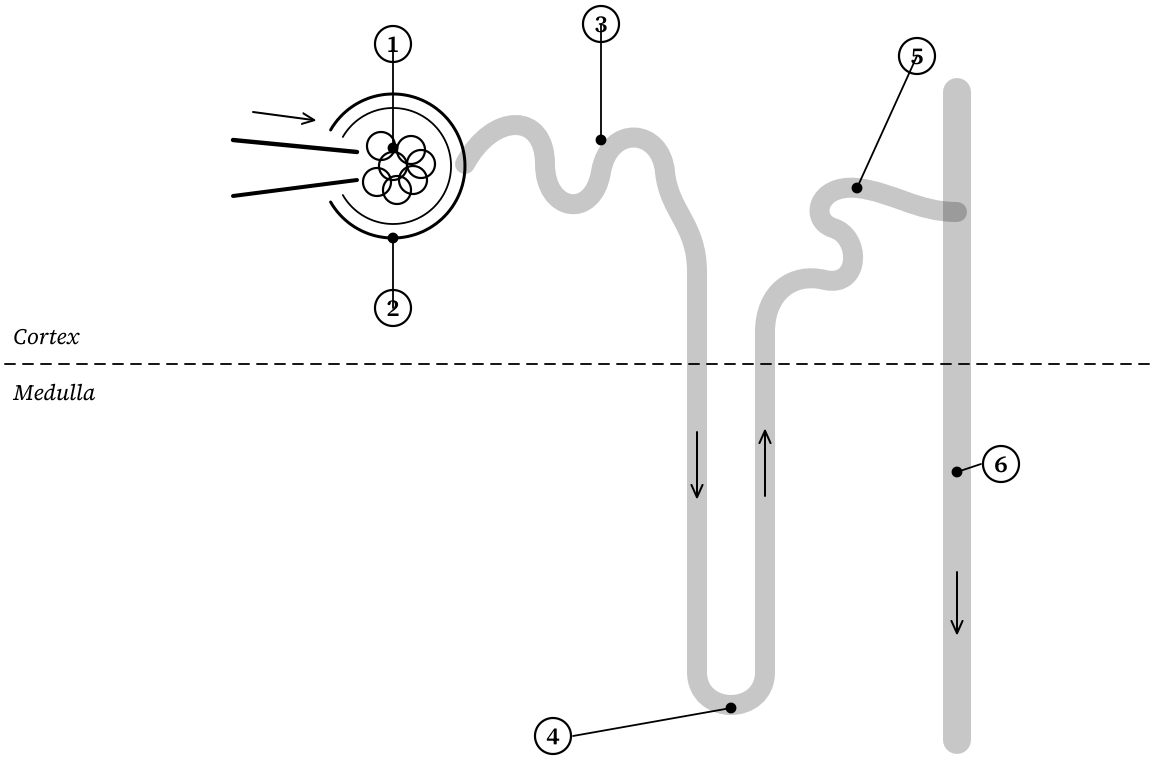
Calculate her pH, classify the disturbance and explain how vomiting caused it and what her lungs are doing.

Show answer

0.03 × 48 = 1.44; 34 ÷ 1.44 = 23.6; log 23.6 = 1.37; pH ≈ 7.47. Metabolic alkalosis: she has lost stomach acid (HCl), leaving extra bicarbonate. Her lungs are breathing more slowly to hold CO_2, a partial compensation.

