Fundamentals of Human Anatomy Laboratory Manual

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Iowa State University is located on the ancestral lands and territory of the Baxoje (bah-kho-dzhe), or Ioway Nation. The United States obtained the land from the Meskwaki and Sauk nations in the Treaty of 1842. We wish to recognize our obligations to this land and to the people who took care of it, as well as to the 17,000 Native people who live in Iowa today.

Contents

Introduction

Welcome to Fundamentals of Human Anatomy Laboratory Manual! This lab manual is designed to accompany a college-level systemic human anatomy laboratory course taken by students early in pre-health related programs of study. It is organized by week, with each chapter providing the necessary background information for the lab activities that will be done that week. The first couple weeks of lab explore introductory information, including anatomical terminology, cells, and tissues. The remaining weeks of the semester are spent going through the organ systems in the human body. The lab activities should be done in lab, based on the human models and dissections provided.

This manual will provide the necessary support for students in a human anatomy laboratory course to:

1. Communicate effectively about anatomical positions, locations and features using a proper anatomical vocabulary.
2. Describe the basic features of animal cells and tissues and explain how the structure of cells and tissues determine the function of the organs that they comprise.
3. Describe the divisions and compartments of the human body and the structures they contain.
4. Identify the major anatomical structures associated with each body system and describe their basic functions.
5. Use proper laboratory technique to dissect preserved animal specimens to explore anatomy.

Download a copy of the lab activities for use in class: **Fundamentals of Human Anatomy Lab Exercises [PDF]**

Lab 1: Introduction to Human Anatomy & Anatomical Terminology

Welcome to the lab for Fundamentals of Human Anatomy! The lecture and lab courses together will provide an introduction to the human body using a systemic anatomy approach. In systemic anatomy, we will look at how the body is organized, going from cells to tissues to organs to organ systems. The human body is an amazing structure, performing many complex functions simultaneously that keep us alive through the actions of the organ systems working individually and together. We will look at each organ system, focusing on the structure and location of cells, tissues, and organs within that system and how those components allow the organ system to perform necessary functions in the body.

Before we start learning about structures in the body, we need to be able to accurately use the language of anatomy. Using anatomical terminology allows us to be precise and share a common frame of reference when describing the location of structures in the body.

Introduction

Anatomy focuses on structure and **physiology** focuses on function. Much of the study of physiology centers on the body's tendency toward **homeostasis**, which is the state of maintaining equlibrium within our internal environment.

Consider the structures of the body in terms of fundamental levels of organization that increase in complexity:

subatomic particles, atoms, molecules, organelles, cells, tissues, organs, and organ systems, which are all within an organism (**Figure 1.1**).

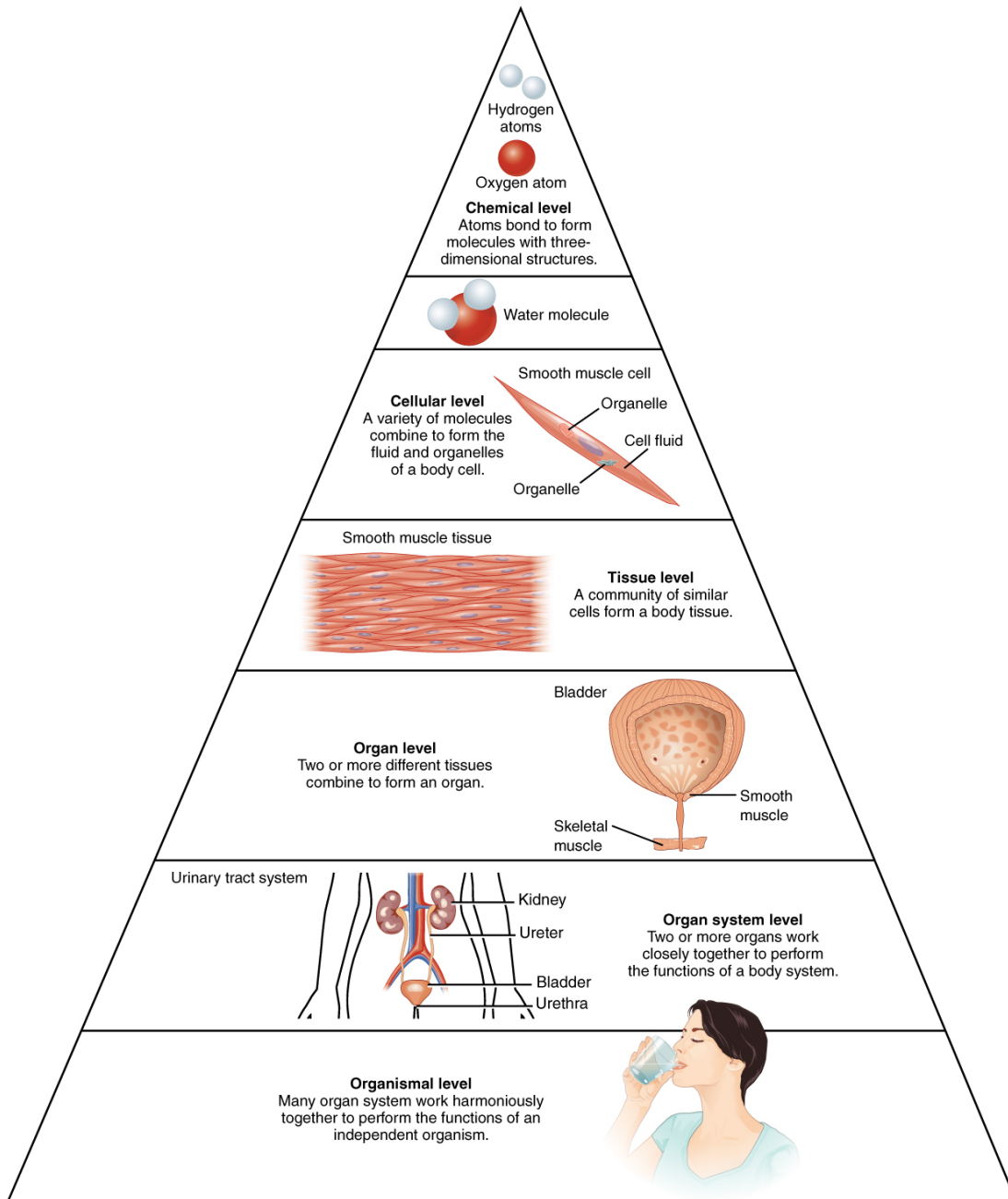**Figure 1.1 Levels of Structural Organization of the Human Body.** The organization of the body often is discussed in terms of six distinct levels of increasing complexity, from the smallest chemical building blocks to a unique human organism.

The Levels of Organization

All matter in the universe is composed of one or more unique pure substances called **elements**, such as hydrogen, oxygen, carbon, nitrogen, calcium, and iron.

- The smallest unit of any of these pure substances (elements) is an **atom**.
  - Atoms are made up of subatomic particles such as the proton, electron, and neutron.
- Two or more atoms combine to form a **molecule**, such as the water molecules, proteins, and sugars found in living things.
  - **Molecules** are the chemical building blocks of all body structures.
- A **cell** is the smallest independently functioning unit of a living organism.
  - Even bacteria, which are extremely small, independently-living organisms, have a cellular structure. Each bacterium is a single cell. All living structures of human anatomy contain cells, and almost all functions of human physiology are performed in cells or are initiated by cells
  - A human cell typically consists of flexible membranes that enclose cytoplasm, a water-based cellular fluid, together with a variety of tiny functioning units called **organelles**. In humans, as in all organisms, cells perform all functions of life.
- A **tissue** is a group of many similar cells (though sometimes composed of a few related types) that work together to perform a specific function.
- An **organ** is an anatomically distinct structure of the body composed of two or more tissue types. Each organ performs one or more specific physiological functions.
- An **organ system** is a group of organs that work together to perform major functions or meet the physiological needs of the body.
  - There are usually eleven distinct organ systems recognized in the human body (**Figure 1.2** and **Figure 1.3**).
- The **organism** level is the highest level of organization. An organism is a living being that has a cellular structure and that can independently perform all physiologic functions necessary for life. In multicellular organisms, including humans, all cells, tissues, organs, and organ systems of the body work together to maintain the life and health of the organism.

Organs are very collaborative and can work with multiple organ systems. This can make assigning organs to organ systems imprecise because organs that "belong" to one system may also have functions integral to another system. In fact, most organs contribute to more than one system. Organs and organ systems are reliant on each other and work together to accomplish many complex processes in the body. For example, the heart (cardiovascular system) and lungs (respiratory system) work together to deliver oxygen throughout the body and remove carbon dioxide from the body.

Integumentary System

Hair

Skin

Nails
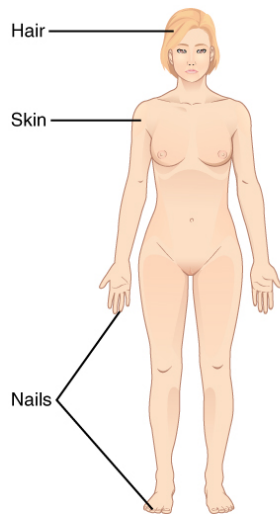
- Encloses internal body structures
- Site of many sensory receptors

Skeletal System

Cartilage

Bones

Joints
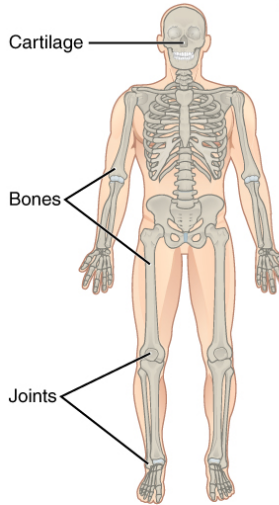
- Supports the body
- Enables movement (with muscular system)

Muscular System

Skeletal muscles

Tendons
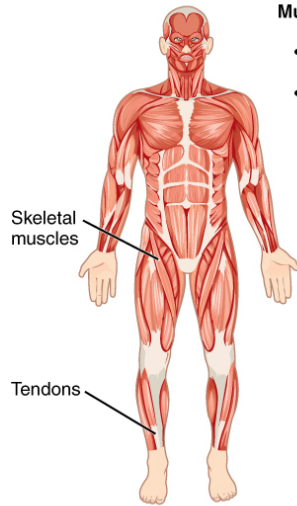
- Enables movement (with skeletal system)
- Helps maintain body temperature

Nervous System

Brain

Spinal cord

Peripheral nerves
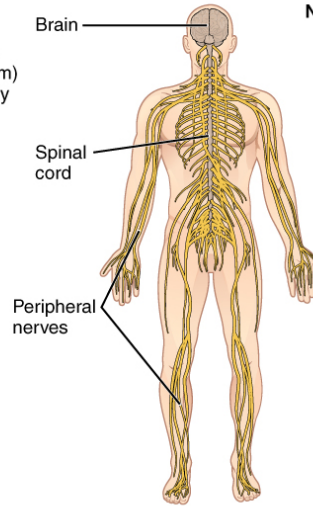
- Detects and processes sensory information
- Activates bodily responses

Endocrine System

Pituitary gland

Thyroid gland

Pancreas

Adrenal glands

Testes

Ovaries
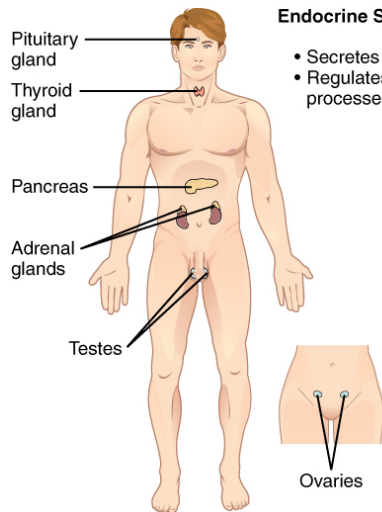
- Secretes hormones
- Regulates bodily processes

Cardiovascular System

Heart

Blood vessels
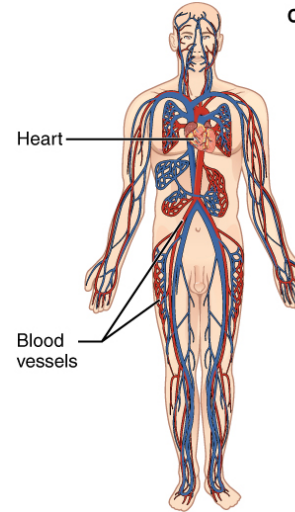
- Delivers oxygen and nutrients to tissues
- Equalizes temperature in the body

Figure 1.2. Organ Systems of the Human Body. Organs that work together are grouped into organ systems.

Lymphatic System

Thymus

Lymph nodes

Spleen

Lymphatic vessels
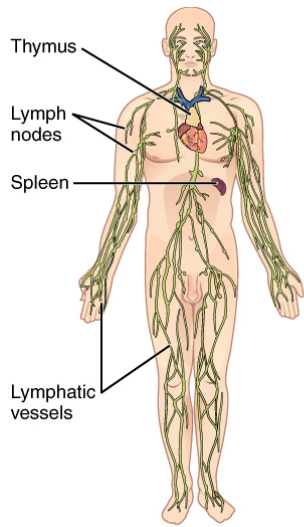
- Returns fluid to blood
- Defends against pathogens

Respiratory System

Nasal passage

Trachea

Lungs
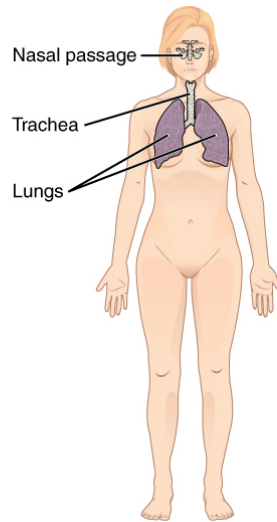
- Removes carbon dioxide from the body
- Delivers oxygen to blood

Digestive System

Stomach

Liver

Gall bladder

Large intestine

Small intestine
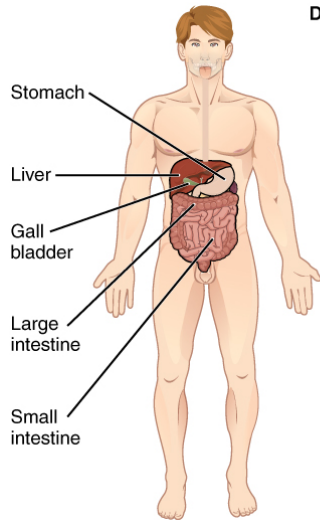
- Processes food for use by the body
- Removes wastes from undigested food

Urinary System

Kidneys

Urinary bladder
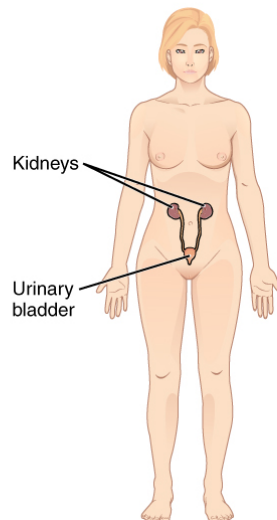
- Controls water balance in the body
- Removes wastes from blood and excretes them

Male Reproductive System

Epididymis

Testes
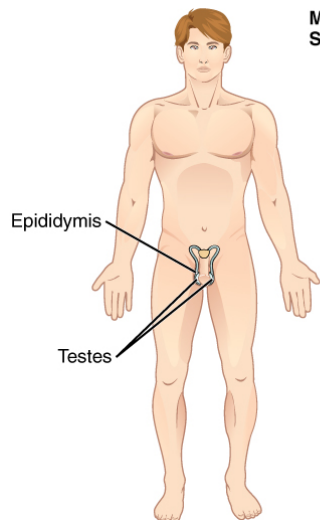
- Produces sex hormones and gametes
- Delivers gametes to female

Female Reproductive System

Mammary glands

Ovaries

Uterus
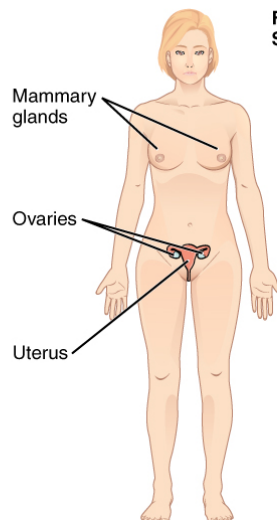
- Produces sex hormones and gametes
- Supports embryo/ fetus until birth
- Produces milk for infant

Figure 1.3. Organ Systems of the Human Body (continued). Organs that work together are grouped into organ systems.

Anatomical Terminology

Anatomical Position

Anatomists and health care providers use terminology for the purpose of precision and to reduce medical errors. For example, is a scar "above the wrist" located on the forearm two or three inches away from the hand? Or is it at the base of the hand? Is it on the palm-side or back-side? By using precise anatomical terminology, we eliminate ambiguity. Anatomical terms derive from ancient Greek and Latin words.

To further increase precision, anatomists standardize the way in which they view the body. Just as maps are normally oriented with north at the top, the standard body "map," or **anatomical position**, is that of the body standing upright, with the feet at shoulder width and parallel, toes forward. The upper limbs are held out to each side, and the palms of the hands face forward (see **Figure 1.4**).

Using this standard position reduces confusion. It does not matter how the body being described is oriented, the terms are used as if it is in anatomical position. For example, a scar in the "anterior (front) carpal (wrist) region" would be present on the palm side of the wrist. The term "anterior" would be used even if the hand were palm down on a table.

A body that is lying down is described as either prone (face down) or supine (face up). These terms are sometimes used in describing the position of the body during specific physical examinations or surgical procedures.
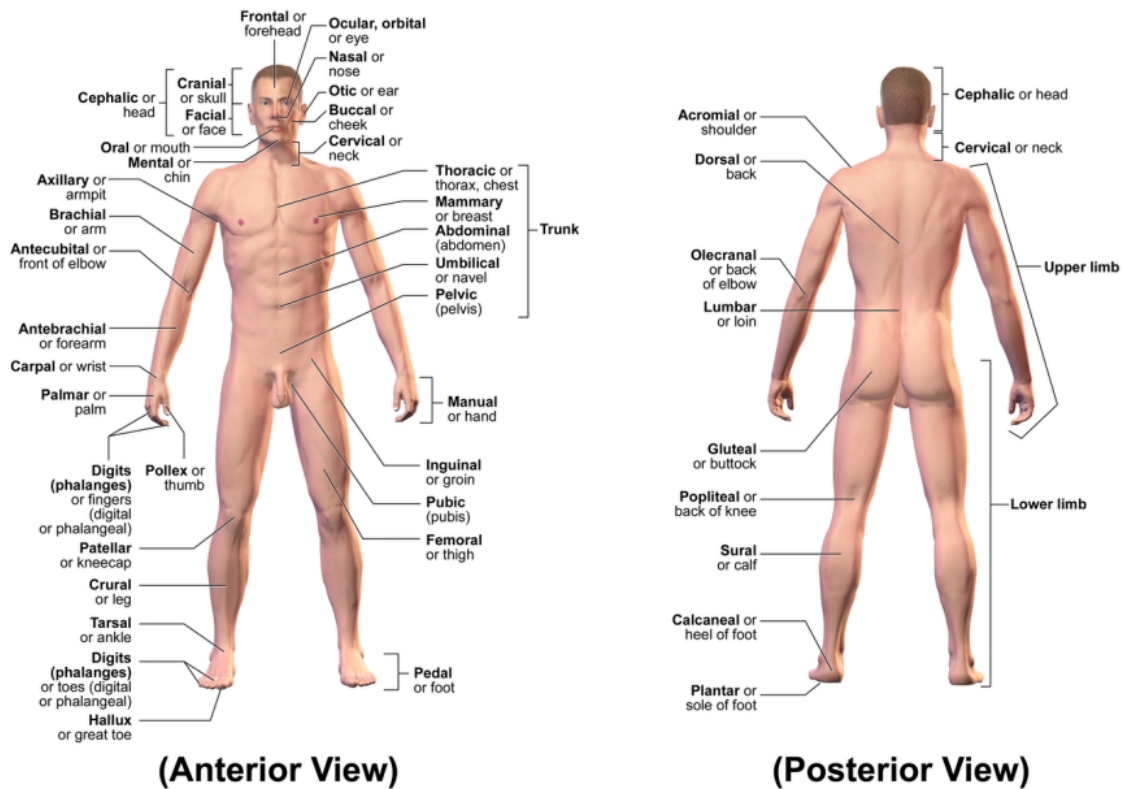
Figure 1.4. Regions of the Human Body. The human body is shown in anatomical position in an (a) anterior view and a (b) posterior view. The regions of the body are labeled in boldface. From Blausen Medical Licensed under CC BY 3.0.

Regional Terms

The human body's numerous regions have specific terms to help increase precision. Notice that the term "brachial" or "arm" is reserved for the "upper arm" and "antebrachial" or "forearm" is used rather than "lower arm." Similarly, "femoral" or "thigh" is correct, and "leg" or "crural" is reserved for the portion of the lower limb between the knee and the ankle. The commonly used regional terms are in **Figure 1.4**. It is also helpful to learn anatomical regions because often the names of structures are based on the region they are found in (e.g., brachial artery, cervical vertebrae, gluteus maximus, femur bone, etc.).

Directional Terms

Directional terms are essential for describing the relative locations of different body structures. For instance, an anatomist might describe one band of tissue as "inferior to" another or a physician might describe a tumor as "superficial to" a deeper body structure. Commit these terms to memory to avoid confusion when you are studying or describing the locations of particular body parts (**Figure 1.5**).

- **Anterior** (or **ventral**) describes the front or direction toward the front of the body. The toes are anterior to the foot.
- **Posterior** (or **dorsal**) describes the back or direction toward the back of the body. The popliteus is posterior to the patella.
- **Superior** (or **cranial**) describes a position above or higher than another part of the body proper. The orbits are superior to the oris.
- **Inferior** (or **caudal**) describes a position below or lower than another part of the body proper; near or toward the tail (in humans, the coccyx, or lowest part of the spinal column). The pelvis is inferior to the abdomen.
- **Lateral** describes the side or direction toward the side of the body. The thumb (pollex) is lateral to the digits.
- **Medial** describes the middle or direction toward the middle of the body. The hallux is the medial toe.
- **Proximal** describes a position in a limb that is nearer to the point of attachment or the trunk of the body. The brachium is proximal to the antebrachium.
- **Distal** describes a position in a limb that is farther from the point of attachment or the trunk of the body. The crus is distal to the femur.
- **Superficial** describes a position closer to the surface of the body. The skin is superficial to the bones.
- **Deep** describes a position farther from the surface of the body. The brain is deep to the skull.
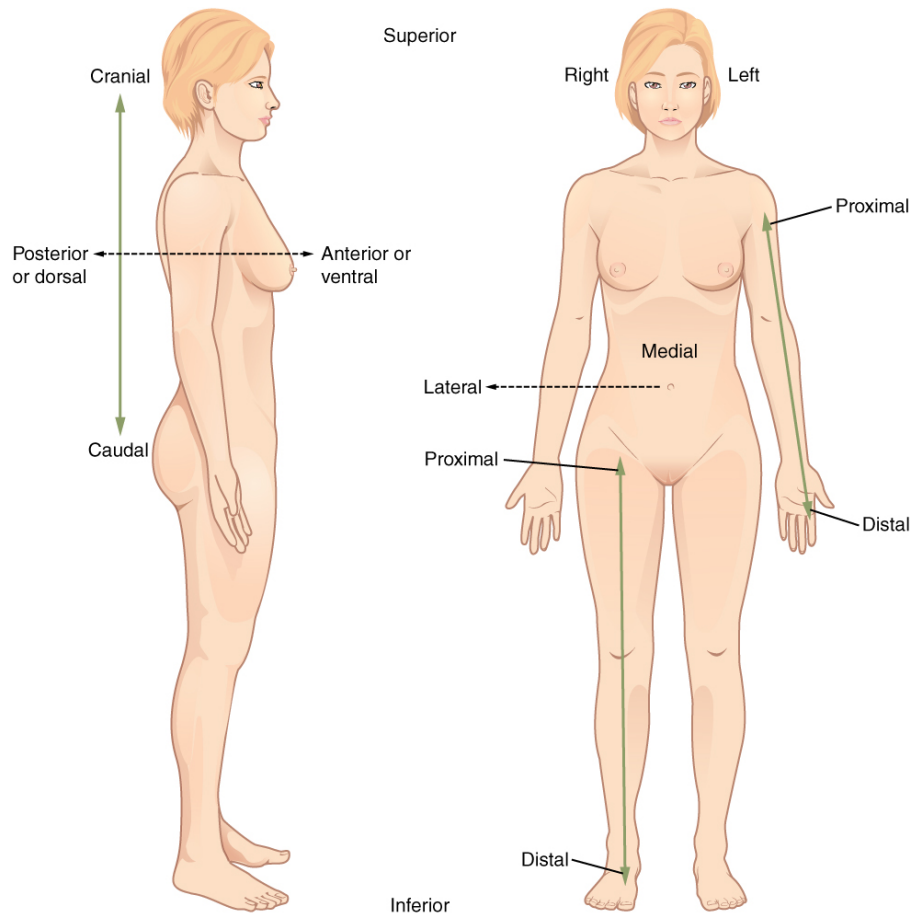
Figure 1.5. Directional Terms Applied to the Human Body. Paired directional terms are shown as applied to the human body.

Body Planes

A section is a two-dimensional surface of a three-dimensional structure that has been cut. Modern medical imaging devices enable clinicians to obtain "virtual sections" of living bodies. We call these scans. Body sections and scans can be correctly interpreted, however, only if the viewer understands the plane along which the section was made. A plane is an imaginary two-dimensional surface that passes through the body. There are three planes commonly referred to in anatomy and medicine (**Figure 1.6**):

- The **sagittal plane** is the plane that divides the body or an organ vertically into right and left sides. If this vertical plane runs directly down the middle of the body, it is called the midsagittal or median plane. If it divides the body into unequal right and left sides, it is called a parasagittal plane or less commonly a longitudinal section.
- The **frontal plane** is the plane that divides the body or an organ into an anterior (front) portion and a posterior (rear) portion. The frontal plane is often referred to as a coronal plane. ("Corona" is Latin for "crown.")
- The **transverse plane** is the plane that divides the body or organ horizontally into upper and lower portions. Transverse planes produce images referred to as cross sections.
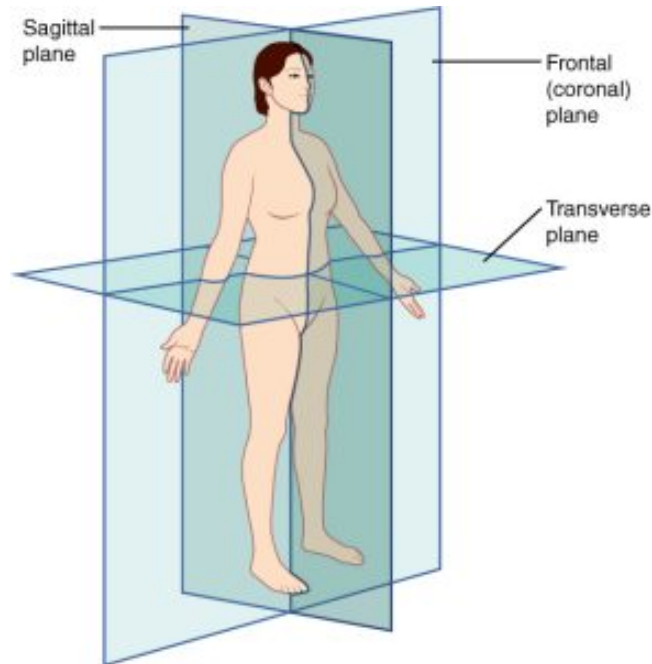
Figure 1.6. Planes of the Body. The three planes most commonly used in anatomical and medical imaging are the sagittal, frontal (or coronal), and transverse plane.