TEAS-STYLE REVIEW

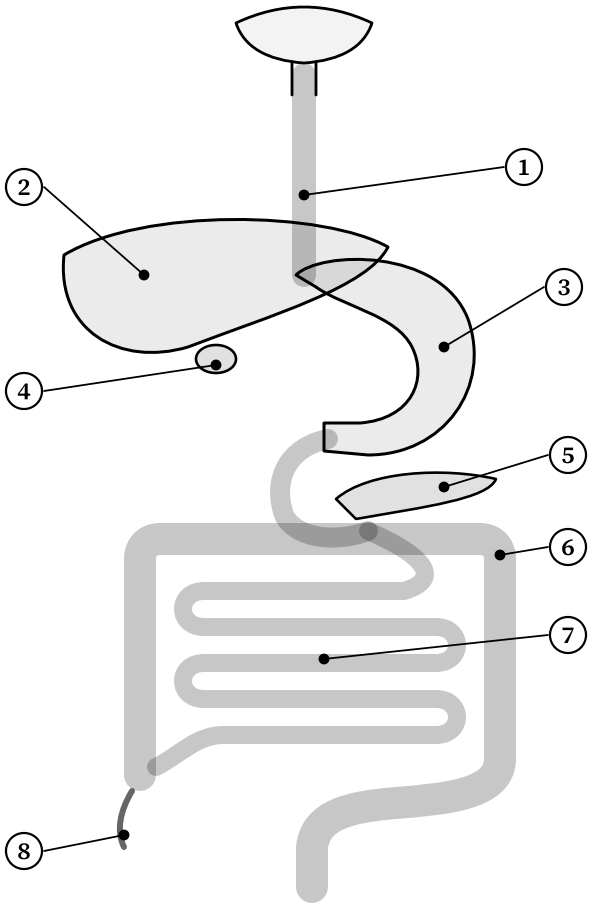
5. **Medium** Hot spot. On the nephron diagram, which number marks where glucose is normally reabsorbed, and which marks where ADH acts?



Show answer

3, the proximal convoluted tubule, reabsorbs glucose; 6, the collecting duct, is where ADH opens water channels.

6. **Medium** Hot spot. On the digestive-tract diagram, which number marks the organ where most nutrients are absorbed, and which marks the organ that makes bile?



Show answer

7, the small intestine, absorbs most nutrients; 2, the liver, makes bile.

7. **Medium** Ordered response. Put in order the path of blood from the body back to the body: left ventricle, right atrium, lungs, aorta, right ventricle, left atrium.

Show answer

Right atrium → right ventricle → lungs → left atrium → left ventricle → aorta.

8. **Medium** Select all that apply. Which are normal adult resting values? (A) pulse 72 per minute (B) breathing rate 30 per minute (C) temperature 37.0 °C (D) arterial pH 7.40 (E) oxygen saturation 88%

Show answer

A, C and D.

9. **Easy** Fill in the blank. The hormone that lowers blood glucose is _____, made by the _____ cells of the pancreatic islets.

Show answer

Insulin; beta cells.

10. **Medium** Which gland is called the master gland, though it is itself controlled by the hypothalamus? (A) thyroid (B) adrenal (C) anterior pituitary (D) pineal

Show answer

(C) the anterior pituitary.

11. **Medium** Which type of muscle tissue is striated and involuntary? (A) skeletal (B) cardiac (C) smooth (D) both skeletal and smooth

Show answer

(B) cardiac.

12. **Medium** A patient's sympathetic nervous system is strongly activated. Select all expected effects: (A) faster heart rate (B) dilated pupils (C) increased peristalsis (D) dilated airways (E) glucose released by the liver

Show answer

A, B, D and E (peristalsis slows).

COMMON MISTAKES

- Explaining each sign separately instead of tracing them all back to one failed mechanism.
- Forgetting the ABCs and jumping to the lab values first.
- Reading a lab value without its normal range or its units.
- On select-all items, stopping after the first correct choice; read and judge every option.
- On ordered-response items, starting from the wrong end; first find the true starting point in the stem.

Make it a game · Case Detective. The parent reads one clue at a time from a case card (thirst, frequent urination, fast breathing, fruity breath, glucose 450, pH 7.22…). After each clue the student may guess the diagnosis and the failed mechanism. A correct guess after one clue scores 5, after two clues 4, and so on. Then switch roles: the student writes a case card for another disorder from the course (a kidney stone, celiac disease, diabetes insipidus, hyponatremia) and the parent plays detective.

Scripture. “And the King shall answer and say unto them, Verily I say unto you, Inasmuch as ye have done it unto one of the least of these my brethren, ye have done it unto me.” (Matthew 25:40, KJV)

Every patient is someone Christ calls his brother. The knowledge of this course is meant to become care: at a bedside, in an ambulance, or at home with an aging parent.

How was this lesson?

Tap Send to share your thoughts with us.

👍 Thumbs up | 👎 Thumbs down

Too hard | Too easy | Video problem | Found an error | Took too long | Loved it

OPTIONAL COMMENT

What worked? What was confusing? Any typos?

YOUR EMAIL (IF YOU'D LIKE A REPLY)

Optional

Send feedback | **Mark up this lesson**

UNIT 10

Life, Growth and Care

The last unit follows the body through a whole life. Lesson 10.1 shows how genes become proteins and proteins become traits, from Garrod's inborn errors (1902) and Pauling's molecular disease (1949) to newborn screening. Lesson 10.2 follows growth and aging, from Montbeillard's first growth chart to the telomeres of aging cells, and how exercise and nutrition build a lifetime's bone and muscle. Lesson 10.3 is a **parent-led lesson**: it treats the testes and ovaries only as endocrine glands, links them to meiosis, and traces the child's development before birth week by week alongside Psalm 139, with schematic diagrams of glands and a timeline only. Lesson 10.4 is the capstone: one patient's case traced through every system of the course, and a review in the formats of nursing entrance exams.

Parents: please read Lesson 10.3 before your student and read it together. It contains no external anatomy and no discussion of sexual activity, contraception or abortion; it describes the hormone axis, the menstrual cycle in one clinical sentence, fertilization, and development to birth.

PREREQUISITES

- Units 6–9 of this course (hormones, blood and heart, breathing, digestion and the kidneys)
- Biology Unit 5 (Mendel, Punnett squares and meiosis)
- Unit 3 (bone tissue and growth)

MASTERY CHECKLIST

- ☐ I can explain how a gene becomes a trait and predict recessive, dominant, X-linked and codominant inheritance with Punnett squares and pedigrees.
- ☐ I can explain how long bones grow at the growth plates and which hormones drive and end growth.
- ☐ I can describe how the body systems change with age and how exercise and nutrition slow those changes.
- ☐ I can describe the gonads as endocrine glands, the feedback loop that controls them, and how sperm and egg formation differ in meiosis.
- ☐ I can trace development from fertilization to birth and explain the placenta and the newborn's first breath.
- ☐ I can reason through a clinical case system by system and answer exam items of every format.

LESSONS IN THIS UNIT

10.1 Inheritance in the Body: Garrod's Inborn Errors (1902) and Pauling's Molecular Disease (1949)

4 sessions of 45 minutes

10.2 Growth and Aging Across the Lifespan: Montbeillard's Growth Chart (1759–1777)

4 sessions of 45 minutes

10.3 Reproduction and Development: The Gonads as Glands and Psalm 139

3 sessions of 45 minutes

10.4 Capstone: A Body-Systems Case Study and TEAS-Style Review

4 sessions of 45 minutes

Unit 10 test

Show your work. For every calculation write the equation, substitute with units and give the answer with its unit. The test is worth 100 points.

1. **7 pts** **Lesson 10.1**

   Two parents are both carriers of sickle cell disease. Give the chance that a child (a) has the disease, (b) is a carrier, (c) has two copies of the usual allele. (d) What is the chance that two of their children both have the disease?

2. **7 pts** **Lesson 10.1**

   A woman who carries red–green color blindness and a color-blind man have children. What are the chances for sons and for daughters?

3. **6 pts** **Lesson 10.1**

   Explain how one changed DNA letter causes the signs of sickle cell disease.

4. **7 pts** **Lesson 10.2**

   Describe how a long bone grows in length and why growth stops after the teen years. Name two hormones involved.

5. **6 pts** **Lesson 10.2**

   A man's GFR is 120 mL/min at 40 and falls 0.8 mL/min a year. Estimate it at 75, and give one reason this matters for his medicines.

6. **7 pts** **Lesson 10.2**

   Explain why the teen years matter most for preventing osteoporosis.

7. **8 pts** **Lesson 10.3**

   Draw or describe the hypothalamus–pituitary–testis loop, naming each hormone. Predict the effect of an anabolic steroid on LH and on the young man's own testosterone.

8. **6 pts** **Lesson 10.3**

   Name the one positive-feedback event in the ovarian cycle and the positive-feedback loop of birth.