Body Cavities and Serous Membranes

The body maintains its internal organization by means of membranes, sheaths, and other structures that separate compartments. The **dorsal (posterior) cavity** and the **ventral (anterior) cavity** are the largest body compartments (**Figure 1.7**). These cavities contain and protect delicate internal organs, and the ventral cavity allows for significant changes in the size and shape of the organs as they perform their functions. The lungs, heart, stomach, and intestines, for example, can expand and contract without distorting other tissues or disrupting the activity of nearby organs.
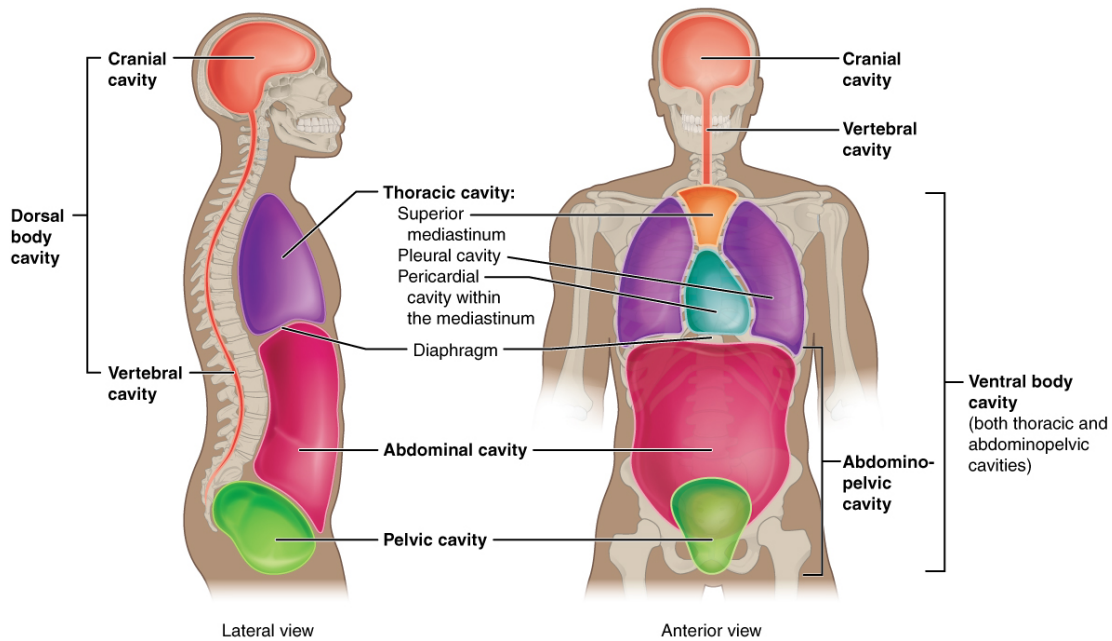
Figure 1.7. Dorsal and Ventral Body Cavities. The ventral cavity includes the thoracic and abdominopelvic cavities and their subdivisions. The dorsal cavity includes the cranial and spinal cavities.

Subdivisions of the Posterior (Dorsal) and Anterior (Ventral) Cavities

The posterior (dorsal) and anterior (ventral) cavities are each subdivided into smaller cavities.

The **posterior** (dorsal) cavity has two main subdivisions:

- In the posterior (dorsal) cavity, the **cranial cavity** houses the brain
  - Protected by the bones of the skulls and cerebrospinal fluid
- The **spinal cavity** (or vertebral cavity) encloses the spinal cord.
  - Protected by the vertebral column and cerebrospinal fluid

The **anterior** (ventral) cavity has two main subdivisions:

- The **thoracic cavity** is the more superior subdivision of the anterior cavity, and it is enclosed by the rib cage. The diaphragm forms the floor of the thoracic cavity and separates it from the more inferior abdominopelvic cavity. Within the thoracic cavity there are smaller cavities:
  - The right and left **pleural cavities** contain the right and left lungs, respectively.
  - The **mediastinum** is medial to the pleural cavities and contains the heart, major blood vessels going to and from the heart, trachea, espophagus, and thymus.
  - The **pericardial cavity** is found within the mediastinum and surrounds the heart.
- The **abdominopelvic cavity** is inferior to the thoracic cavity and houses the digestive organs, the pelvic cavity, and the reproductive organs. It is the largest cavity in the body. While no membrane physically divides the abdominopelvic cavity, it can still be helpful to divide it into two cavities:
  - the **abdominal cavity** is between the diaphragm and superior border of the hip bones. It contains most

of the digestive organs, along with the kidneys and ureters of the urinary system.
- ◦ the **pelvic cavity** is inferior to the abdominal cavity. It contains the internal reproductive organs, along with the urinary bladder and urethra of the urinary system.

Tissue Membranes

A **tissue membrane** is a thin layer or sheet of cells that covers the outside of the body (for example, skin), the organs (for example, pericardium), internal passageways that lead to the exterior of the body (for example, abdominal mesenteries), and the lining of the movable joint cavities. There are two basic types of tissue membranes: connective tissue and epithelial membranes (**Figure 1.8**).

Mucous membranes line the digestive, respiratory, urinary, and reproductive tracts. They are coated with the secretions of mucous glands.

Serous membranes line body cavities closed to the exterior of the body: the peritoneal, pleural, and pericardial cavities.

Cutaneous membrane, or the skin, covers the body surface.

Synovial membranes line joint cavities and produce the fluid within the joint.

Figure 1.8. Tissue Membranes. The two broad categories of tissue membranes in the body are (1) connective tissue membranes, which include synovial membranes, and (2) epithelial membranes, which include mucous membranes, serous membranes, and the cutaneous membrane, in other words, the skin.

Connective tissue membranes are formed solely from connective tissue. These membranes can encapsulate organs, such as kidneys. Synovial membranes, which line movable joints, are also a type of connective tissue membrane.Epithelial membranes are composed of epithelium attached to a layer of connective tissue. They include the cutaneous membrane (skin), mucous membranes (linings of body cavities and hollow passageways that open to the external environment), and serous membranes. Serous membranes are found in the anterior (ventral) body cavities.A **serous membrane** (also referred to as serosa) is an epithelial membrane composed of mesodermally derived epithelium called the mesothelium that is supported by connective tissue. These

membranes line the coelomic cavities (cavities that do not open to the outside) of the body and they cover the organs located within those cavities. They are essentially membranous bags, with mesothelium lining the inside and connective tissue on the outside (**Figure 1.9**). Serous membranes consist of two layers and the space between them:

- the **parietal layer** lines the walls of the body cavity
- the **visceral layer** covers the organs (the viscera)
- the **serous cavity** is a thin, fluid-filled space between the parietal and visceral layers
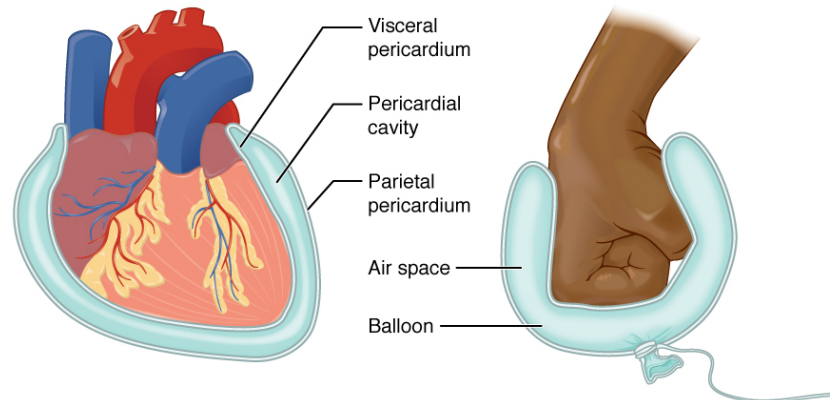
Figure 1.9. Serous Membrane. Serous membrane lines the pericardial cavity and reflects back to cover the heart—much the same way that an underinflated balloon would form two layers surrounding a fist.

The fluid in serous cavities is called serous fluid. **Serous fluid** provides protection to the organs by reducing friction as the organs move against other organs and the walls of the cavities. There are three serous membranes found in the ventral cavity:

- **Pleura**: surrounds the lungs in the pleural cavity and reduces friction between the lungs and the body wall.
- **Pericardium:** surrounds the heart in the pericardial cavity and reduces friction between the heart and the wall of the pericardium.
- **Peritoneum:** surrounds several organs in the abdominopelvic cavity. The peritoneal cavity reduces friction between the abdominal and pelvic organs and the body wall.

Abdominal Regions and Quadrants

To promote clear communication, for instance about the location of a patient's abdominal pain or a suspicious mass, health care providers typically divide up the cavity into either nine regions or four quadrants (**Figure 1.10**). The more detailed regional approach subdivides the cavity with one horizontal line immediately inferior to the ribs and one immediately superior to the pelvis, and two vertical lines drawn as if dropped from the midpoint of each clavicle (collarbone). There are nine resulting regions. The simpler quadrants approach, which is more commonly used in medicine, subdivides the cavity with one horizontal and one vertical line that intersect at the patient's umbilicus (navel).

Figure 1.10 Regions and Quadrants of the Peritoneal Cavity. There are (a) nine abdominal regions and (b) four abdominal quadrants in the peritoneal cavity.

Lab 2: Cells and Tissues I

Cell Structures, Cell Cycle, Epithelial Tissue

Learning Objectives

*When you are prepared for the **Test on Week 2 Learning Objectives** in Week 3, you will be able to:*

1. Identify parts of a microscope and their functions.
2. Describe and demonstrate correct usage of a microscope by observing slides of cells and tissues with proper lighting and magnification.
3. Identify cell structures visible at different scales and describe their functions.
4. Identify stages of the cell cycle and mitosis.
5. Differentiate between the general functions of epithelial, connective, muscle, and nervous tissues.
6. Identify epithelial tissue types, their features, and their basic functions using slides.

All living things are composed of cells. This remarkable fact was first discovered some 300 years ago and is one of the tenets of the Cell Theory, a basic theory of biology. **Cell Theory** states that:

1. All life is composed of cells
2. Cells are the fundamental units which possess all the characteristics of living things
3. New cells can only come into existence by the division of previously existing cells

Notice that this scientific concept about life is called a theory. In science, unlike the layman's definition, the word theory is used for a hypothesis about which there is a large body of convincing evidence. Under experimental conditions all observations have thus far confirmed the theory. The evidence that helped formulate the theory was obtained using the microscope. The microscope is of enormous importance to biology and has extended our ability to see beyond the scope of the naked eye.

The Compound Microscope

The compound microscope is a precision instrument. Treat it with respect. When carrying it, always use two hands, one on the **base** and one on the **arm** (**Figure 2.1**).

The microscope consists of a **stand** (base + arm), on which is mounted the **stage** (for holding microscope slides) and lenses. The lens that you look through is the **ocular lens** (paired in binocular scopes); the lens that focuses on the specimen is the **objective**.

Your microscope has three **objective lenses** of varying magnifications (**4x, 10x, and 40x**) mounted on a revolving nosepiece.

Positioning the specimen requires that you turn the **mechanical stage controls**, which operate the slide bracket on the surface of the stage. One control moves the specimen in the x-direction, and the other moves the specimen in the y-direction.

Focusing on the specimen is achieved by knobs that move the stage up and down, so that it is closer or farther from the objective lens. There are two knobs, an outer **coarse focus** and an inner **fine focus**.

The **substage condenser** directs light through the slide into the objective. An **iris diaphragm** on the substage condenser controls the amount of light reaching the objective, and also affects the contrast of the specimen.
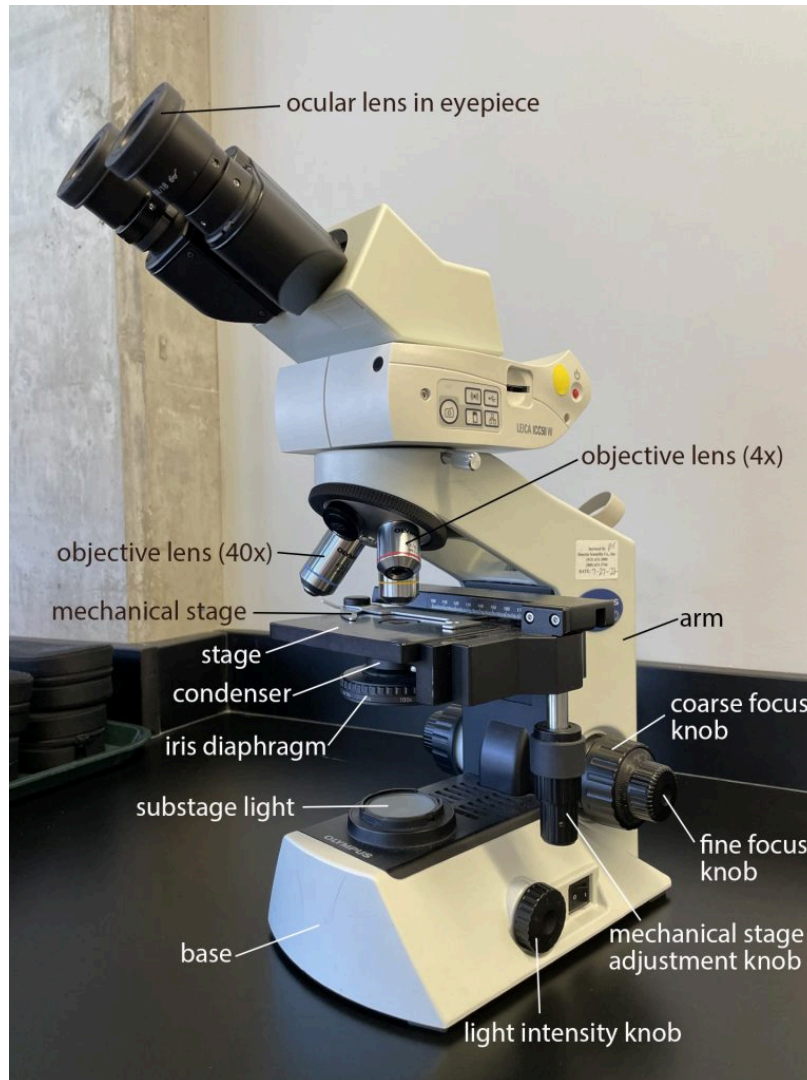
Figure 2.1 Compound Microscope. Compound microscopes magnify cell and tissue slides so that they are visible in lab. The important components of the microscope are labeled.

Magnification

The compound microscope has two sets of lenses; the **ocular lens** (or eye piece) which magnifies an object 10 times its normal size, and the **objective lenses** located on a revolving nosepiece. Rotate the nosepiece and notice how each objective lens clicks into place. Each objective lens has a different magnification of power written on it (such as 4, 10, or 40). This number is the power of magnification for each of the objective lenses. For total magnification multiply the ocular power (10x) times the objective lens that is in place. For example, if you have a 10x ocular and a 10x objective, the total magnification is: 10x × 10x = 100x.

Use this information to fill in the following table:

Ocular Lens		Objective Lens		Total Magnification
10	×	_____ (scanning)	=	_____
10	×	_____ (low power)	=	_____
10	×	_____ (high power)	=	_____

Using the Microscope

After the instructor explains the proper carrying procedures, each student should get out a compound microscope and place it before them on the bench. The instructor will then go over the procedures for using your scope.

Complete the following procedure EVERY TIME you get your microscope out and EVERY TIME you put it away.

Getting Started

1. Get your microscope out of the cabinet in the lab. Carry it with TWO HANDS.
2. Before plugging in your scope, always make sure that the voltage control is at its lowest level and the light switch is off.
3. Plug in the microscope and turn on the light source.
4. Raise the substage condenser to its top position and open the iris diaphragm all the way.
5. Turn the nosepiece so that the 4x objective is lined up with the light source.
6. Place a slide on the stage and use the mechanical stage controls to move it into place.
7. Turn up the light to a comfortable level.

Getting a Focused Image

1. Adjust the interocular distance (distance between the oculars) by gently pressing the oculars together or pulling them apart until you see a single circular field of view.
2. Look through both oculars (i.e., keep both eyes open), but concentrate on the right ocular and adjust focus until the specimen is clear in your right eye.
3. Now concentrate on the left ocular and turn the diopter adjustment (the moveable ring) on the left eyepiece to adjust the focus for your left eye. You should have a sense of the image suddenly "popping out" at you, sharp and clear.

Optimizing Resolution and Contrast

Resolution is the ability to distinguish two closely spaced points on your specimen, and it is always best with the iris diaphragm wide open. Contrast is the magnitude of difference between light and dark objects, and it increases as you close the aperture of the iris diaphragm. Getting the best image, then, requires that you find the right balance. Slowly open and close the iris diaphragm to get a feeling for the effect this has on your image.

Changing Magnification

Always start with the lowest power objective (4x) to get oriented. You should use the coarse focus knob to move the stage up and down and locate an area of interest. Then you can switch to higher power to examine interesting regions more closely. To change magnification, simply rotate the nosepiece to bring one of the other objectives into the light path. When you are using the 10x or 40x objective lenses, ONLY use the fine focus knob. If you use the coarse focus knob, you might bring it up into the objective lens and break it.

Finishing Up

In this order: Turn down the illumination, turn off the power, switch back to the 4X objective lens, remove your slide, and unplug the power cord and wrap it around the back. Then return your scope to the cabinet.

Cells

You developed from a single fertilized egg cell into the complex organism containing trillions of cells that you see when you look in a mirror. During this developmental process, early, undifferentiated cells differentiate and become specialized in their structure and function. These different cell types form specialized tissues that work in concert to perform all of the functions necessary for the living organism. Cellular and developmental biologists study how the continued division of a single cell leads to such complexity and differentiation.

Consider the difference between a structural cell in the skin and a nerve cell. A structural skin cell may be shaped like a flat plate (squamous) and live only for a short time before it is shed and replaced. Packed tightly into rows and sheets, the squamous skin cells provide a protective barrier for the cells and tissues that lie beneath. A nerve cell, on the other hand, may be shaped something like a star, sending out long processes up to a meter in length and may live for the entire lifetime of the organism. With their long winding appendages, nerve cells can communicate with one another and with other types of body cells and send rapid signals that inform the organism about its environment and allow it to interact with that environment. These differences illustrate one very important theme that is consistent at all organizational levels of biology: the form of a structure is optimally suited to perform particular functions assigned to that structure. Keep this theme in mind as you tour the inside of a cell and are introduced to the various types of cells in the body.

The Cell Membrane

The **cell membrane** is an extremely pliable structure composed primarily of back-to-back phospholipids (a "bilayer"). Cholesterol is also present, which contributes to the fluidity of the membrane, and there are various proteins embedded within the membrane that have a variety of functions. Some cells have protrusions of the cell

membrane called microvilli. **Microvilli** increase the surface area of cells and are found in cells lining the digestive system to increase nutrient absorption.

The Cytoplasm and Cellular Organelles

All living cells in multicellular organisms contain an internal cytoplasmic compartment, and a nucleus within the cytoplasm. **Cytosol**, the jelly-like substance within the cell, provides the fluid medium necessary for biochemical reactions. Eukaryotic cells, including all animal cells, also contain various cellular organelles. An **organelle** ("little organ") is one of several different types of membrane-enclosed bodies in the cell, each performing a unique function. Just as the various bodily organs work together in harmony to perform all of a human's functions, the many different cellular organelles work together to keep the cell healthy and performing all of its important functions. The organelles and cytosol, taken together, compose the cell's **cytoplasm**. The nucleus is a cell's central organelle, which contains the cell's DNA (**Figure 2.2**).
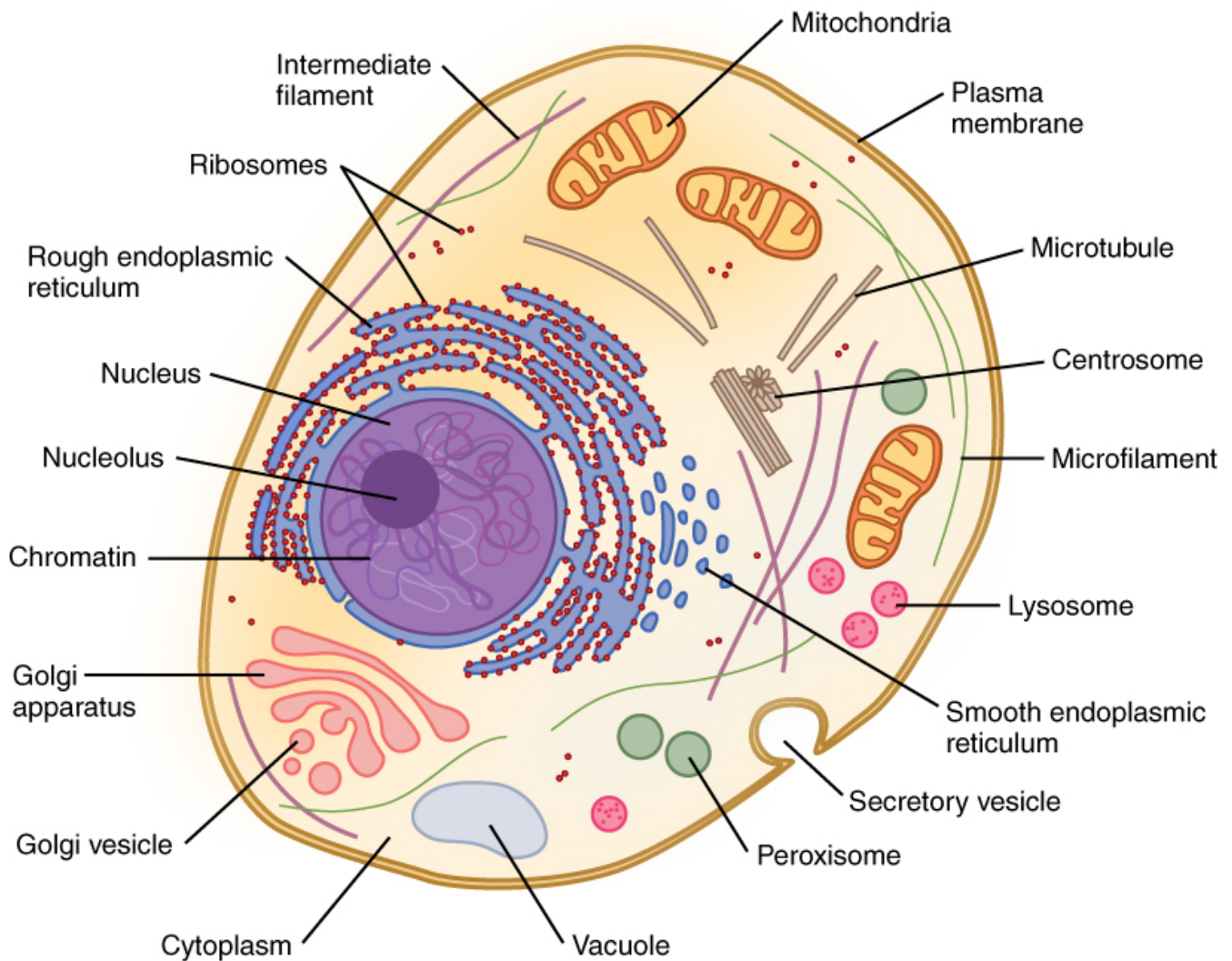
Figure 2.2 Prototypical Human Cell. While this image is not indicative of any one particular human cell, it is a prototypical example of a cell containing the primary organelles and internal structures.

The following sections include brief descriptions of the major cellular organelles and structures and summarizes their functions.

Endoplasmic Reticulum

The endoplasmic reticulum (ER) is a system of channels that is continuous with the nuclear membrane (or "envelope") covering the nucleus and composed of the same lipid bilayer material (**Figure 2.3**). The ER can be thought of as a series of winding thoroughfares similar to the waterway canals in Venice. The ER has a large membranous surface and provides passages throughout much of the cell that function in transporting, synthesizing, and storing materials.