9. **7 pts** **Lesson 10.3**

   Put in order, with approximate times after fertilization: neural tube closes, heart begins to beat, implantation begins, all major organs begun, full term.

10. **6 pts** **Lesson 10.3**

    Explain how the foramen ovale and ductus arteriosus close at birth.

CASE AND DATA

11. **10 pts** **Lesson 10.4**

    A patient has bicarbonate 14 mEq/L and P_{CO_2} 28 mmHg. (a) Calculate the pH. (b) Classify the disturbance. (c) Name one disorder from this course that could cause it, and explain the breathing you would expect to see.

12. **8 pts** **Lesson 10.4**

    Select all that apply. A patient with untreated type 1 diabetes is likely to have: (A) glucose in the urine (B) low urine output (C) a fast pulse (D) ketones in the blood (E) a high blood pH

SHORT ESSAY

13. **15 pts** **Lesson 10.1–10.4**

    Short essay. Choose one patient from this unit (Sam, a child with cystic fibrosis, an older adult with osteoporosis, or a newborn born early without enough surfactant). Explain the failed mechanism, trace its effects through at least three body systems, describe the care that helps, and close with a paragraph on what the course has taught you about the body as “fearfully and wonderfully made.”

ANSWER KEY

1. (a) 1/4 (b) 1/2 (c) 1/4 (d) 1/4 × 1/4 = 1/16.
2. Sons: 1/2 color-blind, 1/2 normal (they receive the mother's X). Daughters: 1/2 color-blind (X^cX^c), 1/2 carriers (X^CX^c).
3. The change alters one amino acid of beta-globin (glutamic acid to valine); hemoglobin S clumps into fibers when it gives up oxygen, bending red cells into stiff sickles that block small vessels and break down early, causing pain, organ damage and anemia.
4. Cartilage cells in the growth plate divide and enlarge and are replaced by bone, so the shaft lengthens; growth hormone (through IGF-1) and thyroid hormone drive it. At the end of puberty estrogen closes the plate, which becomes an epiphyseal line, and the bone can no longer lengthen.
5. 120 − 0.8 × 35 = 120 − 28 = 92 mL/min. Drugs cleared by the kidneys stay in his blood longer, so doses may need to be lowered.
6. Bone mass peaks around 30; most of it is built in the teen years with weight-bearing exercise, calcium, vitamin D and protein. A higher peak means that the slow loss of later life (when breakdown outpaces building) takes longer to reach the level where bones break easily.
7. Hypothalamus (GnRH) → anterior pituitary (FSH, LH) → testis: LH → interstitial cells → testosterone; FSH → sustentacular cells (sperm production, inhibin). Testosterone and inhibin feed back negatively. A steroid suppresses GnRH and LH, so his own testosterone and sperm production fall.
8. Sustained high estrogen triggers the LH surge (which releases an egg); in labor, stretching releases oxytocin, which strengthens contractions, which stretch further.
9. Implantation begins (end of week 1), heart begins to beat (about day 22), neural tube closes (week 4), all major organs begun (week 8), full term (about week 38).
10. When the lungs fill with air, resistance in the lungs falls and more blood returns to the left atrium; the higher left-atrial pressure pushes the flap of the foramen ovale shut. The ductus arteriosus constricts within days as oxygen levels rise.
11. (a) 0.03 × 28 = 0.84; 14 ÷ 0.84 = 16.7; log 16.7 = 1.22; pH ≈ 7.32. (b) Metabolic acidosis with partial respiratory compensation. (c) Diabetic ketoacidosis (or severe diarrhea); deep, rapid (Kussmaul) breathing to blow off CO_2.
12. A, C and D.

13. Answers vary. A full answer (1) states the failed mechanism accurately, (2) traces it correctly through at least three systems, (3) describes appropriate care, and (4) reflects thoughtfully on the body's design and on caring for patients.

COURSE EXAM

Midterm Exam

Covers Units 1–5. Time: 100 minutes.

You have 100 minutes. No notes or books. Use complete anatomical terms, show the work for any calculation with units, and answer in complete sentences where asked. The exam has 14 problems worth a total of 100 points.