(a)

(b)

(c)
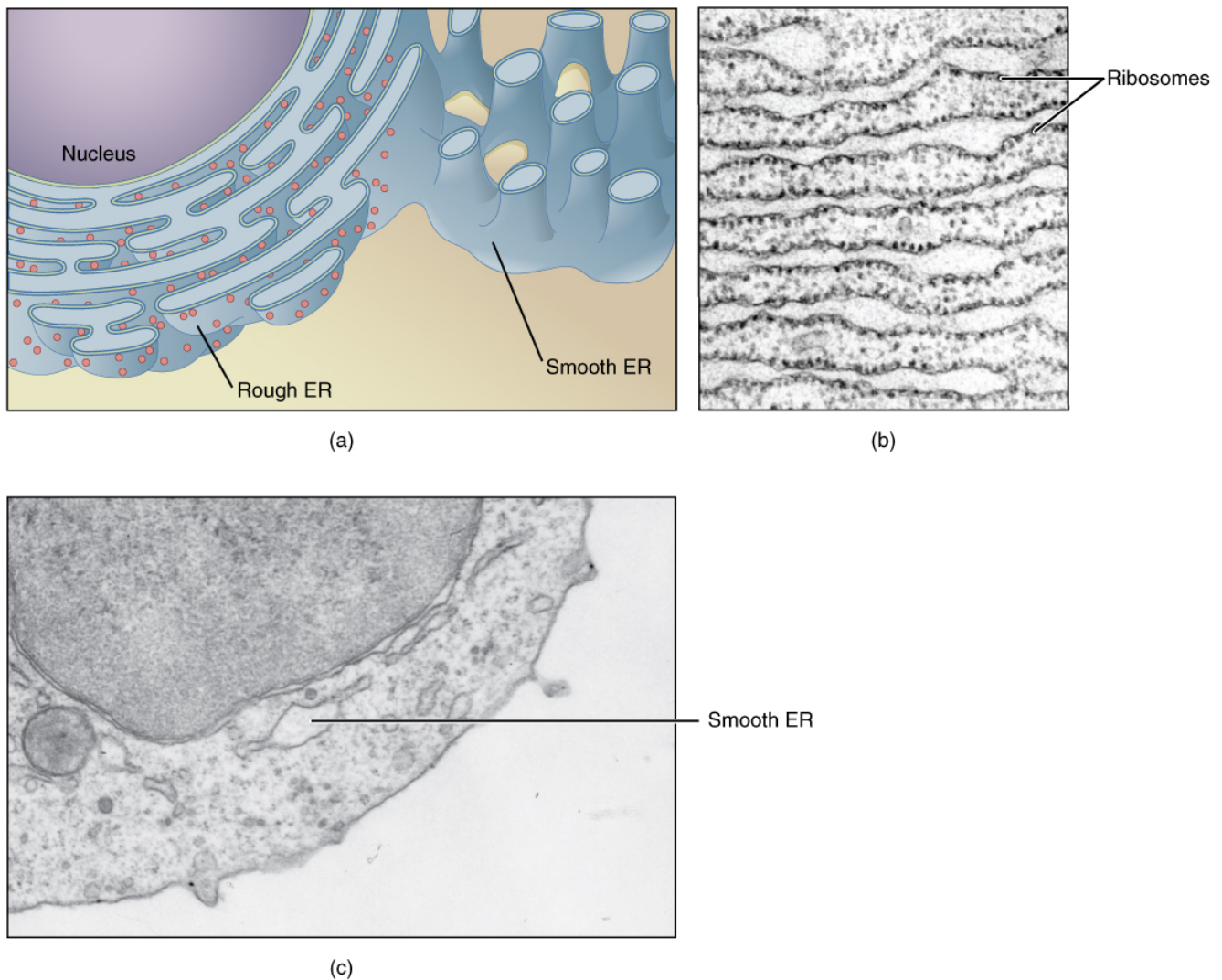
Figure 2.3 Endoplasmic Reticulum. (a) The ER is a winding network of thin membranous sacs found in close association with the cell nucleus. The smooth and rough endoplasmic reticula are very different in appearance and function (source: mouse tissue). (b) Rough ER is studded with numerous ribosomes, which are sites of protein synthesis (source: mouse tissue). EM × 110,000. (c) Smooth ER synthesizes phospholipids, steroid hormones, regulates the concentration of cellular Ca++, metabolizes some carbohydrates, and breaks down certain toxins (source: mouse tissue). EM × 110,510. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Endoplasmic reticulum can exist in two forms: rough ER and smooth ER. These two types of ER perform some very different functions and can be found in very different amounts depending on the type of cell. **Rough endoplasmic reticulum** is so-called because its membrane is dotted with embedded granules—organelles called ribosomes, giving the rough ER a bumpy appearance. A **ribosome** is an organelle that serves as the site of protein synthesis. The primary job of the rough ER is the synthesis and modification of proteins destined for the cell membrane or for export from the cell. Typically, a protein is synthesized within the ribosome and released inside the channel of the rough ER, where it is folded and modified before it is transported within a vesicle to the next stage in the packaging and shipping process: the Golgi apparatus.

The **smooth endoplasmic reticulum** lacks ribsomes, giving it a smooth appearance. One of the main functions of the smooth ER is in the synthesis of lipids, such as phospholipids, the main component of biological membranes, as well as steroid hormones. For this reason, cells that produce large quantities of such hormones, such as those of the female ovaries and male testes, contain large amounts of smooth ER. In addition to lipid synthesis, the smooth ER also sequesters (i.e., stores) and regulates the concentration of cellular Ca^{++}, a function extremely important in cells of the nervous and muscular systems. The smooth ER additionally metabolizes some carbohydrates and performs a detoxification role, breaking down certain toxins.

The Golgi Apparatus

The **Golgi apparatus** is responsible for sorting, modifying, and shipping off the products that come from the rough ER, much like a post-office. The Golgi apparatus looks like stacked flattened discs, almost like stacks of oddly shaped pancakes. Like the ER, these discs are membranous. The Golgi apparatus has two distinct sides, each with a different role. One side of the apparatus receives products in vesicles. These products are sorted through the apparatus, and then they are released from the opposite side after being repackaged into new vesicles. If the product is to be exported from the cell, the vesicle migrates to the cell surface and fuses to the cell membrane, and the cargo is secreted (**Figure 2.4**).
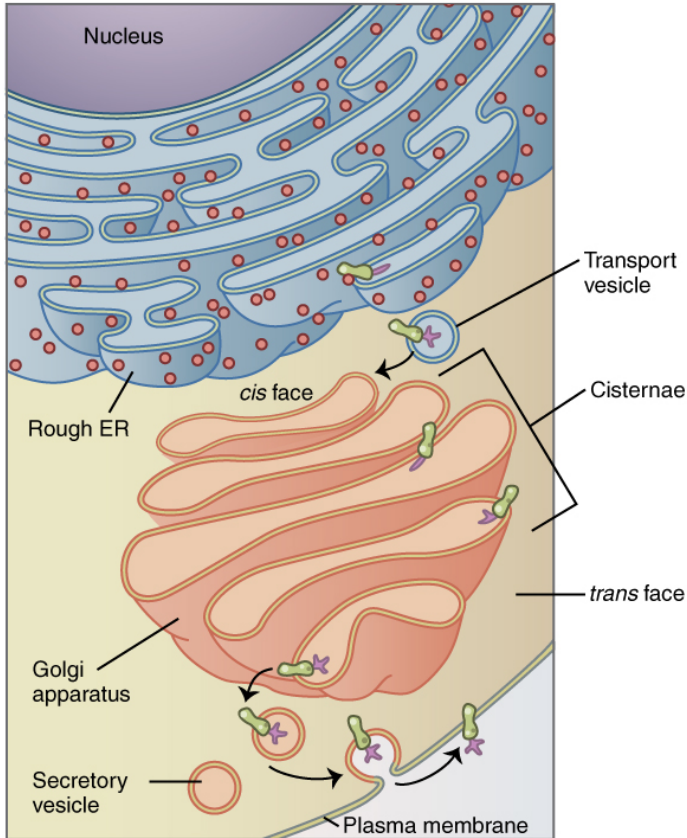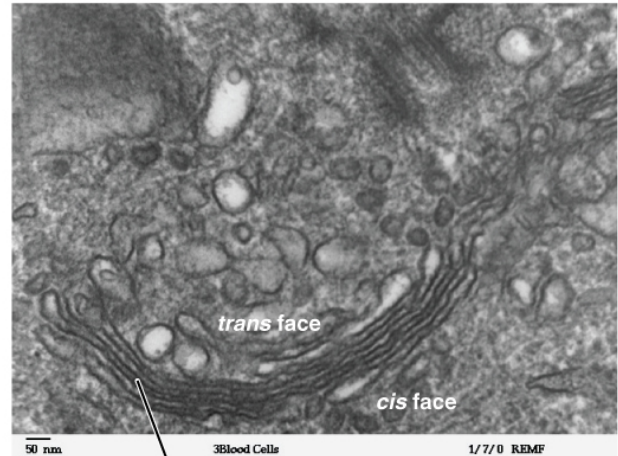
Figure 2.4 Golgi Apparatus (a) The Golgi apparatus manipulates products from the rough ER, and also produces new organelles called lysosomes. Proteins and other products of the ER are sent to the Golgi apparatus, which organizes, modifies, packages, and tags them. Some of these products are transported to other areas of the cell and some are exported from the cell through exocytosis. Enzymatic proteins are packaged as new lysosomes (or packaged and sent for fusion with existing lysosomes). (b) An electron micrograph of the Golgi apparatus.

Lysosomes

Some of the protein products packaged by the Golgi include digestive enzymes that are meant to remain inside the cell for use in breaking down certain materials. The enzyme-containing vesicles released by the Golgi may form new lysosomes, or fuse with existing, lysosomes. A **lysosome** is an organelle that contains enzymes that can break down and digest unneeded cellular components, such as a damaged organelle, or foreign material, such as bacteria. Under certain circumstances, like in the case of damaged or unhealthy cells, lysosomes can be triggered to open up and release their digestive enzymes into the cytoplasm of the cell, killing the cell.

Mitochondria

A mitochondrion (plural = mitochondria) is a membranous, bean-shaped organelle that is the "energy transformer" of the cell. **Mitochondria** consist of an outer lipid bilayer membrane as well as an additional inner lipid bilayer membrane (**Figure 2.5**), along which a series of proteins, enzymes, and other molecules perform the biochemical reactions of cellular respiration. These reactions convert energy stored in nutrient molecules (such as glucose) into adenosine triphosphate (ATP), which provides usable cellular energy to the cell. Cells use ATP constantly, and

so the mitochondria are constantly at work. Oxygen molecules are required during cellular respiration, which is why you must constantly breathe it in. One of the organ systems in the body that uses huge amounts of ATP is the muscular system because ATP is required to sustain muscle contraction. As a result, muscle cells are packed full of mitochondria. Nerve cells also need large quantities of ATP to run their sodium-potassium pumps. Therefore, an individual neuron will be loaded with over a thousand mitochondria. On the other hand, a bone cell, which is not nearly as metabolically-active, might only have a couple hundred mitochondria.

(a)   (b)
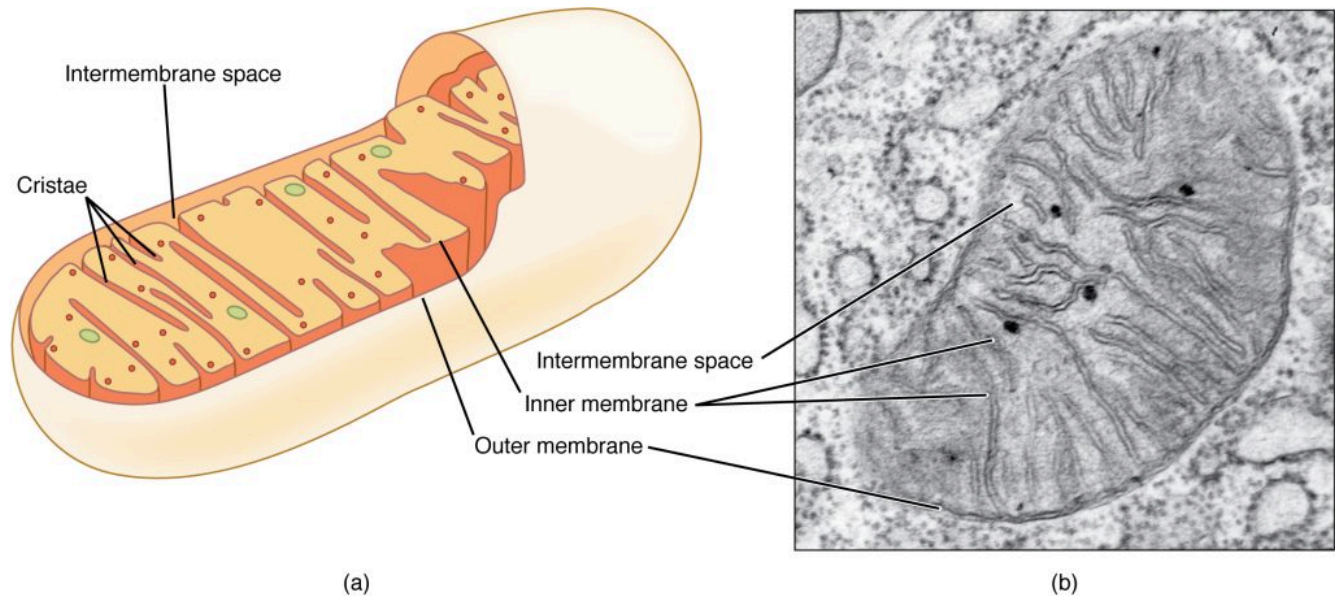
Figure 2.5 Mitochondrion. The mitochondria are the energy-conversion factories of the cell. (a) A mitochondrion is composed of two separate lipid bilayer membranes. Along the inner membrane are various molecules that work together to produce ATP, the cell's major energy currency. (b) An electron micrograph of mitochondria. EM × 236,000. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Peroxisomes

Like lysosomes, a **peroxisome** is a membrane-bound cellular organelle that contains mostly enzymes. Peroxisomes perform a couple of different functions, including lipid metabolism and chemical detoxification. In contrast to the digestive enzymes found in lysosomes, the enzymes within peroxisomes serve to transfer hydrogen atoms from various molecules to oxygen, producing hydrogen peroxide (H_2O_2). In this way, peroxisomes neutralize poisons such as alcohol. H_2O_2 would be toxic to the cell, but peroxisomes contain enzymes that convert H_2O_2 into water and oxygen. These byproducts are then safely released into the cytoplasm. Like miniature sewage treatment plants, peroxisomes neutralize harmful toxins so that they do not wreak havoc in the cells. The liver is the organ primarily responsible for detoxifying the blood before it travels throughout the body, and liver cells contain an exceptionally high number of peroxisomes.

The Cytoskeleton

The **cytoskeleton** is a group of fibrous proteins that play important roles in structural support for cells, cell motility, cell reproduction, and transportation of substances within the cell. The cytoskeleton forms a complex thread-like network throughout the cell consisting of three different kinds of protein-based filaments: microfilaments, intermediate filaments, and microtubules (**Figure 2.6**). Microtubules are the thickest of the three and maintain cell

shape and structure, help resist compression of the cell, and play a role in positioning the organelles within the cell. Microtubules also make up two types of cellular appendages important for motion: cilia and flagella. **Cilia** are found on many cells of the body, including the epithelial cells that line the airways of the respiratory system. Cilia beat constantly, moving waste materials such as dust, mucus, and bacteria upward through the airways, away from the lungs and toward the mouth. A **flagellum** (plural = flagella) is an appendage larger than a cilium and specialized for cell locomotion. The only flagellated cell in humans is the sperm cell that must propel itself towards female egg cells.
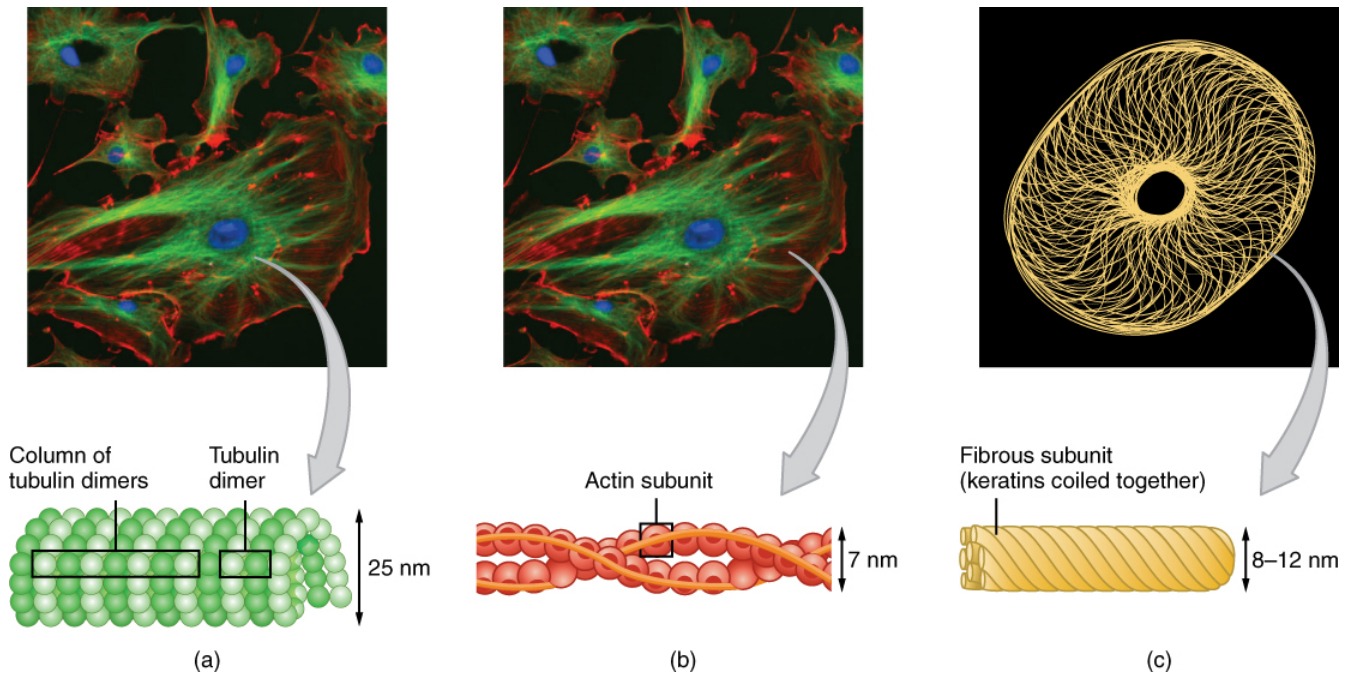
Figure 2.6 The Three Components of the Cytoskeleton. The cytoskeleton consists of (a) microtubules, (b) microfilaments, and (c) intermediate filaments. The cytoskeleton plays an important role in maintaining cell shape and structure, promoting cellular movement, and aiding cell division.

A very important function of microtubules is to set the paths (somewhat like railroad tracks) along which the genetic material can be pulled (a process requiring ATP) during cell division, so that each new daughter cell receives the appropriate set of chromosomes. A **centrosome** is found near the nucleus of cells and consists of two short, identical microtubule structures called **centrioles.** A centriole can serve as the cellular origin point for microtubules extending outward or can assist with the separation of DNA during cell division.

In contrast with microtubules, the microfilament is a thinner type of cytoskeletal filament. Actin, a protein that forms chains, is the primary component of these microfilaments. Actin fibers, twisted chains of actin filaments, constitute a large component of muscle tissue and, along with the protein myosin, are responsible for muscle contraction. Like microtubules, actin filaments are long chains of single subunits (called actin subunits). In muscle cells, these long actin strands, called thin filaments, are "pulled" by thick filaments of the myosin protein to contract the cell.

The final cytoskeletal filament is the intermediate filament. As its name would suggest, an intermediate filament is a filament intermediate in thickness between the microtubules and microfilaments. Intermediate filaments, in concert with the microtubules, are important for maintaining cell shape and structure.

The Nucleus

The nucleus is the largest and most prominent of a cell's organelles (**Figure 2.7**). The nucleus is generally considered the control center of the cell because it stores all of the genetic instructions for manufacturing proteins. Inside the nucleus lies the blueprint that dictates everything a cell will do and all of the products it will make. This information is stored within DNA. The nucleus sends "commands" to the cell via molecular messengers that translate the information from DNA. Each cell in your body (with the exception of germ cells) contains the complete set of your DNA. When a cell divides, the DNA must be duplicated so that the each new cell receives a full complement of DNA. The following section will explore the structure of the nucleus and its contents, as well as the process of DNA replication.
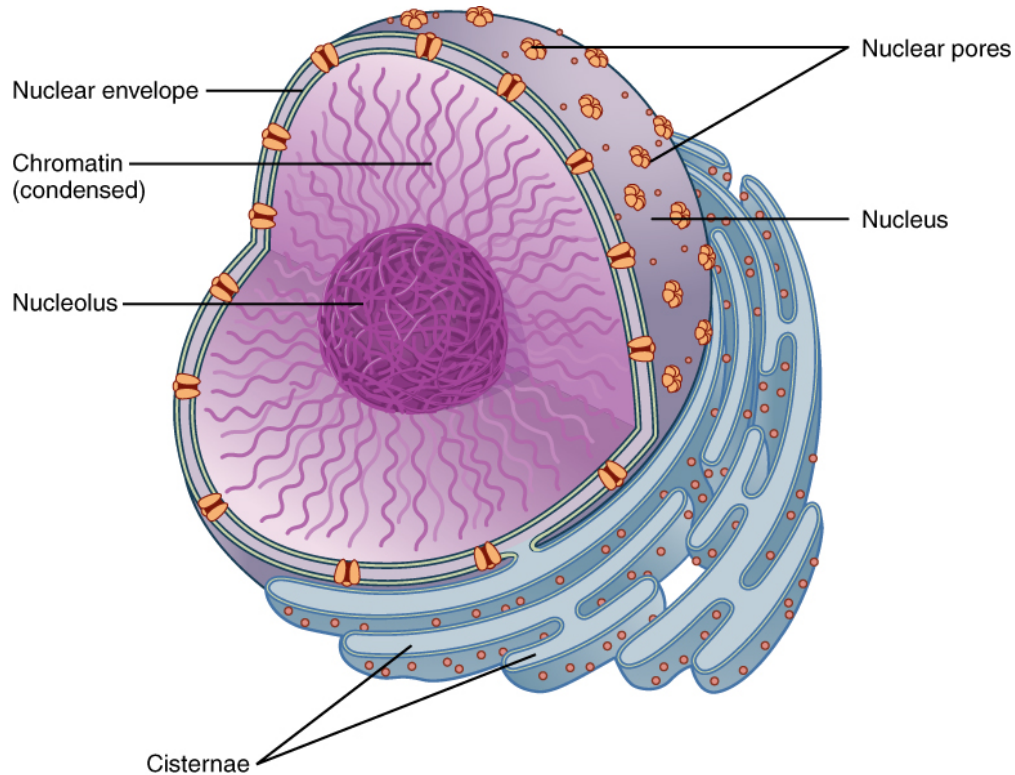
Figure 2.7 The Nucleus. The nucleus is the control center of the cell. The nucleus of living cells contains the genetic material that determines the entire structure and function of that cell.

Organization of the Nucleus and Its DNA

Like most other cellular organelles, the nucleus is surrounded by a membrane called the **nuclear envelope**. This membranous covering consists of two adjacent lipid bilayers with a thin fluid space in between them. Spanning these two bilayers are **nuclear pores**. A nuclear pore is a tiny passageway for the passage of proteins, RNA, and solutes between the nucleus and the cytoplasm. Proteins called pore complexes lining the nuclear pores regulate the passage of materials into and out of the nucleus.

Inside the nuclear envelope is a gel-like nucleoplasm with solutes that include the building blocks of nucleic acids. There also can be a dark-staining mass often visible under a simple light microscope, called a **nucleolus** (plural

= nucleoli). The nucleolus is a region of the nucleus that is responsible for manufacturing the RNA necessary for construction of ribosomes. Once synthesized, newly made ribosomal subunits exit the cell's nucleus through the nuclear pores.

The genetic instructions that are used to build and maintain an organism are arranged in an orderly manner in strands of DNA. Within the nucleus are threads of **chromatin** composed of DNA and associated proteins. When a cell is in the process of division, the chromatin condenses into chromosomes, so that the DNA can be safely transported to the "daughter cells." The **chromosome** is composed of DNA and proteins; it is the condensed form of chromatin. It is estimated that humans have almost 22,000 genes distributed on 46 chromosomes.

The Cell Cycle and Cellular Division

Cells in the body replace themselves over the lifetime of a person. For example, the cells lining the gastrointestinal tract must be frequently replaced when constantly "worn off" by the movement of food through the gut. While there are a few cells in the body that do not undergo cell division (such as gametes, red blood cells, most neurons, and some muscle cells), most somatic cells divide regularly. A **somatic cell** is a general term for a body cell, and all human cells, except for the cells that produce eggs and sperm (which are referred to as germ cells), are somatic cells. Somatic cells contain *two* copies of each of their chromosomes (one copy received from each parent). A homologous pair of chromosomes is the two copies of a single chromosome found in each somatic cell. The human is a diploid organism, having 23 homologous pairs of chromosomes in each of the somatic cells.

The cell cycle is the sequence of events in the life of the cell from the moment it is created at the end of a previous cycle of cell division until it then divides itself, generating two new cells. One "turn" or cycle of the cell cycle consists of two general phases: interphase, followed by mitosis and cytokinesis (**Figure 2.8**). **Interphase** is the period of the cell cycle during which the cell is not dividing. The majority of cells are in interphase most of the time. During interphase, the cell grows and carries out all normal metabolic functions, as well as prepares to divide by replicating its DNA. After DNA replication but before cell division, each cell actually contains two copies of each chromosome. Each copy of the chromosome is referred to as a sister chromatid and is physically bound to the other copy. The centromere is the structure that attaches one sister chromatid to another.
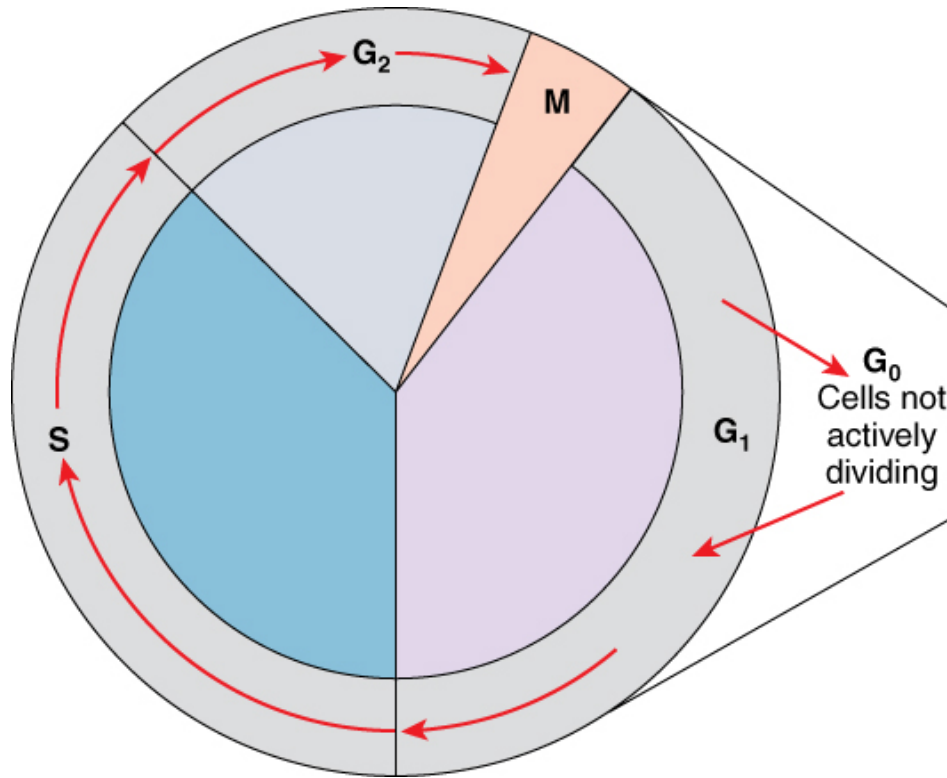
Figure 2.8 Cell Cycle. The two major phases of the cell cycle include mitosis (designated M), when the cell divides, and interphase, when the cell grows and performs all of its normal functions. The cell spends most of its time in interphase (shaded in gray and further subdivided into G1, S, and G2 phases).

Mitosis is the division of genetic material, during which the cell nucleus breaks down and two new, fully functional, nuclei are formed. **Cytokinesis** divides the cytoplasm into two distinctive cells. The mitotic phase of the cell typically takes between 1 and 2 hours. During this phase, a cell undergoes two major processes. First, it completes mitosis, during which the contents of the nucleus are equitably pulled apart and distributed between its two halves. Cytokinesis then occurs, dividing the cytoplasm and cell body into two new cells. Mitosis is divided into four major stages that take place after interphase (**Figure 2.9**) and in the following order: prophase, metaphase, anaphase, and telophase.
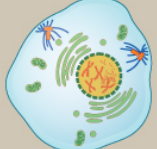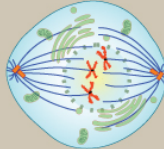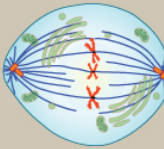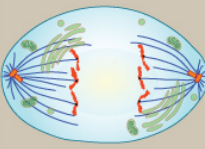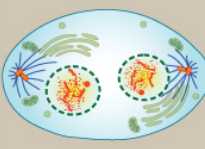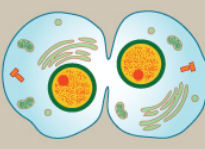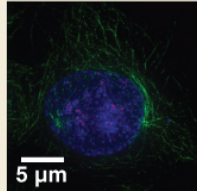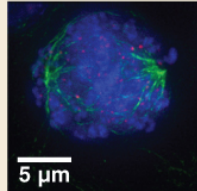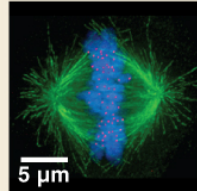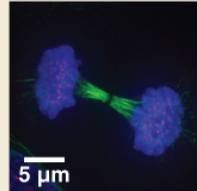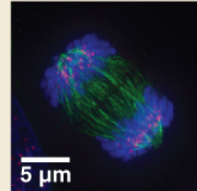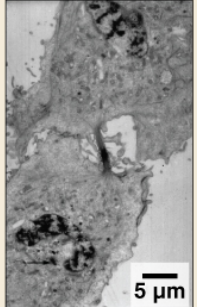
Prophase	Prometaphase	Metaphase	Anaphase	Telophase	Cytokinesis
• Chromosomes condense and become visible • Spindle fibers emerge from the centrosomes • Nuclear envelope breaks down • Centrosomes move toward opposite poles	• Chromosomes continue to condense • Kinetochores appear at the centromeres • Mitotic spindle microtubules attach to kinetochores	• Chromosomes are lined up at the metaphase plate • Each sister chromatid is attached to a spindle fiber originating from opposite poles	• Centromeres split in two • Sister chromatids (now called chromosomes) are pulled toward opposite poles • Certain spindle fibers begin to elongate the cell	• Chromosomes arrive at opposite poles and begin to decondense • Nuclear envelope material surrounds each set of chromosomes • The mitotic spindle breaks down • Spindle fibers continue to push poles apart	• Animal cells: a cleavage furrow separates the daughter cells • Plant cells: a cell plate, the precursor to a new cell wall, separates the daughter cells

MITOSIS

Figure 2.9 Cell Division: Mitosis and Cytokinesis. The stages of cell division oversee the separation of identical genetic material into two new nuclei, followed by the division of the cytoplasm.

Prophase is the first phase of mitosis, during which the loosely packed chromatin coils and condenses into visible chromosomes. During prophase, each chromosome becomes visible with its identical partner attached, forming the familiar X-shape of sister chromatids. The nucleolus disappears early during this phase, and the nuclear envelope also disintegrates. Also during prophase, the cell contains two centrosomes side-by-side, which begin to move apart. As the centrosomes migrate to two different sides of the cell, microtubules begin to extend from each like long fingers from two hands extending toward each other. The **mitotic spindle** is the structure composed of the centrosomes and their emerging microtubules.

Near the end of prophase there is an invasion of the nuclear area by microtubules from the mitotic spindle. The nuclear membrane has disintegrated, and the microtubules attach themselves to the centromeres that adjoin pairs of sister chromatids. This stage is referred to as late prophase or "prometaphase" to indicate the transition between prophase and metaphase.

Metaphase is the second stage of mitosis. During this stage, the sister chromatids, with their attached microtubules, line up along a linear plane in the middle of the cell and mitotic spindle. This plane is called the

metaphase plate, and it is formed between the centrosomes that are now located at either end of the cell.T he microtubules are now poised to pull apart the sister chromatids and bring one from each pair to each side of the cell.

Anaphase is the third stage of mitosis. Anaphase takes place over a few minutes, when the pairs of sister chromatids are separated from one another, forming individual chromosomes once again. These chromosomes are pulled to opposite ends of the cell as the microtubules shorten. Each end of the cell receives one partner from each pair of sister chromatids, ensuring that the two new daughter cells will contain identical genetic material.

Telophase is the final stage of mitosis. Telophase is characterized by the formation of two new daughter nuclei at either end of the dividing cell. These newly formed nuclei surround the genetic material, which uncoils such that the chromosomes return to loosely packed chromatin. Nucleoli also reappear within the new nuclei, and the mitotic spindle breaks apart, each new cell receiving its own complement of DNA, organelles, membranes, and centrioles. At this point, the cell is already beginning to split in half as cytokinesis begins.

During cytokinesis, a contractile band called the **cleavage furrow** forms around the midline of the cell. This contractile band squeezes the two cells apart until they finally separate. Two new cells are now formed.

Tissues

The body contains at least 200 distinct cell types. These cells contain essentially the same internal structures, yet they vary enormously in shape and function. The different types of cells are not randomly distributed throughout the body; rather they occur in organized layers, a level of organization referred to as tissue.

The term **tissue** is used to describe a group of cells found together in the body. The cells within a tissue share a common embryonic origin. Microscopic observation reveals that the cells in a tissue share morphological features and are arranged in an orderly pattern that achieves the tissue's functions. From the evolutionary perspective, tissues appear in more complex organisms. For example, multicellular protists, ancient eukaryotes, do not have cells organized into tissues. Having tissue level organization increases the efficiency of the body as different shapes and internal structures are better suited to carry out different functions. Having different tissues for different functions allows for a greater speed of activity and a greater effectiveness in performing the various activities.

Although there are many types of cells in the human body, they are organized into four broad categories of tissues: epithelial, connective, muscle, and nervous (**Figure 2.10**). Each of these categories is characterized by specific functions that contribute to the overall health and maintenance of the body. **Epithelial tissue**, also referred to as epithelium, refers to the sheets of cells that cover exterior surfaces of the body, lines internal cavities and passageways, and forms certain glands. **Connective tissue**, as its name implies, binds the cells and organs of the body together and functions in the protection, support, and integration of all parts of the body. **Muscle tissue** is excitable, responding to stimulation and contracting to provide movement, and occurs as three major types: skeletal muscle, smooth muscle, and cardiac muscle in the heart. **Nervous tissue** is also excitable, allowing the propagation of electrochemical signals in the form of nerve impulses that communicate between different regions of the body.

The next level of organization is the organ, where several types of tissues come together to form a working unit.

Just as knowing the structure and function of cells helps you in your study of tissues, knowledge of tissues will help you understand how organs function.

Nervous tissue
Brain
Spinal cord
Nerves

Epithelial tissue
Lining of GI tract organs
  and other hollow organs
Skin surface (epidermis)

Muscle tissue
Cardiac muscle
Smooth muscle
Skeletal muscle

Connective tissue
Fat and other soft
  padding tissue
Bone
Tendon
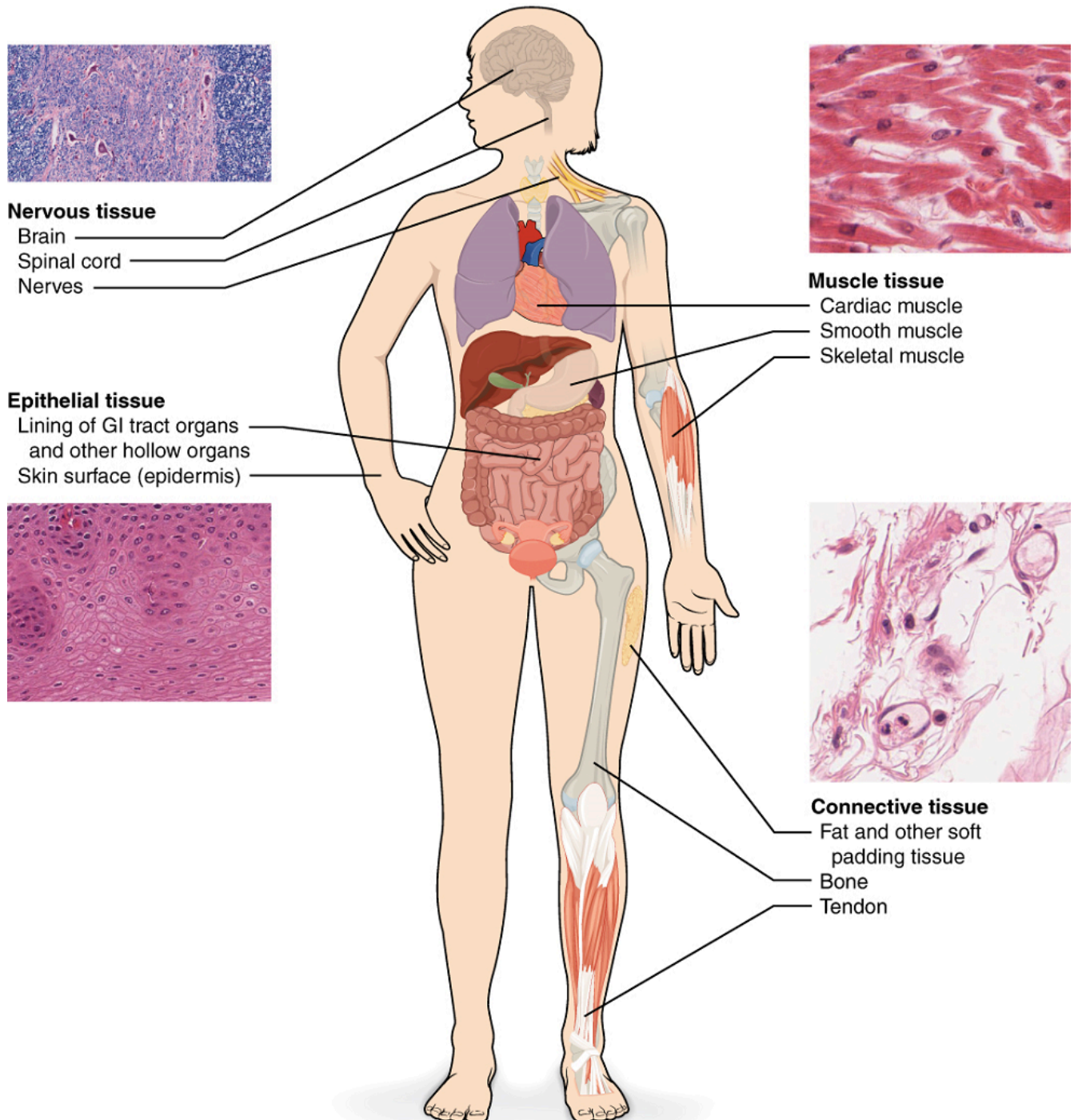
Figure 2.10. Four Types of Tissue: Body. The four types of tissues are exemplified in nervous tissue, stratified squamous epithelial tissue, cardiac muscle tissue, and connective tissue in small intestine. Clockwise from nervous tissue, LM × 872, LM × 282, LM × 460, LM × 800. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

This week we will just examine epithelial tissue. Next week we will look more closely at the remaining three tissue types.

Epithelial Tissue

Most epithelial tissues are essentially large sheets of cells covering all the surfaces of the body exposed to the outside world, and lining the outside of organs and the body cavities. Epithelium also forms much of the glandular tissue of the body. Skin is not the only area of the body exposed to the outside. Other areas include the airways, the digestive tract, as well as the urinary and reproductive systems, all of which are lined by an epithelium. Hollow organs and body cavities that do not connect to the exterior of the body, which includes, blood vessels and serous membranes, are lined by endothelium (plural = endothelia), which is a type of epithelium.

Epithelial tissues provide the body's first line of protection from physical, chemical, and biological wear and tear. The cells of an epithelium act as gatekeepers of the body controlling permeability and allowing selective transfer of materials across a physical barrier. All substances that enter the body must cross an epithelium. Many epithelial cells are capable of secretion and release mucous and specific chemical compounds onto their apical surfaces. The epithelium of the small intestine releases digestive enzymes, for example. Cells lining the respiratory tract secrete mucous that traps incoming microorganisms and particles.

General Structure of Epithelial Tissue

All **epithelia** share some important structural and functional features. This tissue is highly **cellular**, with little or no extracellular material present between cells. The epithelial cells exhibit polarity with differences in structure and function between the exposed or **apical** facing surface of the cell and the **basal** surface close to the underlying body structures. Particular structures found in some epithelial cells are an adaptation to specific functions. Certain organelles are segregated to the basal sides, whereas other organelles and extensions, such as **cilia**, when present, are on the apical surface. The basal lamina of the epithelial cells attaches to underlying connective tissue. via a basement membrane that helps hold it all together.

Epithelial tissues are nearly completely **avascular**. For instance, no blood vessels cross the basement membrane to enter the tissue, and nutrients must come by diffusion or absorption from underlying tissues or the surface. Many epithelial tissues are capable of rapidly replacing damaged and dead cells. Sloughing off of damaged or dead cells is a characteristic of surface epithelium and allows our airways and digestive tracts to rapidly replace damaged cells with new cells.

Classification of Epithelial Tissues

Epithelial tissues are classified according to the shape of the cells and number of the cell layers formed (**Figure 2.11**). Cell shapes can be **squamous** (flattened and thin), **cuboidal** (boxy, as wide as it is tall), or **columnar** (rectangular, taller than it is wide). Similarly, the number of cell layers in the tissue can be one—where every cell rests on the basal lamina—which is a **simple epithelium**, or more than one, which is a **stratified epithelium** and only the basal layer of cells rests on the basal lamina. **Pseudostratified** (pseudo- = "false") describes tissue with a single layer of irregularly shaped cells that give the appearance of more than one layer. **Transitional** describes a form of specialized stratified epithelium in which the shape of the cells can vary.
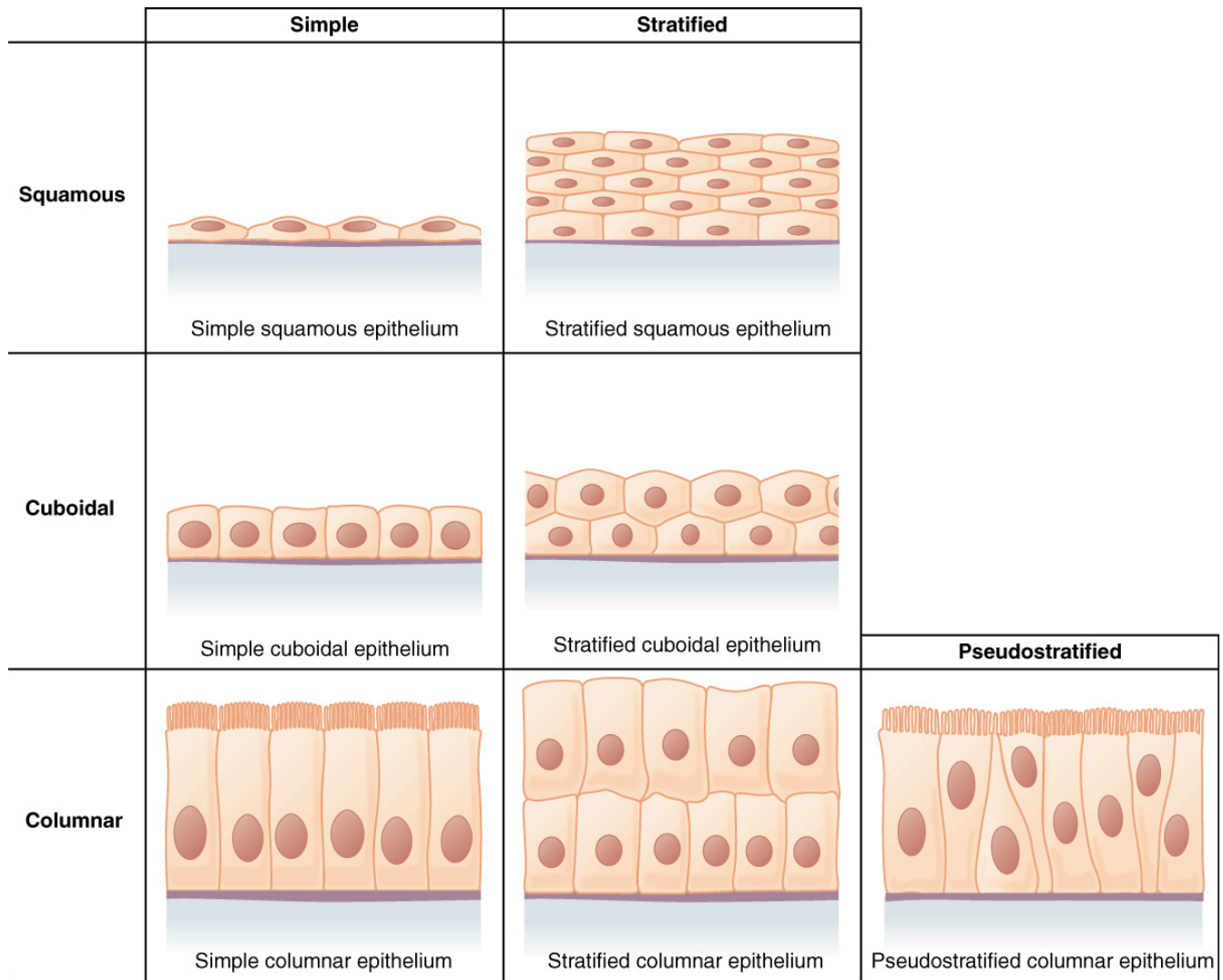
Figure 2.11. Types of Epithelial Tissue. Simple epithelial tissue is organized as a single layer of cells and stratified epithelial tissue is formed by several layers of cells. Pseudostratified epithelial tissue is a single layer of cells that appear to be multiple layers because of the position of their nuclei. Epithelial tissue is further defined by the shape of the apical layer of cells in the tissue.

Simple Epithelium

The shape of the cells in the single cell layer of simple epithelium reflects the functioning of those cells (**Figure 2.12**). The cells in **simple squamous epithelium** have the appearance of thin scales. Squamous cell nuclei tend to be flat, horizontal, and elliptical, mirroring the form of the cell. Simple squamous epithelium, because of the thinness of the cell, is present where rapid passage of chemical compounds is observed. The alveoli of lungs where gases diffuse, segments of kidney tubules, and the lining of capillaries are also made of simple squamous epithelial tissue.

In **simple cuboidal epithelium**, the nucleus of the box-like cells appears round and is generally located near the center of the cell. These epithelia are active in the secretion and absorptions of molecules. Simple cuboidal epithelia are observed in the lining of the kidney tubules and in the ducts of glands.

In **simple columnar epithelium**, the nucleus of the tall column-like cells tends to be elongated and located in the basal end of the cells. Like the cuboidal epithelia, this epithelium is active in the absorption and secretion of molecules. Simple columnar epithelium forms the lining of some sections of the digestive system and parts of the female reproductive tract. Ciliated columnar epithelium is composed of simple columnar epithelial cells with cilia on their apical surfaces. These epithelial cells are found in the lining of the uterine tubes and parts of the respiratory system, where the beating of the cilia helps remove particulate matter.

Pseudostratified columnar epithelium is a type of epithelium that appears to be stratified but instead consists of a single layer of irregularly shaped and differently sized columnar cells. In pseudostratified epithelium, nuclei of neighbouring cells appear at different levels rather than clustered in the basal end. The arrangement gives the appearance of stratification; but in fact, all the cells are in contact with the basal lamina, although some do not reach the apical surface. Pseudostratified columnar epithelium is found in the respiratory tract, where some of these cells have cilia.
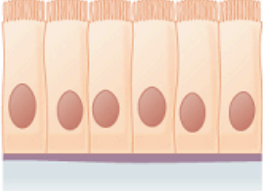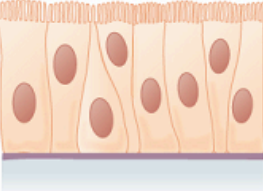
Cells	Location	Function
Simple squamous epithelium	Air sacs of lungs and the lining of the heart, blood vessels, and lymphatic vessels	Allows materials to pass through by diffusion and filtration, and secretes lubricating substance
Simple cuboidal epithelium	In ducts and secretory portions of small glands and in kidney tubules	Secretes and absorbs
Simple columnar epithelium	Ciliated tissues are in bronchi, uterine tubes, and uterus; smooth (nonciliated tissues) are in the digestive tract, bladder	Absorbs; it also secretes mucous and enzymes
Pseudostratified columnar epithelium	Ciliated tissue lines the trachea and much of the upper respiratory tract	Secretes mucus; ciliated tissue moves mucus
Stratified squamous epithelium	Lines the esophagus, mouth, and vagina	Protects against abrasion
Stratified cuboidal epithelium	Sweat glands, salivary glands, and the mammary glands	Protective tissue
Stratified columnar epithelium	The male urethra and the ducts of some glands	Secretes and protects
Transitional epithelium	Lines the bladder, uretha, and the ureters	Allows the urinary organs to expand and stretch

Figure 2.12. Summary of Epithelial Tissue Types. Different types of epithelial tissue serve

Stratified Epithelium

A stratified epithelium consists of several stacked layers of cells. This epithelium protects against physical and chemical wear and tear. The stratified epithelium is named by the shape of the most apical layer of cells, closest to the free space (**Figure 2.12**).

Stratified squamous epithelium is the most common type of stratified epithelium in the human body. The apical cells are squamous, whereas the basal layer contains either columnar or cuboidal cells. The top layer may be covered with dead cells filled with **keratin**. Mammalian skin is an example of this keratinized stratified squamous epithelium. The lining of the mouth cavity is an example of an nonkeratinized stratified squamous epithelium. **Stratified cuboidal epithelium** and **stratified columnar epithelium** can also be found in certain glands and ducts, but are uncommon in the human body.

Transitional epithelium is called that because of the gradual changes in the shapes of the apical cells as the bladder fills with urine. It is found only in the urinary system, specifically the ureters and urinary bladder. When the bladder is empty, this epithelium is convoluted and has cuboidal apical cells with convex, umbrella shaped, apical surfaces. As the bladder fills with urine, this epithelium loses its convolutions and the apical cells transition from cuboidal to squamous. It appears thicker and more multi-layered when the bladder is empty, and more stretched out and less stratified when the bladder is full and distended.

Lab 3: Tissues II and Integumentary system

Connective, muscle, and nervous tissues; the integumentary system

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Learning Objectives

When you are prepared for the Test on Week 3 Learning Objectives in Week 4, you will be able to:

1. Review from Week 2: Differentiate between the general functions of epithelial, connective, muscle, and nervous tissues.
2. Review from Week 2: Identify epithelial tissue types, their features, and their basic functions using slides.
3. Identify connective tissue types, their features, and their basic functions.
4. Identify muscle tissue types.
5. Identify nervous tissue.
6. Identify layers of the skin, layers within the epidermis, and their functions.
7. Identify accessory structures in the skin and explain their functions.

Last week we looked at the four different categories of tissue in the body: epithelial, connective, muscle, and nervous. We then observed different types of epithelial tissue and learned how to differentiate between them. This week we will look at examples of the remaining three tissue categories and learn how to differentiate between specific types of connective tissue and muscle tissue. We will then look at the first organ system of the class, the Integumentary system. This consists of the skin and its accessory structures.

Tissues II

Connective tissue

General structure of connective tissue

As may be obvious from its name, one of the major functions of connective tissue is to connect tissues and organs. Unlike epithelial tissue, which is composed of cells closely packed with little or no extracellular space in between, connective tissue cells are dispersed in a matrix. The matrix usually includes a large amount of extracellular material produced by the connective tissue cells that are embedded within it. The matrix plays a major role in the functioning of this tissue. The major component of the matrix is a ground substance often crisscrossed by protein fibers. This ground substance is usually a fluid, but it can also be mineralized and solid, as in bones. Connective tissues come in a vast variety of forms, yet they typically have in common three

characteristic components: cells, large amounts of amorphous ground substance, and protein fibers. The amount and structure of each component correlates with the function of the tissue, from the rigid ground substance in bones supporting the body to the inclusion of specialized cells; for example, a phagocytic cell that engulfs pathogens and also rids tissue of cellular debris.

Functions of Connective Tissues

Connective tissues perform many functions in the body, but most importantly, they support and connect other tissues; from the connective tissue sheath that surrounds muscle cells, to the tendons that attach muscles to bones, and to the skeleton that supports the positions of the body. Protection is another major function of connective tissue, in the form of fibrous capsules and bones that protect delicate organs and, of course, the skeletal system. Specialized cells in connective tissue defend the body from microorganisms that enter the body. Transport of fluid, nutrients, waste, and chemical messengers is ensured by specialized fluid connective tissues, such as blood and lymph. Adipose cells store surplus energy in the form of fat and contribute to the thermal insulation of the body.

Classification of Connective Tissue

The three broad categories of connective tissue are classified according to the characteristics of their ground substance and the types of fibers found within the matrix (**Table 3.1**). **Connective tissue proper** includes **loose connective tissue** and **dense connective tissue**. Both tissues have a variety of cell types and protein fibers suspended in a viscous ground substance. Dense connective tissue is reinforced by bundles of fibers that provide tensile strength, elasticity, and protection. In loose connective tissue, the fibers are loosely organized, leaving large spaces in between. **Supportive connective tissue** – **bone** and **cartilage** – provide structure and strength to the body and protect soft tissues. A few distinct cell types and densely packed fibers in a matrix characterize these tissues. In bone, the matrix is rigid and described as calcified because of the deposited calcium salts. In **fluid connective tissue** – **lymph** and **blood** – various specialized cells circulate in a watery fluid containing salts, nutrients, and dissolved proteins.