---

1. **7 pts** **Lesson 1.2**

   A chart note reads: “Abrasion on the anterior left forearm, 4 cm proximal to the wrist; a deep bruise on the lateral right thigh.” (a) Rewrite it in plain English. (b) Name the plane that divides the body into right and left halves, and the plane of a usual CT slice. (c) In which abdominal quadrant does the appendix lie?

2. **7 pts** **Lesson 1.3**

   During an infection, chemicals raise the hypothalamus’s set point from 37 °C to 39 °C. (a) While the body is still at 37 °C, why does the person shiver and feel cold? (b) Name the control center and two effectors at work. (c) When the infection clears and the set point returns to 37 °C, what does the body do?

3. **7 pts** **Lesson 1.4**

   An ultrasound echo returns 65 µs after the pulse is sent. Sound travels at 1540 m/s in soft tissue. How deep is the boundary? Why would ultrasound be a poor choice for looking at the lungs?

4. **7 pts** **Lesson 2.2**

   A bag of 3% NaCl (30 g per liter; molar mass 58.44 g/mol) is hung by mistake in place of 0.9% saline. (a) Find its osmolarity. (b) Compare it with plasma (about 290 mOsm/L) and predict what happens to the patient’s red blood cells.

5. **7 pts** **Lesson 2.3**

   Name the tissue described and give the job its structure fits: (a) many layers of flat cells, the top ones dead and filled with keratin; (b) parallel bundles of collagen with few cells, joining muscle to bone; (c) glassy cartilage with no blood vessels on the ends of long bones; (d) one layer of tall cells with microvilli lining the small intestine.

6. **7 pts** **Lesson 3.2**

   An 80 kg adult has partial-thickness burns of the whole right arm, the front of the trunk and the front of the right leg. (a) Estimate the TBSA by the rule of nines. (b) Using the Parkland formula (4 mL × kg × %TBSA), find the 24-hour fluid and the hourly rate for the first 8 hours.

7. **7 pts** **Lesson 3.3**

   Broken mechanism: a patient's parathyroid glands are accidentally damaged in neck surgery and make almost no PTH. Predict what happens to blood calcium, and explain the effect on bone, kidneys and gut that leads to it.

8. **7 pts** **Lesson 3.5**

   List the bones of the lower limb in order from hip to toes, giving the number of each in one foot. Which bone of the leg carries the body's weight?

9. **7 pts** **Lesson 4.2**

   Broken mechanism: a poison stops the sarcoplasmic reticulum from releasing calcium, but nerve impulses and acetylcholine are normal. Which step of contraction fails, and what happens to the muscle?

10. **7 pts** **Lesson 4.3**

    The biceps inserts 5.0 cm from the elbow. A 40 N load is held in the hand 35 cm from the elbow with the forearm level. Ignoring the forearm's own weight, find the biceps force and the mechanical advantage. What class of lever is this, and what does the body gain from it?

11. **7 pts** **Lesson 4.1**

    Normal shoulder flexion is 180°. After an injury a patient reaches 135°. What percent of the normal range has she? Which movement is the opposite of flexion, and what type of joint is the shoulder?

12. **7 pts** **Lesson 5.2**

    A neuron rests at −70 mV and fires at −55 mV. It receives 5 EPSPs of 3 mV each and 1 IPSP of 4 mV at the same moment. Does it fire? Show the sum. Then find how long an impulse takes to travel a 0.9 m myelinated axon at 75 m/s, in milliseconds.

13. **7 pts** **Lesson 5.5**

Put the parts of the reflex arc for touching a hot pan in order: motor neuron, receptor, effector, interneuron, sensory neuron. Then: a frightened student's pupils are wide, his heart is racing and his mouth is dry. Which division of the autonomic nervous system is in charge, and which neurotransmitter acts on most of its targets?

ESSAY

14. **9 pts**

Choose one disorder from Units 1–5 (heat stroke, sickle-cell disease, a full-thickness burn, osteoporosis, myasthenia gravis, multiple sclerosis or Parkinson's disease). Describe the normal mechanism, name the step that fails, trace how the symptoms follow, and explain how treatment repairs or works around the broken step.