Table 3.1: Connective tissue examples

Connective tissue proper	Supportive connective tissue	Fluid connective tissue

• Loose connective tissue:
  ◦ Areolar
  ◦ Adipose
  ◦ Reticular
	• Cartilage:
	  ◦ Hyaline
	  ◦ Fibrocartilage
	  ◦ Elastic
		Blood

• Dense connective tissue:
  ◦ Regular
  ◦ Irregular
	• Bones:
	  ◦ Compact bone
	  ◦ Spongy bone
		Lymph

Connective Tissue Proper

The most abundant cell in connective tissue proper is the fibroblast. Fibroblasts secrete a viscous ground substance that, with embedded fibrous proteins, forms the extra-cellular matrix (**Figure 3.1**). Fibrocytes, along with adipocytes, and mesenchymal cells, are fixed cells, which means they remain within the connective tissue. Adipocytes are cells that store lipids as droplets that fill most of the cytoplasm. The mesenchymal cell is a multipotent adult stem cell. These cells can differentiate into any type of connective tissue cells needed for repair and healing of damaged tissue. Other cells move in and out of the connective tissue in response to chemical signals. Macrophages, mast cells, lymphocytes, plasma cells, and phagocytic cells are found in connective tissue proper but are actually part of the immune system protecting the body.

Three main types of protein fibers are secreted by fibroblasts: collagen fibers, elastic fibers, and reticular fibers. Collagen fibers, while flexible, have great tensile strength, resist stretching, and give ligaments and tendons their characteristic resilience and strength. Elastic fibers, after being stretched or compressed will return to its original shape. Reticular fibers are narrow and are arrayed in a branching network. They are found throughout the body, but are most abundant in the reticular tissue of soft organs, such as liver and spleen, where they anchor and provide structural support to the the functional cells, blood vessels, and nerves of the organ. All of these fiber types are embedded in ground substance, a clear, viscous, colorless matrix made of polysaccharides and proteins, forming the extracellular matrix of connective tissue proper (Figure 3.1).
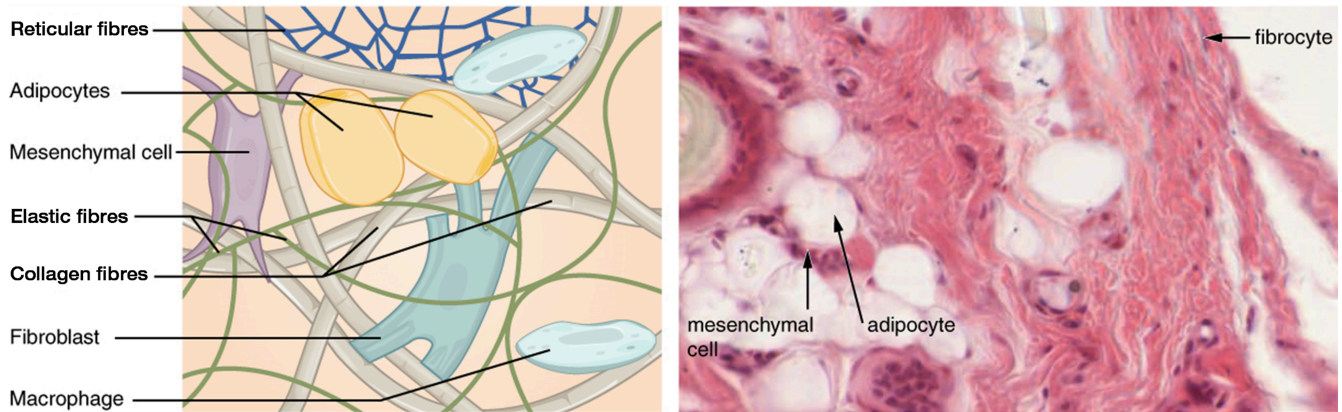
Figure 3.1 Connective Tissue Proper. Fibroblasts produce this fibrous tissue. Connective tissue proper includes the fixed cells fibrocytes, adipocytes, and mesenchymal cells. LM × 400. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Loose Connective Tissue

Loose connective tissue is found between many organs where it acts both to absorb shock and bind tissues together. It allows water, salts, and various nutrients to diffuse through to adjacent or imbedded cells and tissues.

Areolar tissue shows little specialization. It contains all the cell types and fibers previously described and is distributed in a random, web-like fashion. It fills the spaces between muscle fibers, surrounds blood and lymph vessels, and supports organs in the abdominal cavity. Areolar tissue underlies most epithelia and represents the connective tissue component of epithelial membranes, which are described further in a later section.

Adipose tissue consists mostly of fat storage cells, with little extracellular matrix (**Figure 3.2**). A large number of capillaries allow rapid storage and mobilization of lipid molecules. Fat contributes mostly to lipid storage and can serve as insulation from cold temperatures and mechanical injuries.
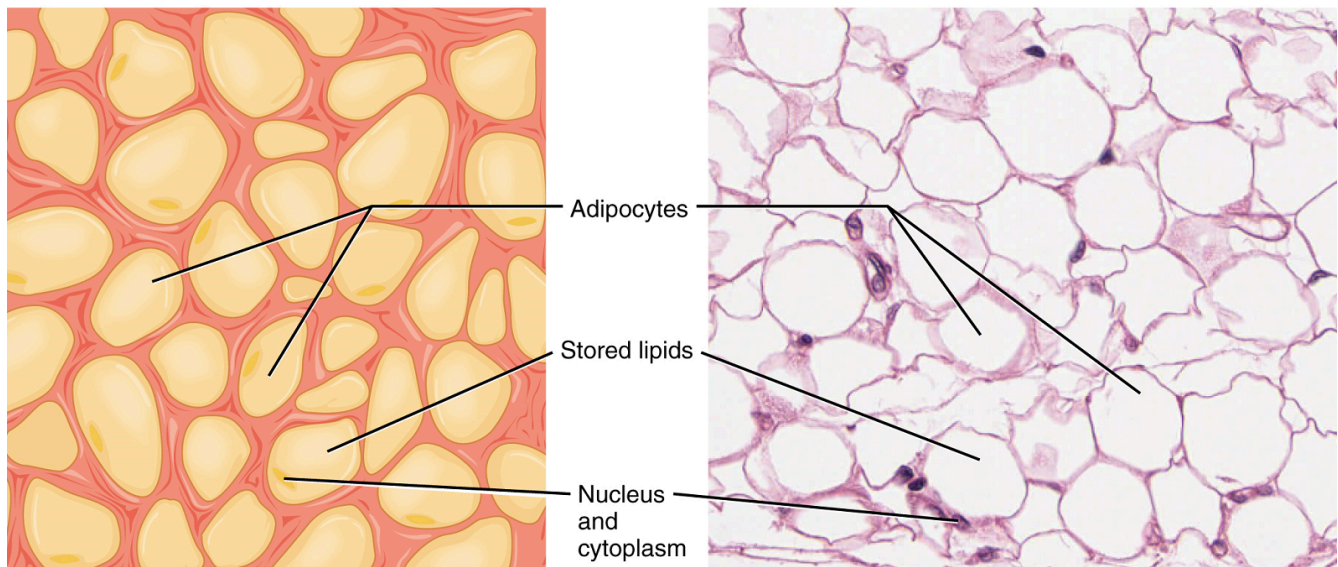
Figure 3.2. Adipose Tissue. This is a loose connective tissue that consists of fat cells with little extracellular matrix. It stores fat for energy and provides insulation. LM × 800. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Reticular tissue is a mesh-like, supportive framework for soft organs such as lymphatic tissue, the spleen, and the liver (**Figure 3.3**). Reticular cells produce the reticular fibers that form the network onto which other cells attach. It derives its name from the Latin reticulus, which means "little net."
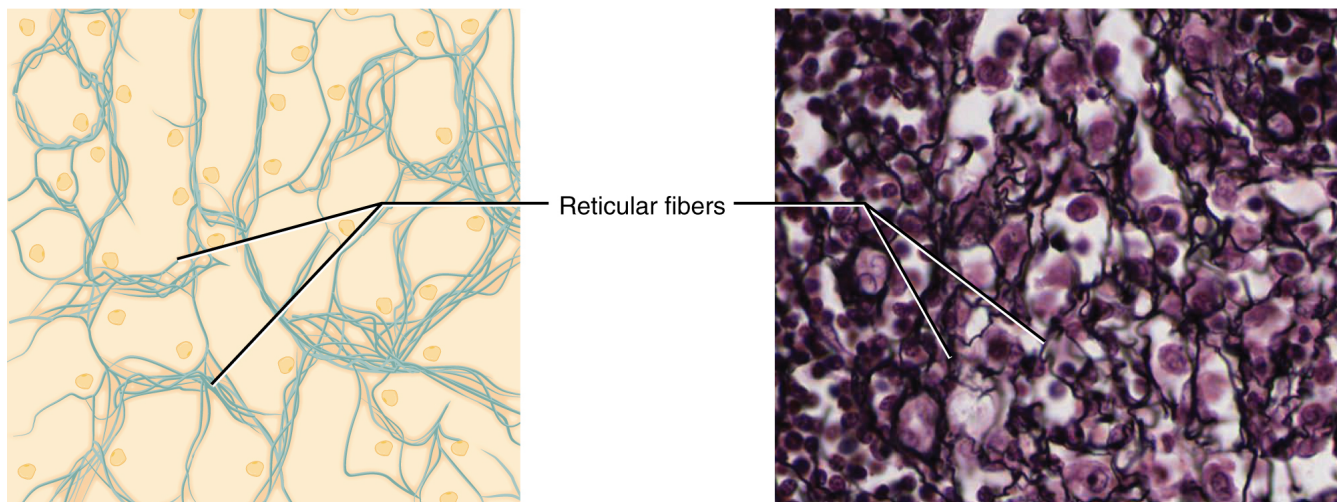
Figure 3.3 Reticular Tissue. This is a loose connective tissue made up of a network of reticular fibers that provides a supportive framework for soft organs. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Dense Connective Tissue

Dense connective tissue contains more collagen fibers than does loose connective tissue. As a consequence, it displays greater resistance to stretching. There are two major categories of dense connective tissue: regular and irregular. **Dense regular connective tissue** fibers are parallel to each other, enhancing tensile strength and

resistance to stretching in the direction of the fiber orientations. Ligaments and tendons are made of dense regular connective tissue, but in ligaments not all fibers are parallel. **Dense regular elastic connective tissue** contains elastin fibers in addition to collagen fibers, which allows the ligament to return to its original length after stretching. The ligaments in the vocal folds and between the vertebrae in the vertebral column are elastic.

In **dense irregular connective tissue**, the direction of fibers is random. This arrangement gives the tissue greater strength in all directions and less strength in one particular direction. In some tissues, fibers crisscross and form a mesh. In other tissues, stretching in several directions is achieved by alternating layers where fibers run in the same orientation in each layer, and it is the layers themselves that are stacked at an angle. The dermis of the skin is an example of dense irregular connective tissue rich in collagen fibers. Dense irregular elastic connective tissue give arterial walls the strength and the ability to regain original shape after stretching (**Figure 3.4**).

Collagen fibers

Fibroblast nuclei

(a) Regular dense

Fibroblast nuclei

Collagen fiber bundles
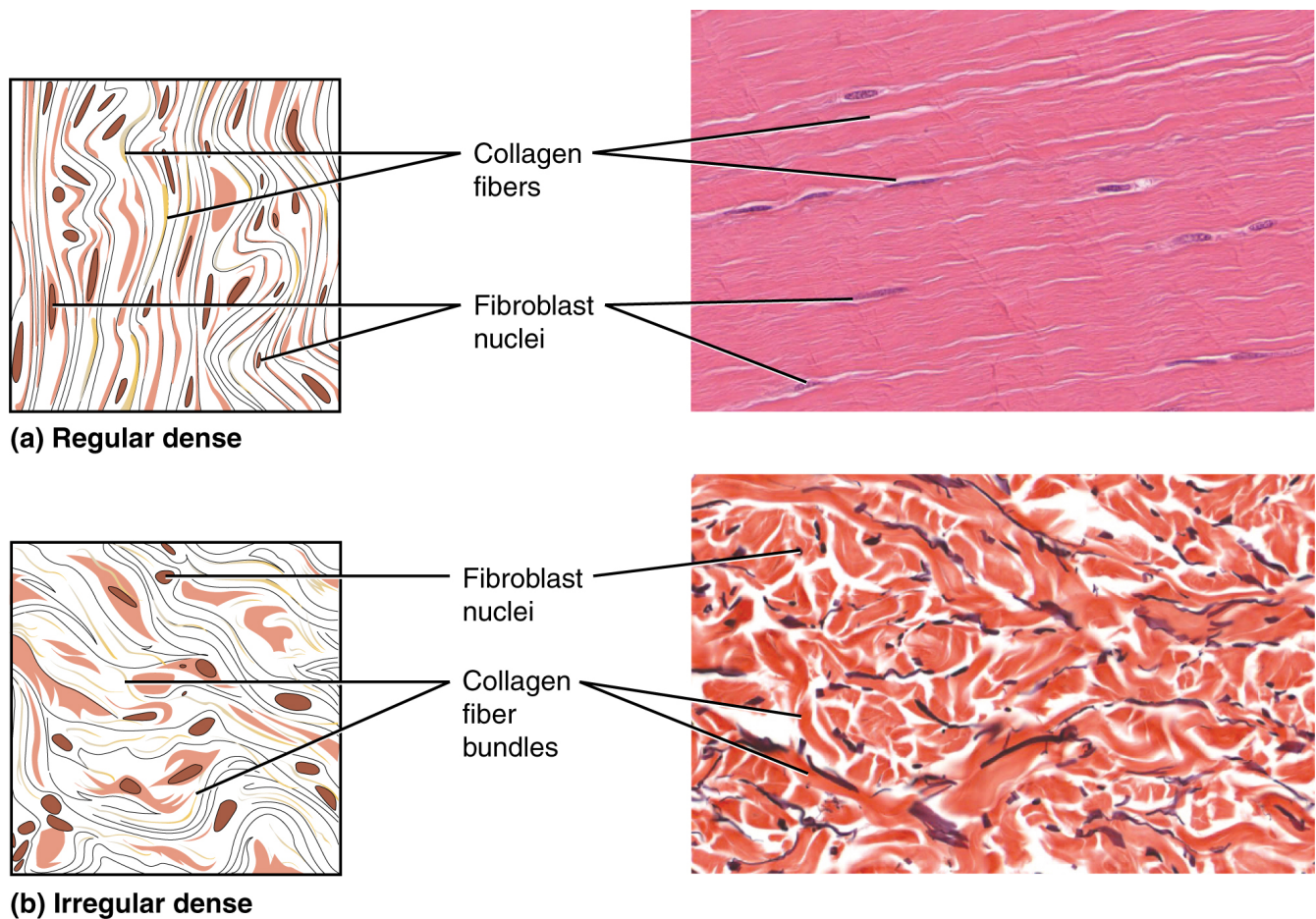
(b) Irregular dense

Figure 3.4 Dense Connective Tissue (a) Dense regular connective tissue consists of collagenous fibers packed into parallel bundles. (b) Dense irregular connective tissue consists of collagenous fibers interwoven into a mesh-like network. From top, LM × 1000, LM × 200. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Supportive Connective Tissues

Two major forms of supportive connective tissue, cartilage and bone, allow the body to maintain its posture and protect internal organs.

Cartilage

The distinctive appearance of cartilage is due to polysaccharides, which bind with ground substance proteins to form the extracellular matrix. Embedded within the cartilage matrix are chondrocytes, or cartilage cells, and the space they occupy are called lacunae (singular = lacuna). Cartilaginous tissue is avascular, thus all nutrients need to diffuse through the matrix to reach the chondrocytes. This is a factor contributing to the very slow healing of cartilaginous tissues.

The three main types of cartilage tissue are hyaline cartilage, fibrocartilage, and elastic cartilage (**Figure 3.5**). **Hyaline cartilage**, the most common type of cartilage in the body, contains short and dispersed collagen fibers in the matrix. Both strong and flexible, the hyaline cartilage is found in the rib cage and nose and covers bones where they meet to form moveable joints. It makes up a template of the embryonic skeleton before bone formation. A plate of hyaline cartilage at the ends of bone allows continued growth until adulthood. **Fibrocartilage** is tough because it has thick bundles of collagen fibers dispersed through its matrix. The knee and jaw joints and the intervertebral discs are examples of fibrocartilage. **Elastic cartilage** contains elastic fibers as well as collagen. This tissue gives rigid support as well as elasticity. Tug gently at your ear lobes, and notice that the lobes return to their initial shape. The external ear contains elastic cartilage.
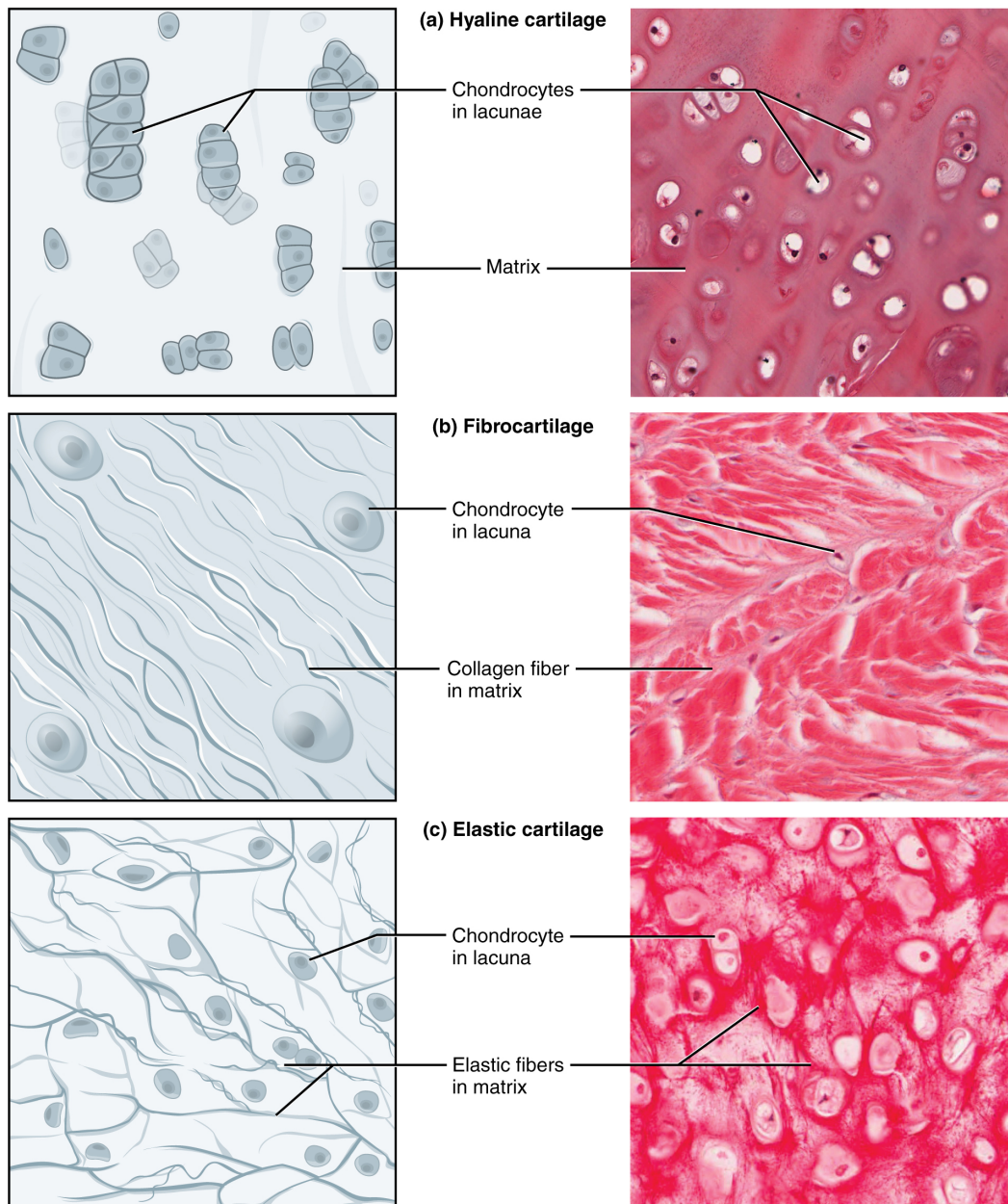
Figure 3.5. Types of Cartilage. Cartilage is a connective tissue consisting of collagenous fibers embedded in a firm matrix of chondroitin sulfates. (a) Hyaline cartilage provides support with some flexibility. The example is from dog tissue. (b) Fibrocartilage provides some compressibility and can absorb pressure. (c) Elastic cartilage provides firm but elastic support. From top, LM × 300, LM × 1200, LM × 1016. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Bone

Bone is the hardest connective tissue. It provides protection to internal organs and supports the body. Bone's rigid extracellular matrix contains mostly collagen fibers embedded in a mineralized ground substance containing hydroxyapatite, a form of calcium phosphate. Both components of the matrix, organic and inorganic, contribute to the unusual properties of bone. Without collagen, bones would be brittle and shatter easily. Without mineral

crystals, bones would flex and provide little support. Osteocytes, bone cells similar to chondrocytes, are located within lacunae. Bone is a highly vascularized tissue. Unlike cartilage, bone tissue can recover from injuries in a relatively short time.

Compact bone tissue is solid and has great structural strength. It is found on the outside of bones and reinforcing the shafts of long bones. The histology of a transverse section of compact bone shows a typical arrangement of osteocytes in concentric circles around a central canal (**Figure 3.6**). **Spongy bone** looks like a sponge under the microscope and contains empty spaces between trabeculae, or arches of bone proper. It is lighter than compact bone and found in the interior of some bones and at the end of long bones.
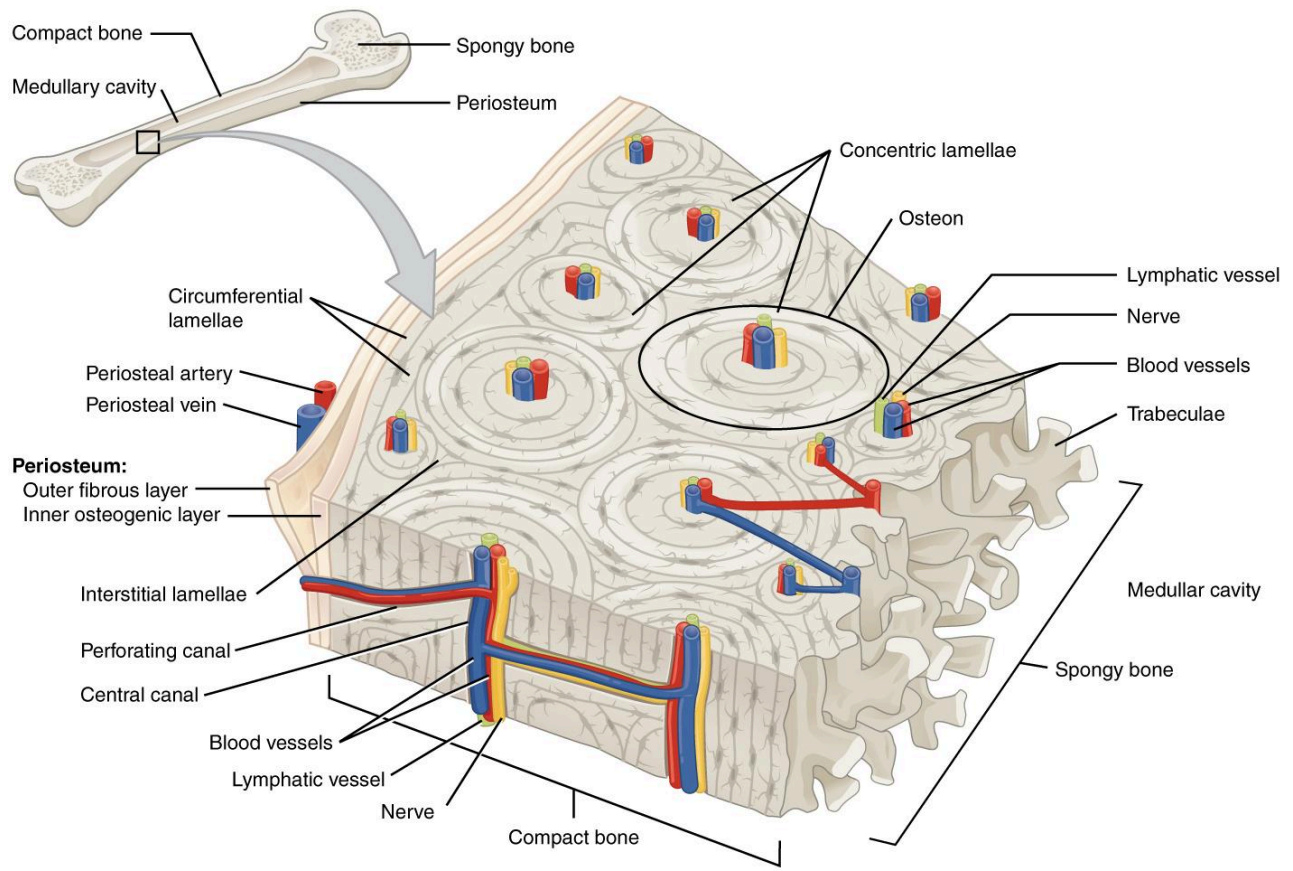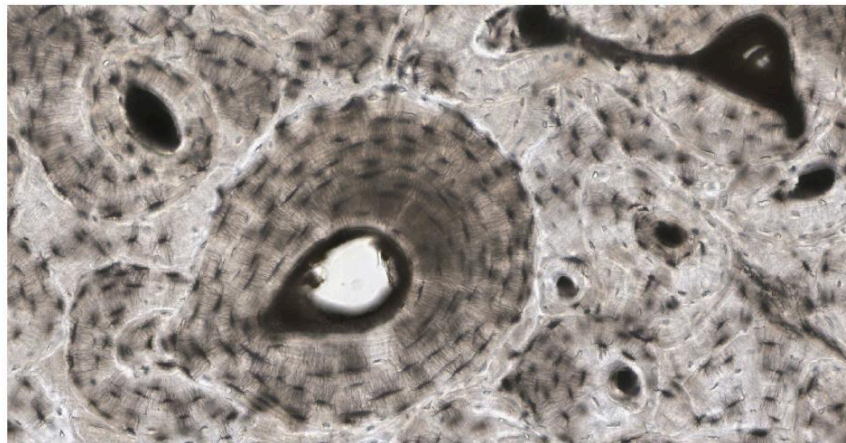
Figure 3.6. Diagram of Compact Bone (a) This cross-sectional view of compact bone shows the basic structural unit, the osteon. (b) In this micrograph of the osteon, you can clearly see the concentric lamellae and central canals. LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Fluid Connective Tissue

Blood and lymph are fluid connective tissues. Cells circulate in a liquid extracellular matrix. The formed elements circulating in blood are all derived from hematopoietic stem cells located in bone marrow. In **blood**, erythrocytes (red blood cells) transport oxygen and some carbon dioxide (**Figure 3.7**). Leukocytes (white blood cells) are responsible for defending against potentially harmful microorganisms or molecules. Platelets are cell fragments involved in blood clotting. Nutrients, salts, and wastes are dissolved in the liquid matrix and transported through the body.

Lymph contains a liquid matrix and white blood cells. Lymphatic capillaries are extremely permeable, allowing larger molecules and excess fluid from interstitial spaces to enter the lymphatic vessels. Lymph drains into blood vessels, delivering molecules to the blood that could not otherwise directly enter the bloodstream. In this way, specialized lymphatic capillaries transport absorbed fats away from the intestine and deliver these molecules to the blood.
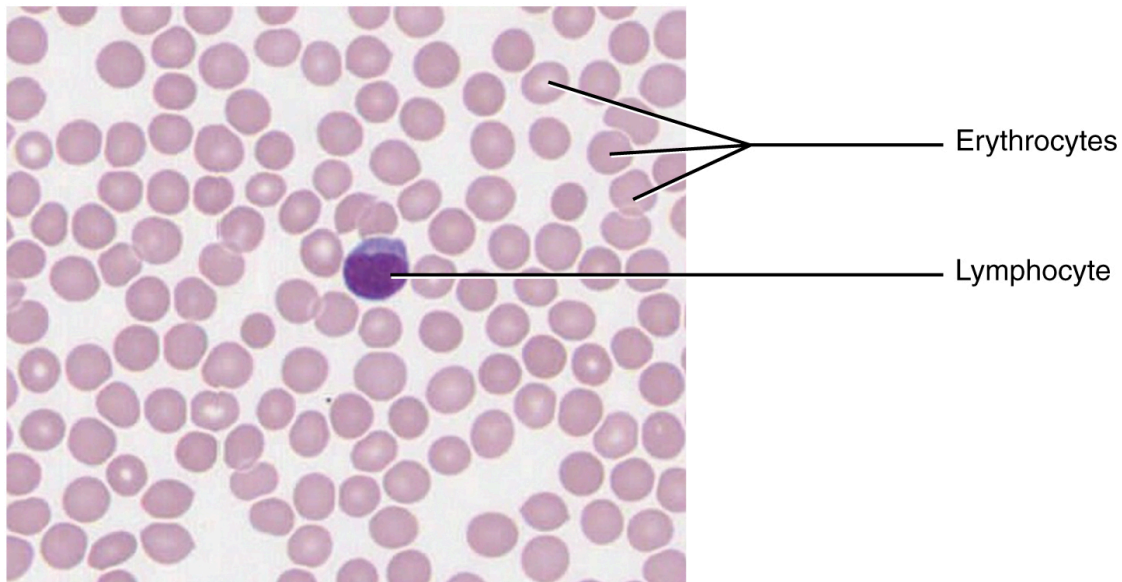
Figure 3.7. Blood: A Fluid Connective Tissue. Blood is a fluid connective tissue containing erythrocytes and various types of leukocytes that circulate in a liquid extracellular matrix. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Muscle Tissue

Muscle tissue is characterized by properties that allow movement. Muscle cells are excitable; they respond to a stimulus. They are contractile, meaning they can shorten and generate a pulling force. When attached between two movable objects, in other words, bones, contractions of the muscles cause the bones to move. Some muscle movement is voluntary, which means it is under conscious control. For example, a person decides to open a book and read a chapter on anatomy. Other movements are involuntary, meaning they are not under conscious control, such as the contraction of your pupil in bright light. Muscle tissue is classified into three types according to structure and function: skeletal, cardiac, and smooth (**Table 3.2**).

Table 3.2: Comparison of structure and properties of muscle tissue types

Tissue	Histology	Function	Location
Skeletal	Long cylindrical fiber; striated; many peripherally-located nuclei	Voluntary movement; thermogenesis; organ protection	Attached to bones; found around entrance points to body (e.g. mouth, anus)
Cardiac	Short, branched fibers; striated; single central nucleus	Contracts to pump blood	Heart walls
Smooth	Short, spindle-shaped fibers; no evident striation; single nucleus	Involuntary movement; moves material through digestive tract and ducts; regulates blood flow in arteries	Walls of major organs and passageways

Skeletal muscle

Skeletal muscle tissue is attached to bones and its contraction makes possible locomotion, facial expressions, posture, and other voluntary movements of the body. Forty percent of your body mass is made up of skeletal muscle. Skeletal muscles generate heat as a byproduct of their contraction and thus participate in thermal homeostasis. Shivering is an involuntary contraction of skeletal muscles in response to perceived lower than normal body temperature.

The muscle cells (muscle fibers) and their numbers remain relatively constant throughout life. Skeletal muscle tissue is arranged in bundles surrounded by connective tissue. Under the light microscope, muscle cells appear striated with many nuclei squeezed along the membranes (**Figure 3.8a**). The striation is due to the regular alternation of the contractile proteins actin and myosin, along with the structural proteins that couple the contractile proteins to connective tissues. The cells are multinucleated as a result of the fusion of the many myoblasts that fuse to form each long muscle fiber.
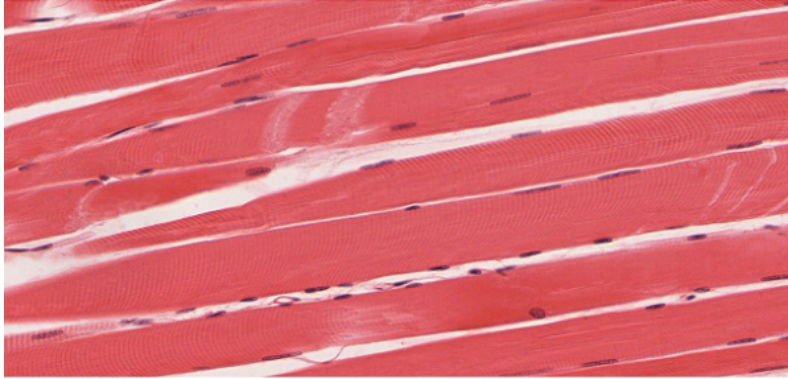
(a)
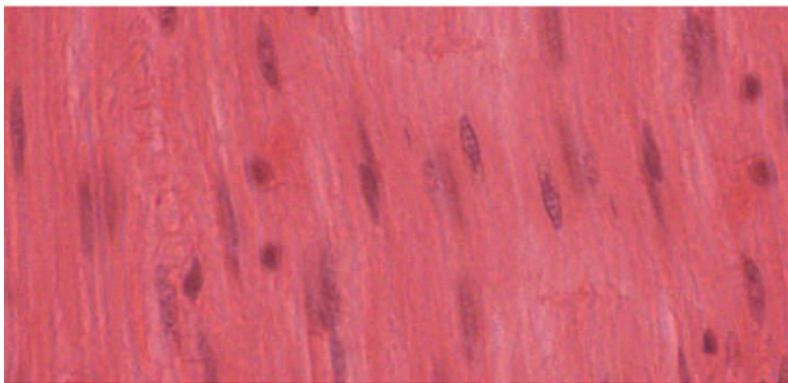
(b)
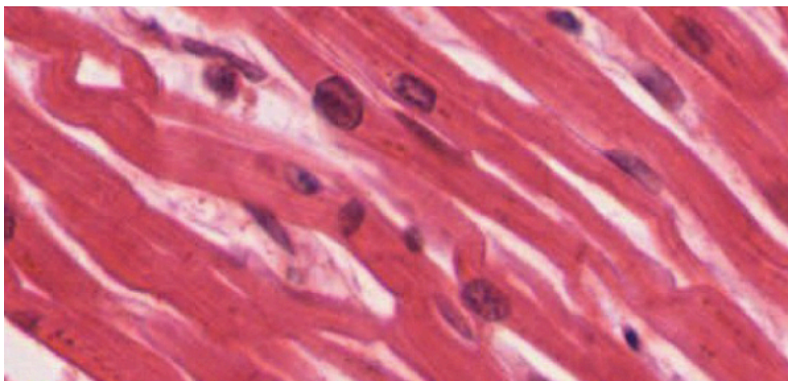
(c)

Figure 3.8. Muscle Tissue. (a) Skeletal muscle cells have prominent striation and nuclei on their periphery. (b) Smooth muscle cells have a single nucleus and no visible striations.(c) Cardiac muscle cells appear striated and have a single nucleus. From top, LM × 1600, LM × 1600, LM × 1600. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Cardiac muscle

Cardiac muscle tissue forms the contractile walls of the heart. The cells of cardiac muscle, known as cardiomyocytes, also appear striated under the microscope. Unlike skeletal muscle fibers, cardiomyocytes are single cells typically with a single centrally located nucleus (**Figure 3.8c**).

A principal characteristic of cardiomyocytes is that they contract on their own intrinsic rhythms without any external stimulation. Cardiomyocytes attach to one another with specialized cell junctions called intercalated discs that contain gap junctions. Attached cells form long, branching cardiac muscle fibers and the ions carrying a contraction signal flow rapidly from cell to cell through the gap junctions, which allows the cells to synchronize their actions. The cardiac muscle pumps blood through the body and is under involuntary control.

Smooth muscle

Smooth muscle tissue contraction is responsible for involuntary movements in the internal organs. It forms the contractile component of the digestive, urinary, and reproductive systems as well as the airways and arteries. Each cell is spindle shaped with a single nucleus and no visible striations (**Figure 3.8b**).

Nervous Tissue

Nervous tissue is characterized as being excitable and capable of sending and receiving electrochemical signals that provide the body with information. Two main classes of cells make up nervous tissue: the neuron and neuroglia . Neurons propagate information via electrochemical impulses, called action potentials, which are biochemically linked to the release of chemical signals. Neuroglia play an essential role in supporting neurons and modulating their information propagation. The presence of the nervous tissue throughout the body and its organization allow it to receive, integrate and provide information to the entire body. This ensures that appropriate responses can occur among all body systems within an intact organism, both under normal conditions as well as during times of stress.

Neurons display distinctive morphology, well suited to their role as conducting cells, with three main parts (**Figure 3.9**). The cell body includes most of the cytoplasm, the organelles, and the nucleus. Dendrites branch off the cell body and appear as thin extensions. A long "tail," the axon, extends from the neuron body and can be wrapped in an insulating layer known as myelin, which is formed by accessory cells. The synapse is the gap between nerve cells, or between a nerve cell and its target, for example, a muscle or a gland, across which the impulse is transmitted by chemical compounds known as neurotransmitters.
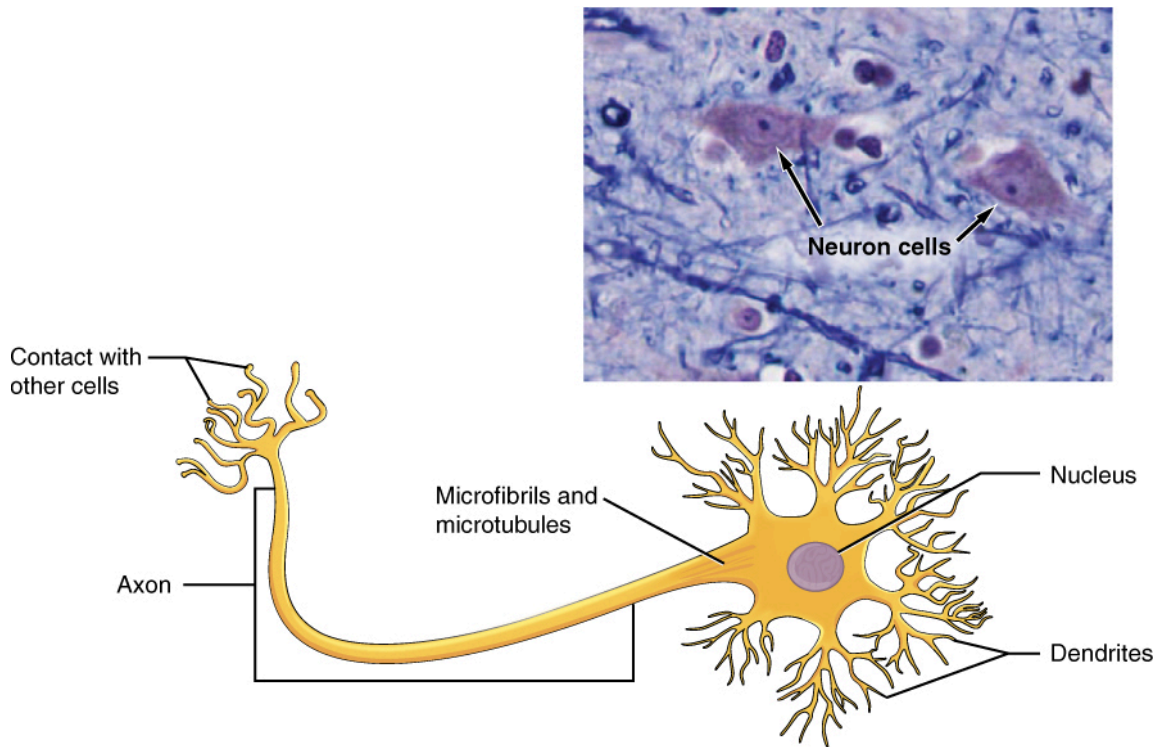
Figure 3.9. The Neuron and Nervous tissue. The upper image shows nervous tissue with large neurons and smaller neuroglia surrounding them. The cell body of a neuron, also called the soma, contains the nucleus and mitochondria. The dendrites transfer the nerve impulse to the soma. The axon carries the action potential away to another excitable cell. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Integumentary System

Although you may not typically think of the skin as an organ, it is in fact made of tissues that work together as a single structure to perform unique and critical functions. The skin and its accessory structures make up the integumentary system, which provides the body with overall protection. The skin is made of multiple layers of cells and tissues, which are held to underlying structures by connective tissue (**Figure 3.10**). The superficial layer, known as the epidermis, is composed primarily of tightly pack epithelial cells. The deeper layer of skin, the dermis, is well vascularized (has numerous blood vessels) and is where several accessory structures, such as hair follicles, sweat glands, and oil glands, can be found. It also has numerous sensory, and autonomic and sympathetic nerve fibers ensuring communication to and from the brain. Below the dermis lies the superficial fascia, or hypodermis, which is not technically part of the skin, but serves to connect the skin to the underlying fascia. This layer is mainly composed of loose, areolar and adipose connective tissues.

The skin and accessory structures perform a variety of essential functions, such as protecting the body from invasion by microorganisms, chemicals, and other environmental factors; preventing dehydration; acting as a sensory organ; modulating body temperature and electrolyte balance; and synthesizing vitamin D. The underlying hypodermis has important roles in storing fats, forming a "cushion" over underlying structures, and providing

insulation from cold temperatures. The skin protects the rest of the body from the basic elements of nature such as wind, water, and UV sunlight. It acts as a protective barrier against water loss, due to the presence of layers of keratin and glycolipids in the stratum corneum. It also is the first line of defense against abrasive activity due to contact with grit, microbes, or harmful chemicals. Sweat excreted from sweat glands deters microbes from over-colonizing the skin surface by generating dermicidin, which has antibiotic properties.
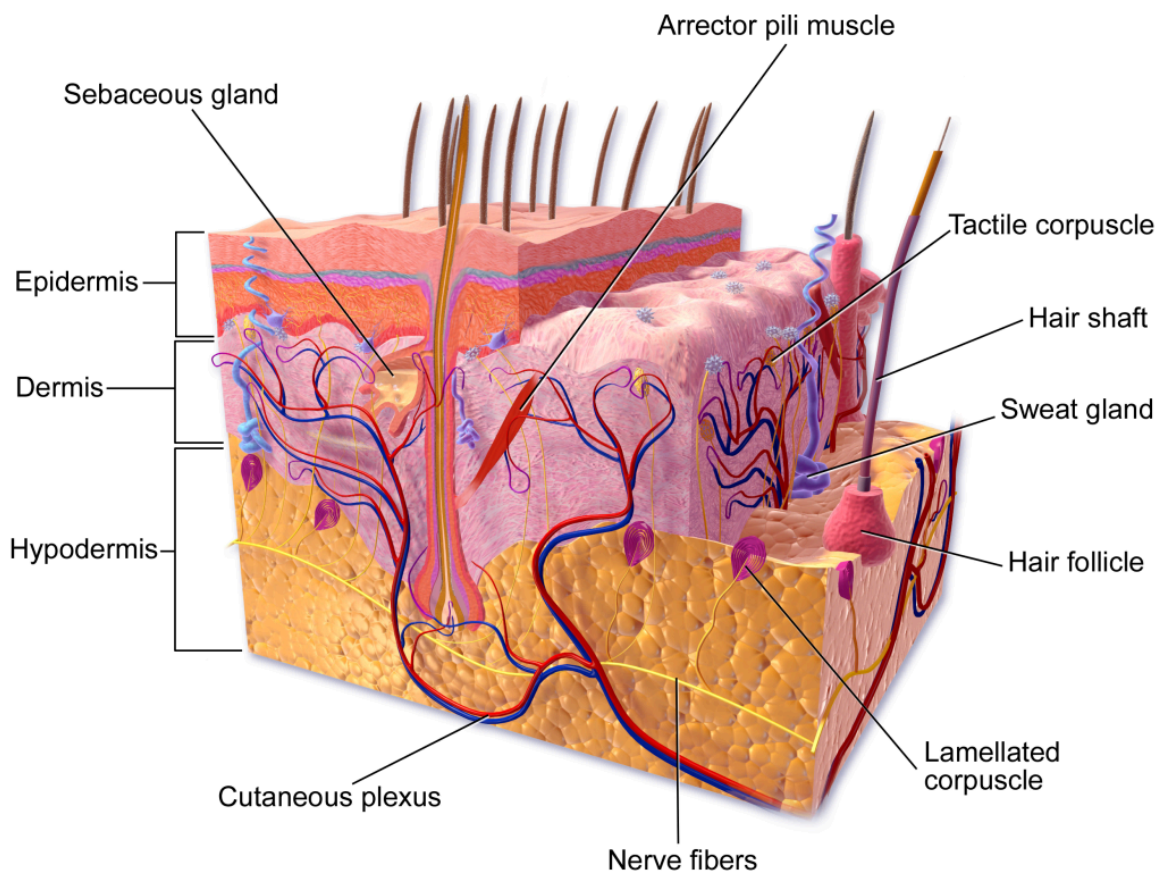
Figure 3.10 Layers of skin. Skin consists of the epidermis superficially and the deeper dermis. The epidermis is made of several layers of epithelial cells that act as a protective barrier. The dermis contains accessory structures that serve other functions.

The Epidermis

The **epidermis** is composed of keratinized, stratified squamous epithelium. It is made of four or five layers, depending on its location in the body. It does not have any blood vessels within it (i.e., it is avascular). Skin that has four epidermal layers is referred to as "**thin skin**." From deep to superficial, these layers are the stratum basale, stratum spinosum, stratum granulosum, and stratum corneum. Most of the skin can be classified as thin skin. "**Thick skin**" is found only on the palms of the hands and the soles of the feet. It has a fifth layer, called the stratum lucidum, located between the stratum corneum and the stratum granulosum (**Figure 3.11**).
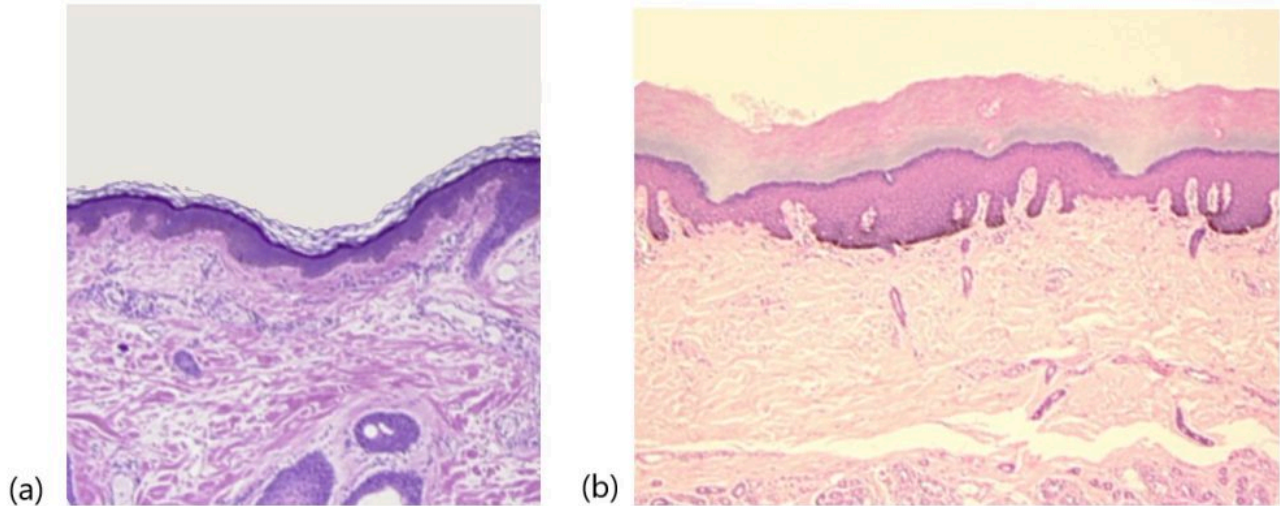
Figure 3.11 Thin Skin versus Thick Skin. These slides show cross-sections of the epidermis and dermis of (a) thin and (b) thick skin. Note the significant difference in the thickness of the epithelial layer of the thick skin. LM × 50. (Image credit: "Thin Skin versus Thick Skin" by Jennifer MacDonald, HistotechnologyProgram, Mt. San Antonio College is licensed under CC BY-NC 4.0)

The majority of cells in the epidermis are called keratinocytes. A keratinocyte is a cell that manufactures and stores the protein keratin. Keratin is an intracellular fibrous protein that gives hair, nails, and skin their hardness and water-resistant properties. The keratinocytes in the stratum corneum are dead and regularly slough away, being replaced by cells from the deeper layers.

Stratum Basale

The **stratum basale** is the deepest epidermal layer and attaches the epidermis to the basal lamina, below which lie the layers of the dermis (**Figure 3.12**). A finger-like projection, or fold, known as the dermal papilla (plural = dermal papillae) is found in the superficial portion of the dermis. Dermal papillae increase the strength of the connection between the epidermis and dermis; the greater the surface area conveyed by folding, the stronger the connections made . In a growing fetus, fingerprints form where the cells of the stratum basale meet the papillae of the underlying dermal layer (papillary layer), resulting in the formation of the ridges on your fingers that you recognize as fingerprints. Fingerprints are unique to each individual and are used for forensic analyses because the patterns do not change with the growth and aging processes.