ANSWER KEY

1. (a) A scrape on the palm side (front, in anatomical position) of the left forearm, 4 cm toward the elbow from the wrist; a bruise reaching below the skin on the outer side of the right thigh. (b) Sagittal (midsagittal if equal halves); transverse. (c) The right lower quadrant (RLQ).
2. (a) The control center compares 37 °C with the new 39 °C set point, reads the body as too cold, and orders heat-making and heat-saving responses. (b) The hypothalamus; skeletal muscles (shivering) and skin blood vessels (narrowing), with goose bumps. (c) The body is now above the set point, so skin vessels widen and sweating begins until the temperature falls back to 37 °C (negative feedback; the fever "breaks").
3. About 5.0 cm

   $1540 \times 65 \times 10^{-6} \div 2 = 0.050$ m

   Air reflects nearly all the sound, so the beam cannot pass into air-filled lung.
4. (a) About 1,027 mOsm/L

   $30 \div 58.44 = 0.513$ mol/L $\times 2 = 1.027$ osmol/L

   (b) It is strongly hypertonic, so water leaves the red cells by osmosis and they shrivel into spiky shapes (crenation).
5. (a) Keratinized stratified squamous epithelium: resists rubbing and water loss. (b) Dense regular connective tissue (a tendon): strong pull in one direction. (c) Hyaline cartilage: a smooth, low-friction joint surface. (d) Simple columnar epithelium: absorption over a large surface.
6. (a) 36%

   $9 + 18 + 9 = 36$

   (b) 11,520 mL; 720 mL/h

   $4 \times 80 \times 36 = 11{,}520$; half (5,760 mL) in the first 8 hours: $5{,}760 \div 8 = 720$
7. Without PTH, osteoclasts release less calcium from bone, the kidneys lose more calcium and less vitamin D is activated, so blood calcium falls and stays low: the negative feedback loop has lost its signal. (Lesson 6.3 shows the twitching and cramps, tetany, that follow.)
8. Femur; patella; tibia and fibula; 7 tarsals; 5 metatarsals; 14 phalanges. The tibia (the thick, inner leg bone) carries the weight; the thin fibula does not.
9. The impulse still spreads along the sarcolemma and T tubules, but no calcium is released, so none binds troponin; tropomyosin keeps covering actin's binding sites, myosin heads cannot attach, and no power strokes occur. The muscle stays limp (flaccid) even though the nerve signal arrives.

10. E = 40 × 35 ÷ 5.0 = 280 N; MA = 5.0 ÷ 35 ≈ 0.14. A third-class lever: it needs a large force but gives the hand speed and range of motion.
11. 135 ÷ 180 = 0.75, so 75%. Extension. A ball-and-socket synovial joint.
12. Net = 5 × 3 − 4 = +11 mV, so the membrane reaches −59 mV, below threshold: it does not fire. 0.9 ÷ 75 = 0.012 s = 12 ms.
13. Receptor → sensory neuron → interneuron → motor neuron → effector. The sympathetic division; norepinephrine.
14. Look for: the normal mechanism stated accurately in correct terms; the exact failed step (cooling overwhelmed; changed hemoglobin; skin barrier and nerve endings destroyed; breakdown outpacing building; ACh receptors destroyed by antibodies; myelin stripped; dopamine neurons lost); each symptom linked to that step in a clear chain; a treatment that fits (cooling, fluids and grafts, weight-bearing exercise with calcium and vitamin D, drugs that slow acetylcholinesterase, levodopa); clear organization.

COURSE EXAM

Final Exam

Covers Units 1–10. Time: 120 minutes.

You have 120 minutes. No notes or books. Use complete anatomical terms, show the work for any calculation with units, and answer in complete sentences where asked. The exam has 16 problems worth a total of 100 points.

---

1. **6 pts** **Lesson 1.3**

   Label the parts of this loop and name the type of feedback: blood glucose rises after a meal; beta cells in the pancreatic islets detect it and release insulin; liver, muscle and fat cells take up and store glucose; blood glucose falls. Then give one example of positive feedback from the course.