The stratum basale is a single layer of cells primarily made of basal cells. A basal cell is a cuboidal-shaped stem cell that is a precursor of the keratinocytes of the epidermis. All of the keratinocytes are produced from this single layer of cells, which are constantly going through mitosis to produce new cells. As new cells are formed, the existing cells are pushed superficially away from the stratum basale. Two other cell types are found dispersed among the basal cells in the stratum basale. The first is a tactile cell (Merkel cell)**,** which functions as a receptor and is responsible for stimulating sensory nerves that the brain perceives as touch. These cells are especially abundant on the surfaces of the hands and feet. The second is a melanocyte, a cell that produces the pigment melanin. Melanin gives hair and skin its color, and also helps protect the living cells of the epidermis from ultraviolet (UV) radiation damage.
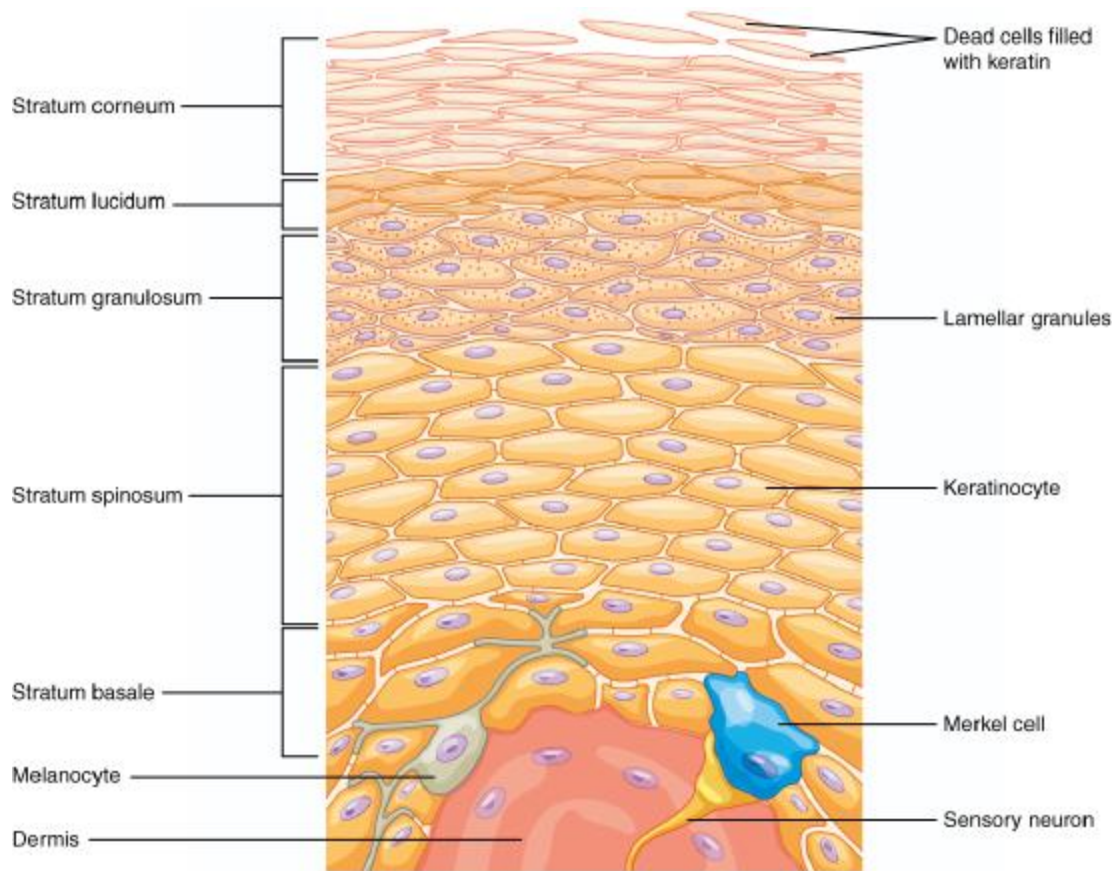
Figure 3.12 Layers of the Epidermis. The epidermis of thick skin has five layers: stratum basale, stratum spinosum, stratum granulosum, stratum lucidum, and stratum corneum. (Image credit: "Layers of Epidermis" by OpenStax is licensed under CC BY 3.0)

Stratum Spinosum

As the name suggests, the **stratum spinosum** is spiny in appearance due to the protruding cell processes that join the cells via an anchoring junction common in epithelial tissues called a desmosome. The desmosomes interlock with each other and strengthen the bond between the cells. It is interesting to note that the "spiny" nature of this layer is an artifact of the staining process. Unstained epidermis samples do not exhibit this characteristic appearance. The stratum spinosum is composed of eight to ten layers of keratinocytes, formed as a result of cell division in the stratum basale (**Figure 3.13**). The keratinocytes in the stratum spinosum begin the synthesis of keratin and release a water-repelling glycolipid that helps prevent water loss from the body, making the skin relatively waterproof. As new keratinocytes are produced atop the stratum basale, the keratinocytes of the stratum spinosum are pushed into the stratum granulosum. Wandering among the keratinocytes of this layer is a type of dendritic cell called the Langerhans cell, also known as a dendritic cell, which differentiates from and functions similarly to a macrophage by engulfing bacteria, foreign particles, and damaged cells that occur in this layer.
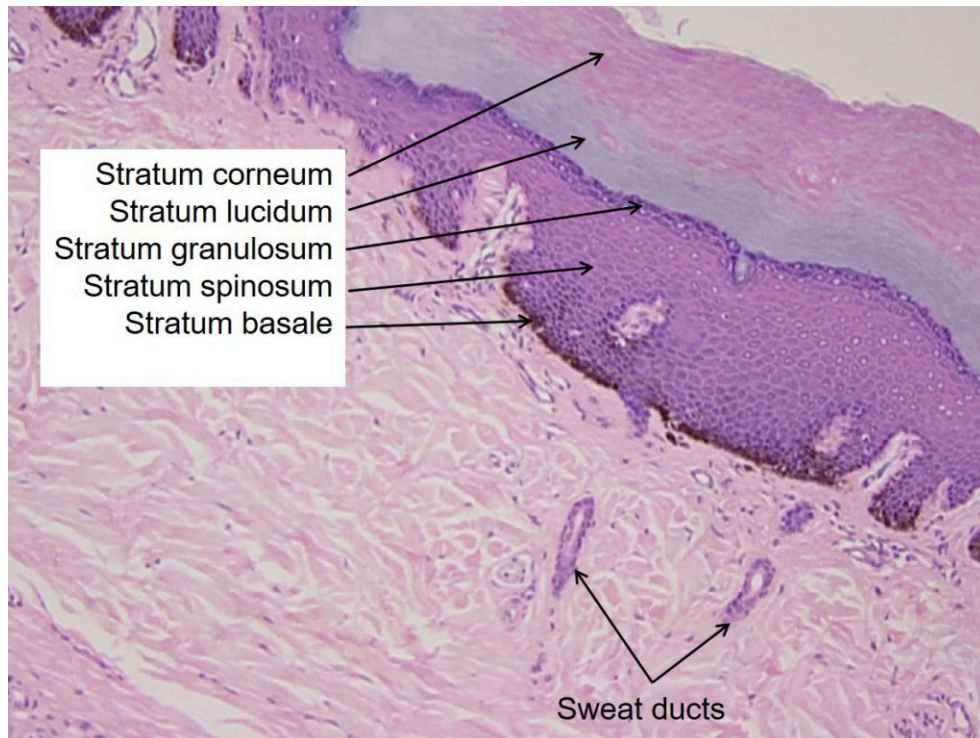
Figure 3.13 Cells of the Epidermis. The keratinocytes in the different layers of the epidermis originate from basal cells located in the stratum basale, yet the cells of each layer change as they are pushed up through the layers of the epidermis. LM × 100. (Image credit: "Cells of the Epidermis" by Jennifer MacDonald, HistotechnologyProgram, Mt. San Antonio College is licensed under CC BY-NC 4.0)

Stratum Granulosum

The **stratum granulosum** has a grainy appearance due to further changes to the keratinocytes as they are pushed from the stratum spinosum. The cells here (three to five layers thick) become flatter, their cell membranes thicken with a coating of lipids secreted by accumulated lamellar granules, and they generate large amounts of the fibrous protein keratin. The accumulated granules give the layer its grainy appearance. The nuclei and other cell organelles disintegrate as the cells die, leaving behind the keratin and coated cell membranes that will form the stratum lucidum, the stratum corneum, and the accessory structures of hair and nails.

Stratum Lucidum

The stratum lucidum is a smooth, seemingly translucent layer of the epidermis located just above the stratum granulosum and below the stratum corneum. This thin layer of cells is found only in the thick skin of the palms, soles, and digits. The keratinocytes that compose the stratum lucidum are dead and flattened. These cells are densely packed with a clear protein derived from keratohyalin, which gives these cells their transparent (i.e., lucid) appearance and provides a barrier to water.

Stratum Corneum

The stratum corneum is the most superficial layer of the epidermis and is the layer exposed to the outside

environment (see **Figure 3.12**). The increased keratinization (also called cornification) of the cells in this layer gives it its name. There are usually 15 to 30 layers of cells in the stratum corneum . This dry, dead layer helps prevent the penetration of microbes and the dehydration of underlying tissues, and provides a mechanical protection against abrasion for the more delicate, underlying layers. Cells in this layer are shed periodically and are replaced by cells pushed up from the

stratum granulosum (or stratum lucidum in the case of the palms and soles of feet). The entire layer is replaced during a period of about 4 weeks. Cosmetic procedures, such as microdermabrasion, help remove some of the dry, upper layer and aim to keep the skin looking "fresh" and healthy.

Dermis

The dermis might be considered the "core" of the integumentary system (derma- = "skin"), as distinct from the epidermis (epi- = "upon" or "over") and hypodermis (hypo- = "below"). It contains blood and lymph vessels, nerves, and other structures, such as hair follicles and sweat glands. The dermis is made of two layers of connective tissue, the superficial papillary layer and deep reticular layer, that compose an interconnected mesh of elastic and collagen fibers, produced by fibroblasts (**Figure 3.14**).
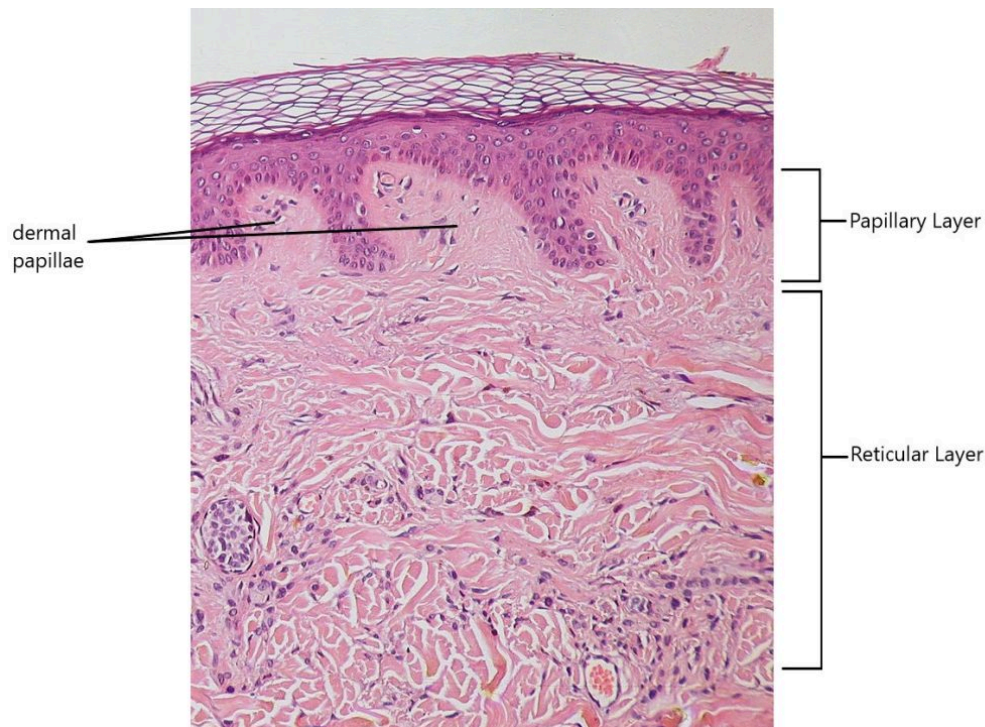
Figure 3.14 Layers of the Dermis. This stained slide shows the two components of the dermis—the papillary layer and the reticular layer. Both are made of connective tissue with fibers of collagen extending from one to the other, making the border between the two somewhat indistinct. The dermal papillae extending into the epidermis belong to the papillary layer, whereas the dense collagen fiber bundles below belong to the reticular layer. LM × 10. (Image credit: "Layers of the Dermis" by Whitney Menefee is licensed under CC BY 4.0 / A derivative from the original work)

Papillary Layer

The papillary layer is made of loose, areolar connective tissue , which means the collagen and elastic fibers of this layer form a loose mesh. This superficial layer of the dermis projects into the stratum basale of the epidermis to form finger-like dermal papillae (**Figure 3.14**). Within the papillary layer are fibroblasts, a small number of fat cells (adipocytes), and an abundance of small blood vessels. In addition, the papillary layer contains phagocytes, defensive cells that help fight bacteria or other infections that have breached epidermis. This layer also contains lymphatic capillaries, nerve fibers, and touch receptors called tactile corpuscles (Meissner corpuscles). Tactile corpuscles can be found located in the dermal papillae, and are responsible for sensing light touch.

Reticular Layer

Underlying the papillary layer is the much thicker reticular layer, composed of dense irregular connective tissue. This layer is well vascularized and has a rich sensory and sympathetic nerve supply. The reticular layer appears reticulated (net-like) due to a tight meshwork of fibers. Elastic fibers provide some elasticity to the skin, enabling movement. Collagen fibers provide structure and tensile strength, with strands of collagen extending into both the papillary layer and the hypodermis. In addition, collagen binds water to keep the skin hydrated. Collagen injections and Retin-A creams help restore skin turgor by either introducing collagen externally or stimulating blood flow and repair of the dermis , respectively.

Hypodermis

The hypodermis (also called the subcutaneous layer or superficial fascia) is a layer directly below the dermis and serves to connect the skin to the underlying fascia (fibrous tissue) of the bones and muscles. It is not strictly a part of the skin, although the border between the hypodermis and dermis can be difficult to distinguish. The hypodermis consists of well-vascularized, loose, areolar connective tissue and adipose tissue, which functions as a mode of fat storage and provides insulation and cushioning for the skin.

Accessory and Sensory Structures of the Skin

Hair

Hair is a keratinous filament growing out of the epidermis. It is primarily made of dead, keratinized cells. Strands of hair originate in an epidermal penetration of the dermis called the **hair follicle**. The **hair shaft** is the part of the hair not anchored to the follicle, and much of this is exposed at the skin's surface. The rest of the hair, which is anchored in the follicle, lies below the surface of the skin and is referred to as the hair root. The hair root ends deep in the dermis at the **hair bulb**, and includes a layer of mitotically active basal cells called the hair matrix. The hair bulb surrounds the hair papilla, which is made of connective tissue and contains blood capillaries and nerve endings from the dermis (**Figure 3.15**).
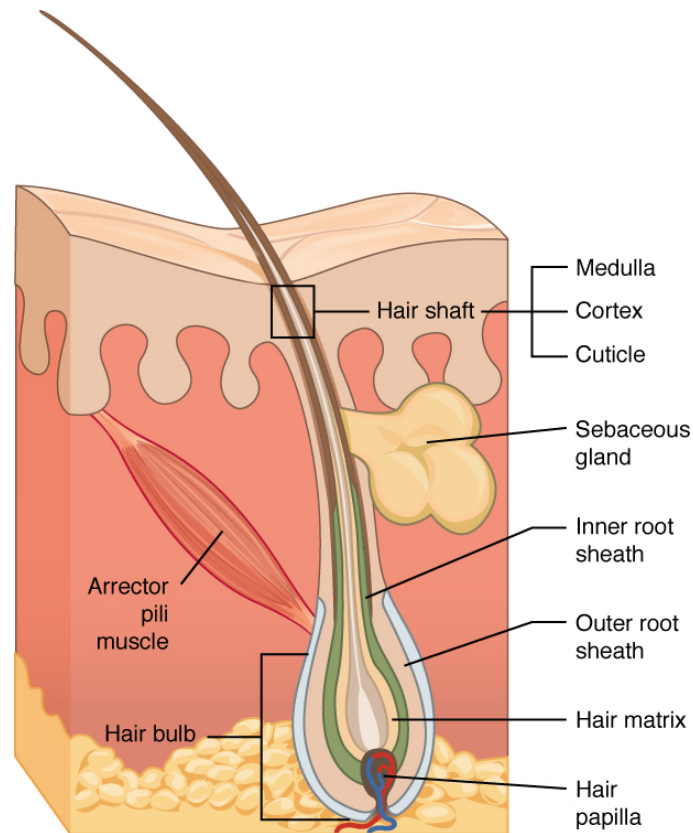
Figure 3.15 Hair. Hair follicles originate in the epidermis and have many different parts.

Just as the basal layer of the epidermis forms the layers of epidermis that get pushed to the surface as the dead skin on the surface sheds, the basal cells of the hair bulb divide and push cells outward in the hair root and shaft as the hair grows (**Figure 3.16**). As new cells are deposited at the hair bulb, the hair shaft is pushed through the follicle toward the surface. Keratinization is completed as the cells are pushed to the skin surface to form the shaft of hair that is externally visible. The external hair is completely dead and composed entirely of keratin. For this reason, our hair does not have sensation. Furthermore, you can cut your hair or shave without damaging the hair structure because the cut is superficial.

Figure 3.16 Hair Follicle. The slide shows a cross-section of a hair follicle. LM × 4. (Image credit: "Hair Follicle – Microscopic" by Whitney Menefee is licensed under CC BY 3.0 / A derivative from the original work)

Hair serves a variety of functions, including protection, sensory input, thermoregulation, and communication. For example, hair on the head protects the skull from the sun. The hair in the nose and ears, and around the eyes (eyelashes) defends the body by trapping and excluding dust particles that may contain allergens and microbes. Hair of the eyebrows prevents sweat and other particles from dripping into and bothering the eyes. Hair also has a sensory function due to sensory innervation by a hair root plexus surrounding the base of each hair follicle. Hair is extremely sensitive to air movement or other disturbances in the environment, much more so than the skin surface. This feature is also useful for the detection of the presence of insects or other potentially damaging substances on the skin surface. Each hair root is connected to a smooth muscle called the **arrector pili** that contracts in response to nerve signals from the sympathetic nervous system, making the external hair shaft "stand up." The primary purpose for this is to trap a layer of air to add insulation. This is visible in humans as goose bumps and even more obvious in animals with a heavier coat than most humans, such as dogs and cats that raise their fur when alarmed.

Sebaceous Glands

A **sebaceous gland** is a type of oil gland that is found all over the body and helps to lubricate and waterproof the skin and hair. Most sebaceous glands are associated with hair follicles (**Figure 3.16**). They generate and excrete sebum, a mixture of lipids, onto the skin surface, thereby naturally lubricating the dry and dead layer of keratinized cells of the stratum corneum, keeping it pliable. The fatty acids of sebum also have antibacterial properties, and prevent water loss from the skin in low-humidity environments. The secretion of sebum is stimulated by

hormones, many of which do not become active until puberty. Thus, sebaceous glands are relatively inactive during childhood.

Sweat Glands

When the body becomes warm, sweat glands produce sweat to cool the body. Sweat glands develop from epidermal projections into the dermis. There are two types of sweat glands, each secreting slightly different products. An **eccrine sweat gland** is type of gland that produces a hypotonic sweat for thermoregulation. These glands are found all over the skin's surface, but are especially abundant on the palms of the hand, the soles of the feet, and the forehead (**Figure 3.17**). They are coiled glands lying deep in the dermis, with the duct rising up to a pore on the skin surface, where the sweat is released. This type of sweat, released by exocytosis, is hypotonic and composed mostly of water, with some salt, antibodies, traces of metabolic waste, and dermicidin, an antimicrobial peptide. Eccrine glands are a primary component of thermoregulation in humans and thus help to maintain homeostasis.
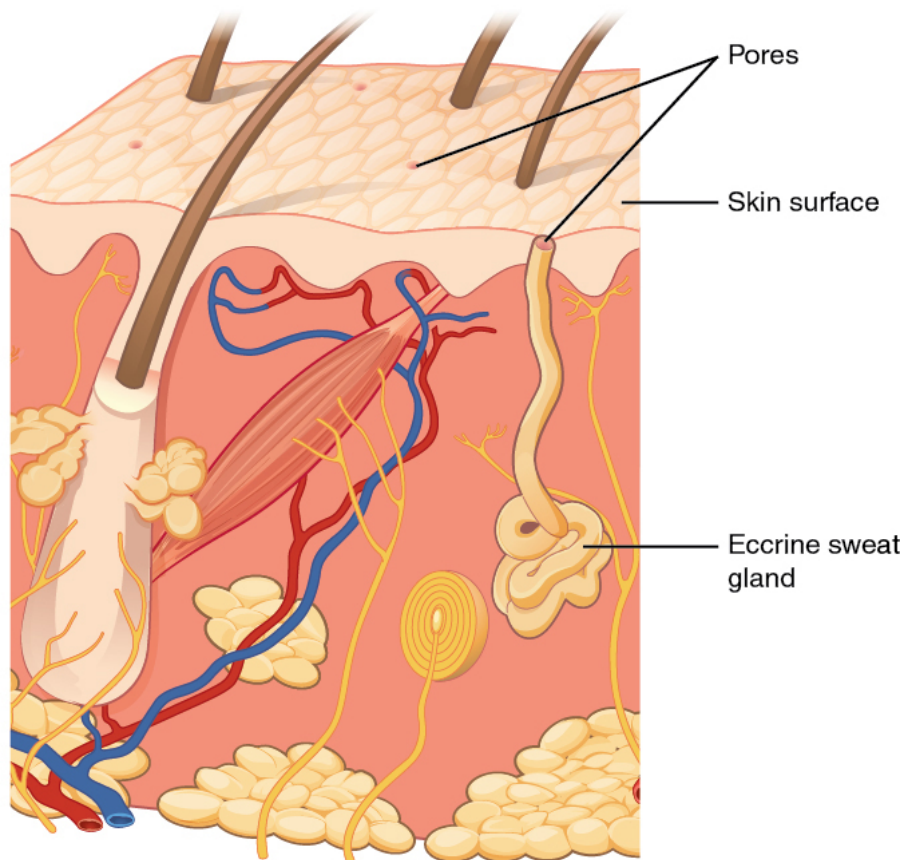
Figure 3.17 Eccrine Gland. Eccrine glands are coiled glands in the dermis that release sweat that is mostly water. (Image credit: "Eccrine gland" by OpenStax is licensed under CC BY 3.0)

An **apocrine sweat gland** is usually associated with hair follicles in densely hairy areas, such as armpits and genital regions. Apocrine sweat glands are larger than eccrine sweat glands and lie deeper in the dermis, sometimes even reaching the hypodermis, with the duct normally emptying into the hair follicle. In addition to water and salts, apocrine sweat includes organic compounds that make the sweat thicker and subject to bacterial

decomposition and subsequent smell. The release of this sweat is under both nervous and hormonal control, and plays a role in the poorly understood human pheromone response. Most commercial antiperspirants use an aluminum-based compound as their primary active ingredient to stop sweat. When the antiperspirant enters the sweat gland duct, the aluminum-based compounds precipitate due to a change in pH and form a physical block in the duct, which prevents sweat from coming out of the pore.

Sensory Structures

The skin acts as a sense organ because the epidermis, dermis, and the hypodermis contain specialized sensory nerve structures that detect touch, surface temperature, and pain. These receptors are more concentrated on the tips of the fingers, which are most sensitive to touch, especially the **tactile (Meissner) corpuscle** (**Figure 3.18**), which responds to light touch, and the **lamellated (Pacinian) corpuscle**, which responds to vibration. **Tactile (Merkel) cells**, seen scattered in the stratum basale, are also touch receptors. In addition to these specialized receptors, there are sensory nerves connected to each hair follicle, pain and temperature receptors scattered throughout the skin, and motor nerves innervating the arrector pili muscles and glands. This rich innervation helps you sense your environment and react accordingly.
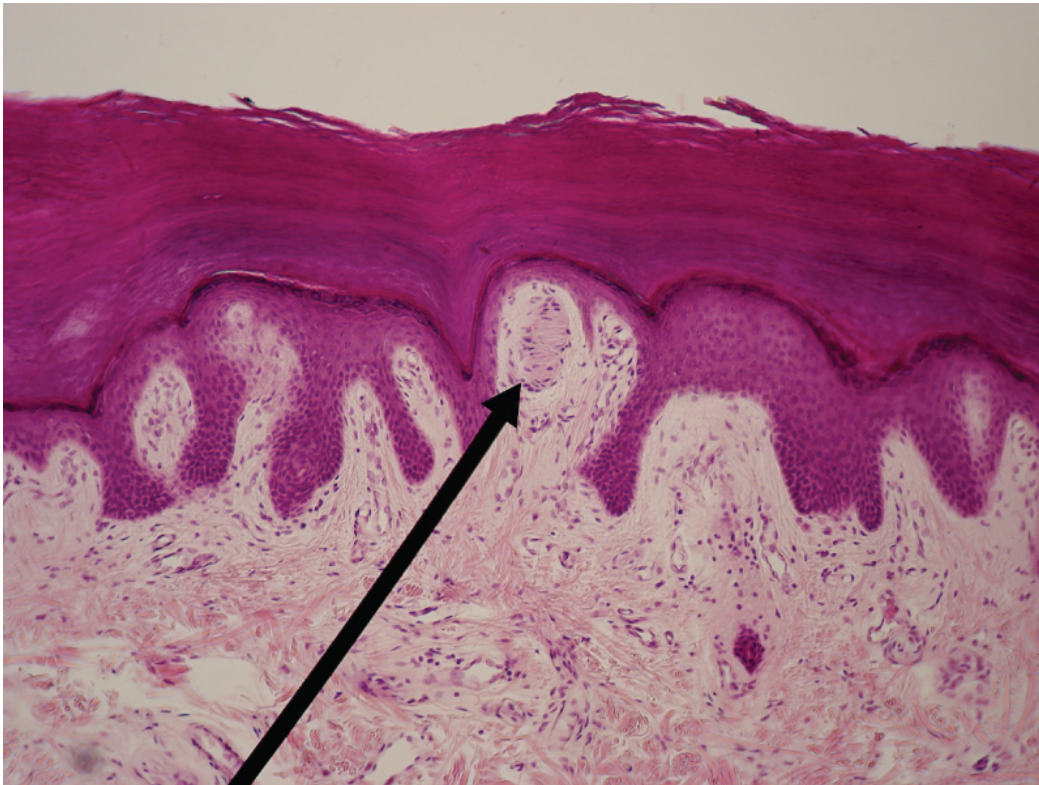
Figure 3.18 Light Micrograph of a Meissner Corpuscle. In this micrograph of a skin cross-section, you can see a Meissner corpuscle (arrow), a type of touch receptor located in a dermal papilla adjacent to the basement membrane and stratum basale of the overlying epidermis. LM × 100. (credit: "Wbensmith"/Wikimedia Commons)

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Lab 4: Skeletal System I - Bone Tissue and Axial Skeleton

Bone structures, Axial Skeleton

Learning Objectives

When you are prepared for the Test on Week 4 Learning Objectives in Week 5, you will be able to:

1. Identify components of long bone structure and their functions.
2. Identify components of bone tissue.
3. Identify zones of the epiphyseal plate and describe how the activities in each zone contribute to bone growth.
4. Identify the bones of the axial skeleton, including all of those in the skull.
5. Identify some of the important morphological features of the skull, which bones they are located in, and their functions (listed in the lab activity).
6. Identify the major sutures of the skull and fontanels of the infant skull.
7. Identify the major regions of the vertebral column, the rib cage, and the sternum.

The skeletal system forms the rigid internal framework of the body. It consists of the bones, cartilages, and ligaments. Bones support the weight of the body, allow for body movements, and protect internal organs. Cartilage provides flexible strength and support for body structures such as the thoracic cage, the external ear, and the trachea and larynx. At joints of the body, cartilage can also unite adjacent bones or provide cushioning between them. Ligaments are the strong connective tissue bands that hold the bones at a moveable joint together and serve to prevent excessive movements of the joint that would result in injury. Providing movement of the skeleton are the muscles of the body, which are firmly attached to the skeleton via connective tissue structures called tendons. As muscles contract, they pull on the bones to produce movements of the body. Thus, without a skeleton, you would not be able to stand, run, or even feed yourself!

The Functions of the Skeletal System

Bone, or **osseous tissue**, is a hard, dense connective tissue that forms most of the adult skeleton, the support structure of the body. In the areas of the skeleton where bones move (for example, the ribcage and joints), cartilage, a semi-rigid form of connective tissue, provides flexibility and smooth surfaces for movement. The skeletal system is the body system composed of bones and cartilage and performs the following critical functions for the human body:

- supports the body

- facilitates movement
- protects internal organs
- produces blood cells
- stores and releases minerals and fat

Support, Movement, and Protection

The most apparent functions of the skeletal system are the gross functions—those visible by observation. Simply by looking at a person, you can see how the bones support, facilitate movement, and protect the human body.

Just as the steel beams of a building provide a scaffold to support its weight, the bones and cartilage of your skeletal system compose the scaffold that supports the rest of your body. Without the skeletal system, you would be a limp mass of organs, muscle, and skin.

Bones also facilitate movement by serving as points of attachment for your muscles. While some bones only serve as a support for the muscles, others also transmit the forces produced when your muscles contract. From a mechanical point of view, bones act as levers and joints serve as fulcrums. Unless a muscle spans a joint and contracts, a bone is not going to move.