2. **6 pts** **Lesson 4.2**

   A sarcomere shortens from 2.6 µm to 2.2 µm. The thick filaments are 1.6 µm and each thin filament is 1.0 µm. Give the A band, I band and H zone before and after, and say which filaments changed length.

3. **6 pts** **Lesson 6.1**

   A hormone has a half-life of 6 minutes. If the gland stops releasing it, what percent remains after 30 minutes? Explain why a lipid-soluble hormone such as cortisol acts more slowly but more lastingly than insulin.

4. **6 pts** **Lesson 6.2**

   Broken mechanism: a patient’s thyroid gland is slowly destroyed by her immune system (Hashimoto’s thyroiditis). Predict whether T4, TSH and TRH will be high or low, explain why, and name two signs she may show.

5. **6 pts** **Lesson 6.4**

   A student’s fasting glucose is 117 mg/dL and his A1C is 6.0%. (a) Convert the glucose to mmol/L. (b) Find his estimated average glucose with eAG = 28.7 × A1C − 46.7. (c) Does the A1C fall in the normal, prediabetes or diabetes range?

6. **6 pts** **Lesson 7.1**

   A patient is type O-positive. Which donor types of red cells can she safely receive? Which donor types of plasma? Explain the plasma answer.

7. **6 pts** **Lesson 7.2**

   A ventricle fills to 120 mL and empties to 50 mL; the heart rate is 65. Find stroke volume, ejection fraction and cardiac output. Then put in order: Purkinje fibers, SA node, bundle branches, AV node, bundle of His.

8. **6 pts** **Lesson 7.3**

   A reading is 128/84 mmHg. Find the pulse pressure and MAP, and classify the reading by the American Heart Association categories. Why does the reading not count as “elevated”?

9. **6 pts** **Lesson 8.1**

   A resting adult breathes 12 times a minute with a tidal volume of 500 mL and 150 mL of dead space. A frightened patient breathes 30 times a minute at 200 mL. Find the minute ventilation and alveolar ventilation of each, and explain why fast, shallow breathing fails.

10. **6 pts** **Lesson 8.2**

    Lungs holding 3.0 L at 760 mmHg expand to 3.04 L before any air enters. Find the new pressure and the direction of air flow. Which muscles caused the expansion?

11. **6 pts** **Lesson 8.4**

    At about 3,000 m the air pressure is roughly 526 mmHg. Find the humidified $P(O_2)$ in the airways (air is 21% oxygen; subtract 47 mmHg water vapor). Name the sensors and control center that make a climber breathe faster.

12. **6 pts** **Lesson 9.2**

    Broken mechanism: explain why a person with lactose intolerance gets bloating and diarrhea after drinking milk, and why lactase drops in the milk prevent it.

13. **6 pts** **Lesson 9.4**

    A patient’s urine creatinine is 100 mg/dL, urine flow 1.2 mL/min and plasma creatinine 1.0 mg/dL. Estimate the GFR and say whether it is normal for a young adult. Then name the part of the nephron where glucose is normally reabsorbed.

14. **6 pts** **Lesson 9.5**

A blood gas shows bicarbonate 24 mEq/L and P_{CO_2} 52 mmHg. (a) Calculate the pH with $pH = 6.1 + \log(HCO_3^- \div (0.03 \times P_{CO_2}))$. (b) Classify the disturbance. (c) Which organ will compensate over several days, and how?

15. **6 pts** **Lesson 10.1**

A man with hemophilia A (an X-linked recessive disorder) and a woman who is not a carrier have children. Give the chances for their sons and for their daughters, and explain why.

ESSAY

16. **10 pts**

Choose one patient: a man with untreated type 1 diabetes, a woman with severe blood loss, or a smoker with emphysema. Explain the failed mechanism, trace its effects through at least three body systems from this course, and describe how the body tries to compensate and what care helps.

ANSWER KEY

1. Stimulus: rising blood glucose. Receptor and control center: the beta cells. Effectors: liver, muscle and fat cells. Response: glucose falls back toward normal. Negative feedback. Positive feedback: blood clotting, or oxytocin strengthening contractions in childbirth.
2. Before: A band 1.6 µm, I band 1.0 µm, H zone 0.6 µm. After: A band 1.6 µm, I band 0.6 µm, H zone 0.2 µm. Neither: the filaments slide past each other without shortening.
3. 30 ÷ 6 = 5 half-lives; $(1/2)^5 = 1/32 \approx 3.1\%$. Cortisol crosses the membrane and binds a receptor inside the cell; the pair switches genes on or off, so new proteins must be made. Insulin binds a surface receptor and works through enzymes that already exist.
4. T4 is low because the gland cannot make it. With little T4 there is weak negative feedback, so the hypothalamus releases more TRH and the anterior pituitary more TSH: TRH and TSH are high. Signs of hypothyroidism: tiredness, feeling cold and sluggishness.
5. (a) 117 ÷ 18 = 6.5 mmol/L. (b) 28.7 × 6.0 − 46.7 = 125.5 mg/dL. (c) Prediabetes (A1C 5.7–6.4%); diabetes begins at 6.5%.
6. Red cells: O+ or O− only (her plasma has anti-A and anti-B; being Rh-positive she may receive Rh-negative or Rh-positive cells). Plasma: any ABO type (O, A, B or AB), because her red cells carry no A or B antigens for donor antibodies to attack.
7. SV 70 mL; EF ≈ 58%; CO 4,550 mL/min ≈ 4.6 L/min

   120 − 50 = 70; 70 ÷ 120 = 0.583; 70 × 65 = 4,550

   SA node, AV node, bundle of His, bundle branches, Purkinje fibers.
8. Pulse pressure 44 mmHg; MAP ≈ 84 + 44/3 ≈ 99 mmHg. Stage 1 high blood pressure, because the diastolic is 80–89; “elevated” requires a diastolic below 80.
9. Resting: 6.0 L/min moved; 4.2 L/min reaches the alveoli. Patient: 6.0 L/min moved; only 1.5 L/min reaches the alveoli

   12 × 500 = 6,000; 12 × 350 = 4,200; 30 × 200 = 6,000; 30 × 50 = 1,500

   Each breath must first fill the 150 mL of dead space, so small breaths waste most of their air.
10. About 750 mmHg

    760 × 3.0 ÷ 3.04 = 750

Below atmospheric pressure, so air flows in. The diaphragm and external intercostals contracted.

11. $0.21 \times (526 - 47) \approx 101$ mmHg (about 150 at sea level). Peripheral chemoreceptors in the carotid and aortic bodies (with central chemoreceptors in the medulla) signal the respiratory centers of the medulla and pons.
12. The brush border of the small intestine makes little lactase, so lactose is not split into glucose and galactose and cannot be absorbed. It passes into the colon, where it draws water in (diarrhea) and bacteria ferment it, making gas (bloating). Lactase drops split the lactose before drinking, so the sugars are absorbed normally.
13. $(100 \times 1.2) \div 1.0 = 120$ mL/min, normal (about 100–125 mL/min). The proximal convoluted tubule.
14. (a) $0.03 \times 52 = 1.56$; $24 \div 1.56 = 15.4$; $\log 15.4 = 1.187$; pH ≈ 7.29. (b) Respiratory acidosis (low pH with high P_{CO_2} and normal bicarbonate). (c) The kidneys, by secreting more hydrogen ions into the urine and reabsorbing or making new bicarbonate.
15. Sons: none affected and none carriers, because sons receive their father's Y, not his X. Daughters: all carriers, because every daughter receives her father's X with the hemophilia allele and a normal X from her mother.
16. Look for: the failed mechanism stated accurately (no insulin from destroyed beta cells; lost blood volume and pressure; destroyed alveolar walls and lost recoil); effects traced through at least three systems with correct terms (e.g. glucose and ketones in urine, dehydration, fast pulse, Kussmaul breathing; baroreceptor reflex, renin–angiotensin–aldosterone, ADH and thirst; less surface area, trapped air, low FEV_1/FVC, raised CO_2 and kidney compensation); fitting care (insulin and fluids; stopping bleeding and transfusion; stopping smoking, oxygen and rehabilitation); clear organization.