Bones also protect internal organs from injury by covering or surrounding them. For example, your ribs protect your lungs and heart, the bones of your vertebral column (spine) protect your spinal cord, and the bones of your cranium (skull) protect your brain.

Mineral Storage, Energy Storage, and Hematopoiesis

On a metabolic level, bone tissue performs several critical functions. For one, the bone matrix acts as a reservoir for a number of minerals important to the functioning of the body, especially calcium, and phosphorus. These minerals, incorporated into bone tissue, can be released back into the bloodstream to maintain levels needed to support physiological processes. Calcium ions, for example, are essential for muscle contractions and controlling the flow of other ions involved in the transmission of nerve impulses.

Bone also serves as a site for fat storage and blood cell production. The softer connective tissue that fills the interior of most bone is referred to as bone marrow. There are two types of bone marrow: yellow marrow and red marrow. **Yellow marrow** contains adipose tissue; the triglycerides stored in the adipocytes of the tissue can serve as a source of energy. **Red marrow** is where **hematopoiesis**—the production of blood cells—takes place. Red blood cells, white blood cells, and platelets are all produced in the red marrow.

Bone Classification

The 206 bones that compose the adult skeleton are divided into five categories based on their shapes (**Figure 4.1**). Their shapes and their functions are related such that each categorical shape of bone has a distinct function.
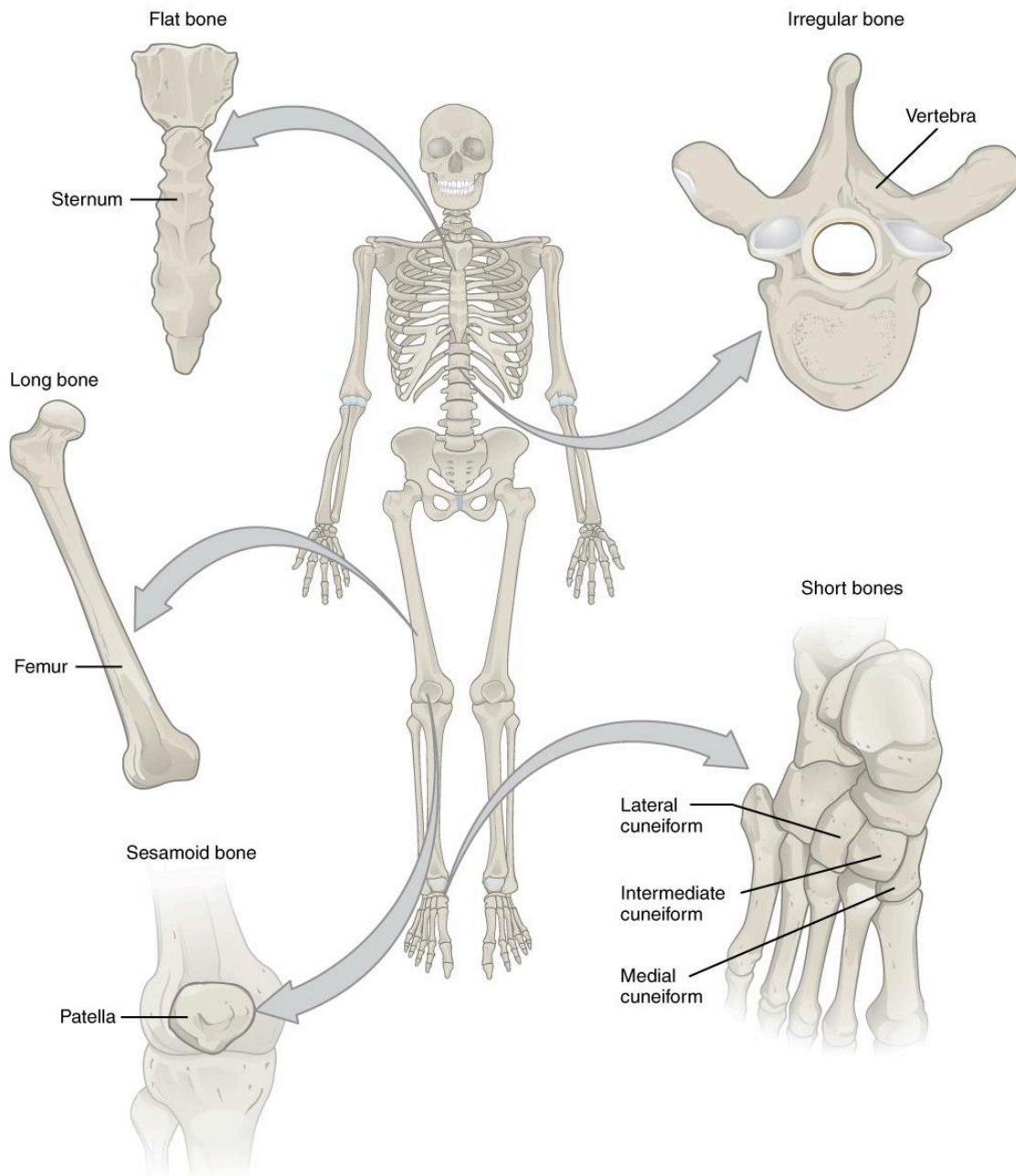
Figure 4.1 Classifications of Bones. Bones are classified according to their shape.

- **Long Bones –** A long bone is one that is cylindrical in shape, being longer than it is wide. Keep in mind, however, that the term describes the shape of a bone, not its size. Long bones are found in the arms (humerus, ulna, radius) and legs (femur, tibia, fibula), as well as in the fingers (metacarpals, phalanges) and toes (metatarsals, phalanges). Long bones function as levers; they move when muscles contract.
- **Short Bones –** A short bone is one that is cube-like in shape, being approximately equal in length, width, and thickness. The only short bones in the human skeleton are in the carpals of the wrists and the tarsals of the ankles. Short bones provide stability and support as well as some limited motion.
- **Flat Bones –** The term "flat bone" is somewhat of a misnomer because, although a flat bone is typically thin,

it is also often curved. Examples include the cranial (skull) bones, the scapulae (shoulder blades), the sternum (breastbone), and the ribs. Flat bones serve as points of attachment for muscles and often protect internal organs.

- **Irregular Bones** – An irregular bone is one that does not have any easily characterized shape and therefore does not fit any other classification. These bones tend to have more complex shapes, like the vertebrae that support the spinal cord and protect it from compressive forces. Many facial bones, particularly the ones containing sinuses, are classified as irregular bones.
- **Sesamoid Bones** – A sesamoid bone is a small, round bone that, as the name suggests, is shaped like a sesame seed. These bones form in tendons (the sheaths of tissue that connect bones to muscles) where a great deal of pressure is generated in a joint. The sesamoid bones protect tendons by helping them overcome compressive forces. Sesamoid bones vary in number and placement from person to person but are typically found in tendons associated with the feet, hands, and knees. The patellae (singular = patella) are the only sesamoid bones found in common with every person.

Bone Structure

Bone tissue (osseous tissue) differs greatly from other tissues in the body. Bone is hard and many of its functions depend on that characteristic hardness. Later discussions in this chapter will show that bone is also dynamic in that its shape adjusts to accommodate stresses. This section will examine the gross anatomy of bone first and then move on to its histology.

Gross Anatomy of Bone

The structure of a long bone allows for the best visualization of all of the parts of a bone (**Figure 4.2**). A long bone has two parts: the **diaphysis** and the **epiphysis**. The diaphysis is the tubular shaft that runs between the proximal and distal ends of the bone. The hollow region in the diaphysis is called the **medullary cavity**, which is filled with yellow marrow. The walls of the diaphysis are composed of dense and hard **compact bone**.
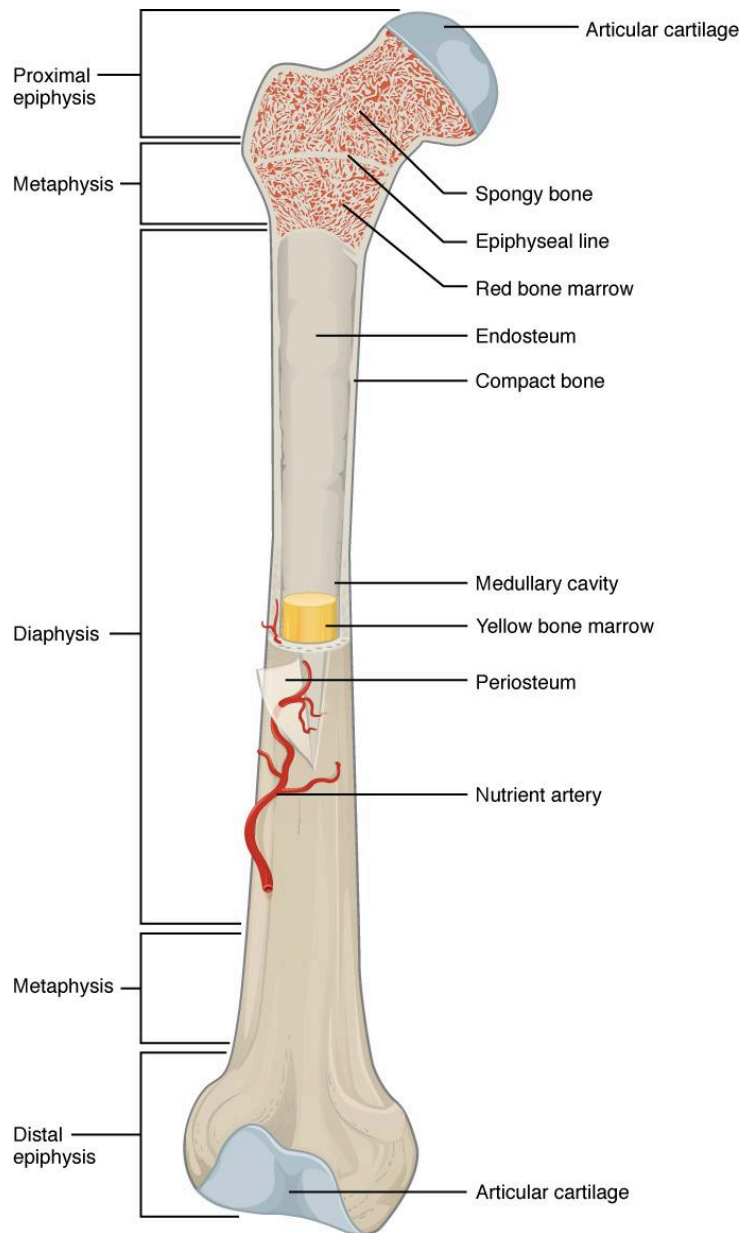
Figure 4.2 Anatomy of a Long Bone. A typical long bone shows the gross anatomical characteristics of bone.

The wider section at each end of the bone is called the epiphysis (plural = epiphyses), which is filled with spongy bone. Red marrow fills the spaces in the spongy bone (**Figure 4.3**). Each epiphysis meets the diaphysis at the metaphysis, the narrow area that contains the **epiphyseal plate** (growth plate), a layer of hyaline (transparent) cartilage in a growing bone. When the bone stops growing in early adulthood (approximately 18–21 years), the cartilage is replaced by osseous tissue and the epiphyseal plate becomes an epiphyseal line.
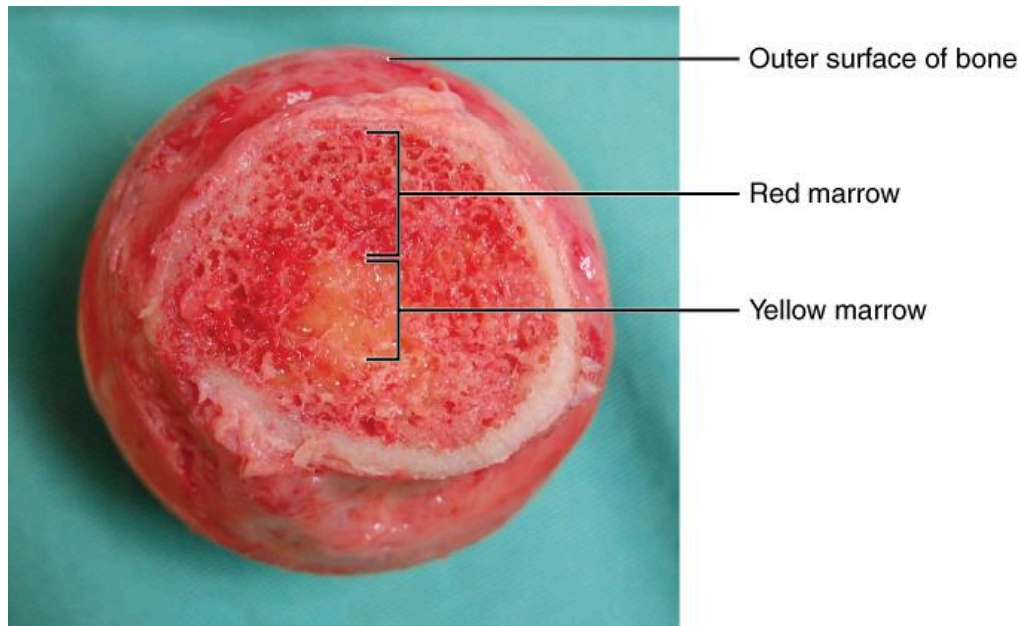
Figure 4.3 Head of Femur Showing Red and Yellow Marrow. The head of the femur contains both yellow and red marrow. Yellow marrow stores fat. Red marrow is responsible for hematopoiesis. (credit: modification of work by "stevenfruitsmaak"/Wikimedia Commons)

The medullary cavity has a delicate membranous lining called the **endosteum** (end- = "inside"; oste- = "bone"), where bone growth, repair, and remodeling occur. The outer surface of the bone is covered with a fibrous membrane called the **periosteum** (peri− = "around" or "surrounding"). The periosteum contains blood vessels, nerves, and lymphatic vessels that nourish compact bone. Tendons and ligaments also attach to bones at the periosteum. The periosteum covers the entire outer surface except where the epiphyses meet other bones to form joints. In this region, the epiphyses are covered with **articular cartilage**, a thin layer of cartilage that reduces friction and acts as a shock absorber.

Flat bones, like those of the cranium, consist of a layer of spongy bone, lined on either side by a layer of compact bone. The two layers of compact bone and the interior spongy bone work together to protect the internal organs. If the outer layer of a cranial bone fractures, the brain is still protected by the intact inner layer.

Bone Cells and Tissue

Bone contains a relatively small number of cells entrenched in a matrix of collagen fibers that provide a surface for inorganic salt crystals to adhere. These salt crystals form when calcium phosphate and calcium carbonate combine to create hydroxyapatite, which incorporates other inorganic salts like magnesium hydroxide, fluoride, and sulfate as it crystallizes, or calcifies, on the collagen fibers. The hydroxyapatite crystals give bones their hardness and strength, while the collagen fibers give them flexibility so that they are not brittle.

Although bone cells compose a small amount of the bone volume, they are crucial to the function of bones. Four types of cells are found within bone tissue: osteoblasts, osteocytes, osteogenic cells, and osteoclasts.

The **osteoblast** is the bone cell responsible for forming new bone and is found in the growing portions of bone,

including the periosteum and endosteum (**Figure 4.4**). Osteoblasts, which do not divide, synthesize and secrete the collagen matrix and calcium salts. As the secreted matrix surrounding the osteoblast calcifies, the osteoblast become trapped within it; as a result, it changes in structure and becomes an **osteocyte**, the primary cell of mature bone and the most common type of bone cell. Each osteocyte is located in a space called a **lacuna** and is surrounded by bone tissue. Osteocytes maintain the mineral concentration of the matrix via the secretion of enzymes. Like osteoblasts, osteocytes lack mitotic activity. They can communicate with each other and receive nutrients via long cytoplasmic processes that extend through **canaliculi** (singular = canaliculus), channels within the bone matrix.
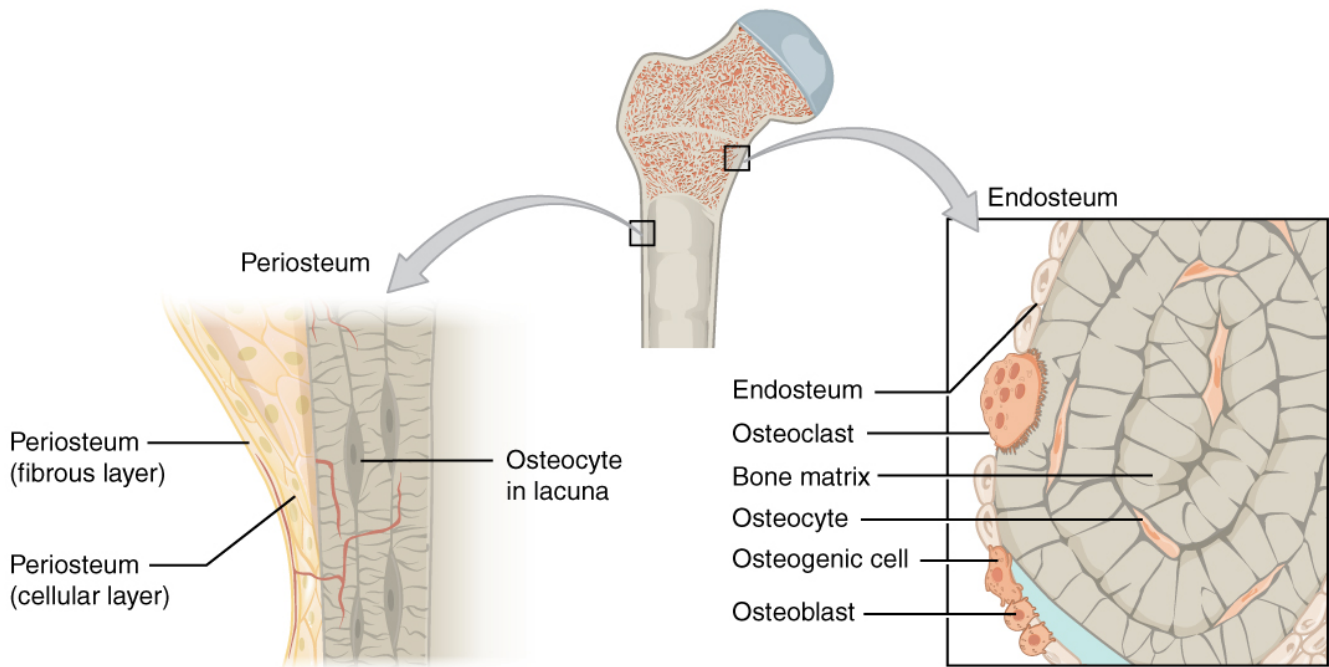
Figure 4.4 Periosteum, Endosteum, and Bone cells. The periosteum forms the outer surface of bone, and the endosteum lines the medullary cavity. Osteoblasts and osteoprogenitor cells can be found in both and are involved in bone growth and repair. Osteoclasts resorb bone during remodeling.

If osteoblasts and osteocytes are incapable of mitosis, then how are they replenished when old ones die? The answer lies in the properties of a third category of bone cells—the **osteogenic cell**. These osteogenic cells are undifferentiated with high mitotic activity and they are the only bone cells that divide. Immature osteogenic cells are found in the deep layers of the periosteum and the marrow. They differentiate and develop into osteoblasts.

The dynamic nature of bone means that new tissue is constantly formed, and old, injured, or unnecessary bone is dissolved for repair or for calcium release. The cell responsible for bone resorption, or breakdown, is the **osteoclast**. They are found on bone surfaces, are multinucleated, and originate from monocytes and macrophages, two types of white blood cells, not from osteogenic cells. Osteoclasts are continually breaking down old bone while osteoblasts are continually forming new bone. The ongoing balance between osteoblasts and osteoclasts is responsible for the constant but subtle reshaping of bone.

Compact and Spongy Bone

The differences between compact and spongy bone are best explored via their histology. Most bones contain

compact and spongy osseous tissue, but their distribution and concentration vary based on the bone's overall function. Compact bone is dense so that it can withstand compressive forces, while spongy (cancellous) bone has open spaces and supports shifts in weight distribution.

Compact Bone

Compact bone is the denser, stronger of the two types of bone tissue (**Figure 4.5**). It can be found under the periosteum and in the diaphyses of long bones, where it provides support and protection.
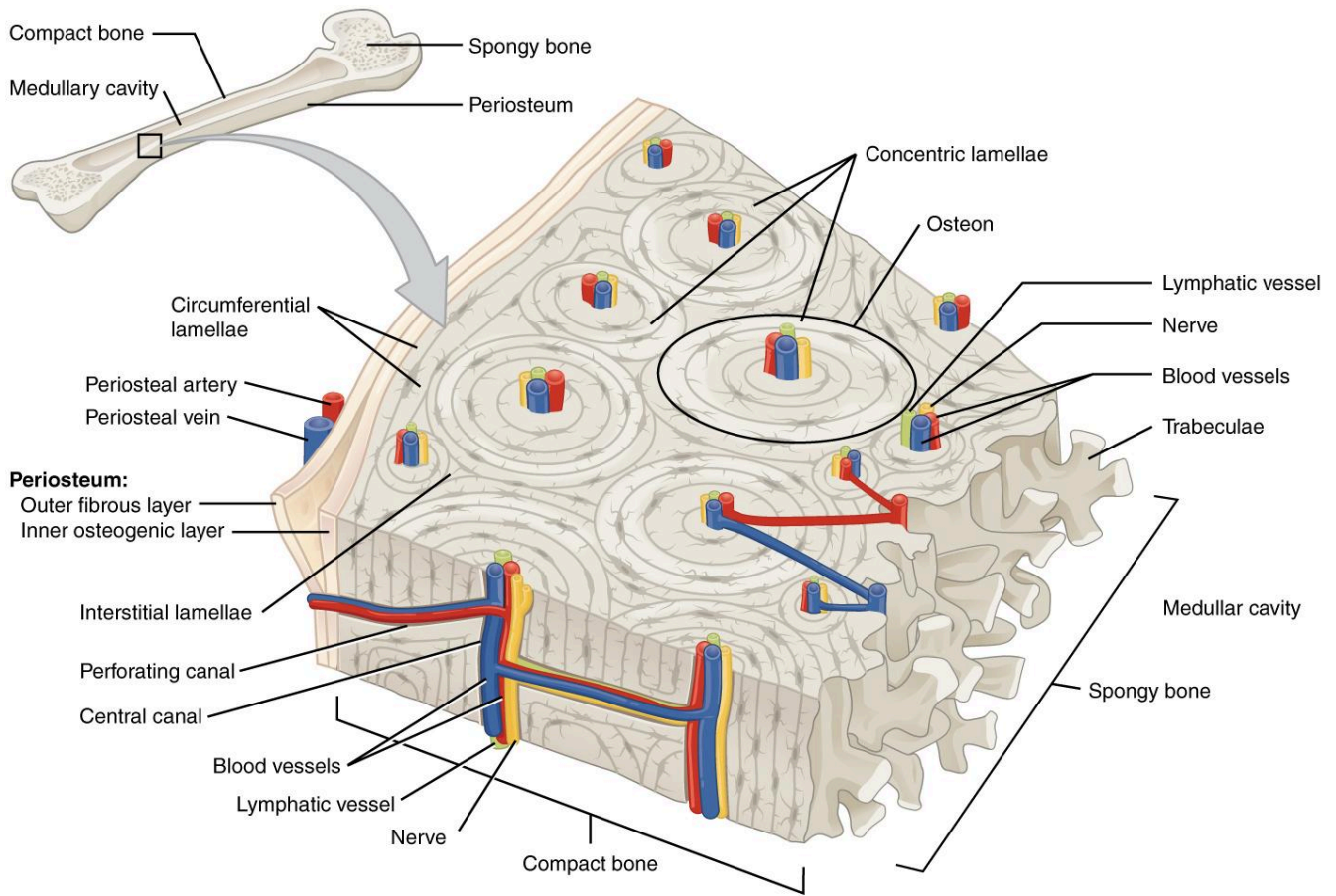
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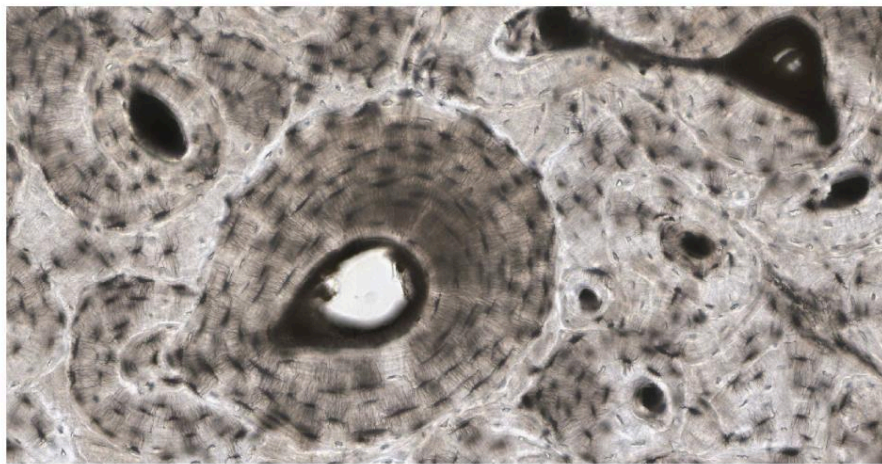
(b)

Figure 4.5 Diagram of Compact Bone. This cross-sectional view of compact bone shows the basic structural unit, the osteon.

The microscopic structural unit of compact bone is called an **osteon**, or Haversian system. Each osteon is composed of concentric rings of calcified matrix called lamellae (singular = lamella). Running down the center of each osteon is the **central canal**, or Haversian canal, which contains blood vessels, nerves, and lymphatic vessels. These vessels and nerves branch off at right angles through a **perforating canal**, also known as Volkmann's canals, to extend to the periosteum and endosteum.

The osteocytes are located inside spaces called **lacunae** (singular = lacuna), found at the borders of adjacent lamellae. **Canaliculi** connect with the canaliculi of other lacunae and eventually with the central canal. This system allows nutrients to be transported to the osteocytes and wastes to be removed from them.

Spongy Bone

Like compact bone, **spongy bone**, also known as cancellous bone, contains osteocytes, but they are not arranged in concentric circles. Instead, the osteocytes are found in a lattice-like network of matrix spikes called **trabeculae** (singular = trabecula) (**Figure 4.6**). The trabeculae may appear to be a random network, but each trabecula forms along lines of stress to provide strength to the bone. The spaces of the trabeculated network provide balance to the dense and heavy compact bone by making bones lighter so that muscles can move them more easily. In addition, the spaces in some spongy bones contain red marrow, protected by the trabeculae, where hematopoiesis occurs.
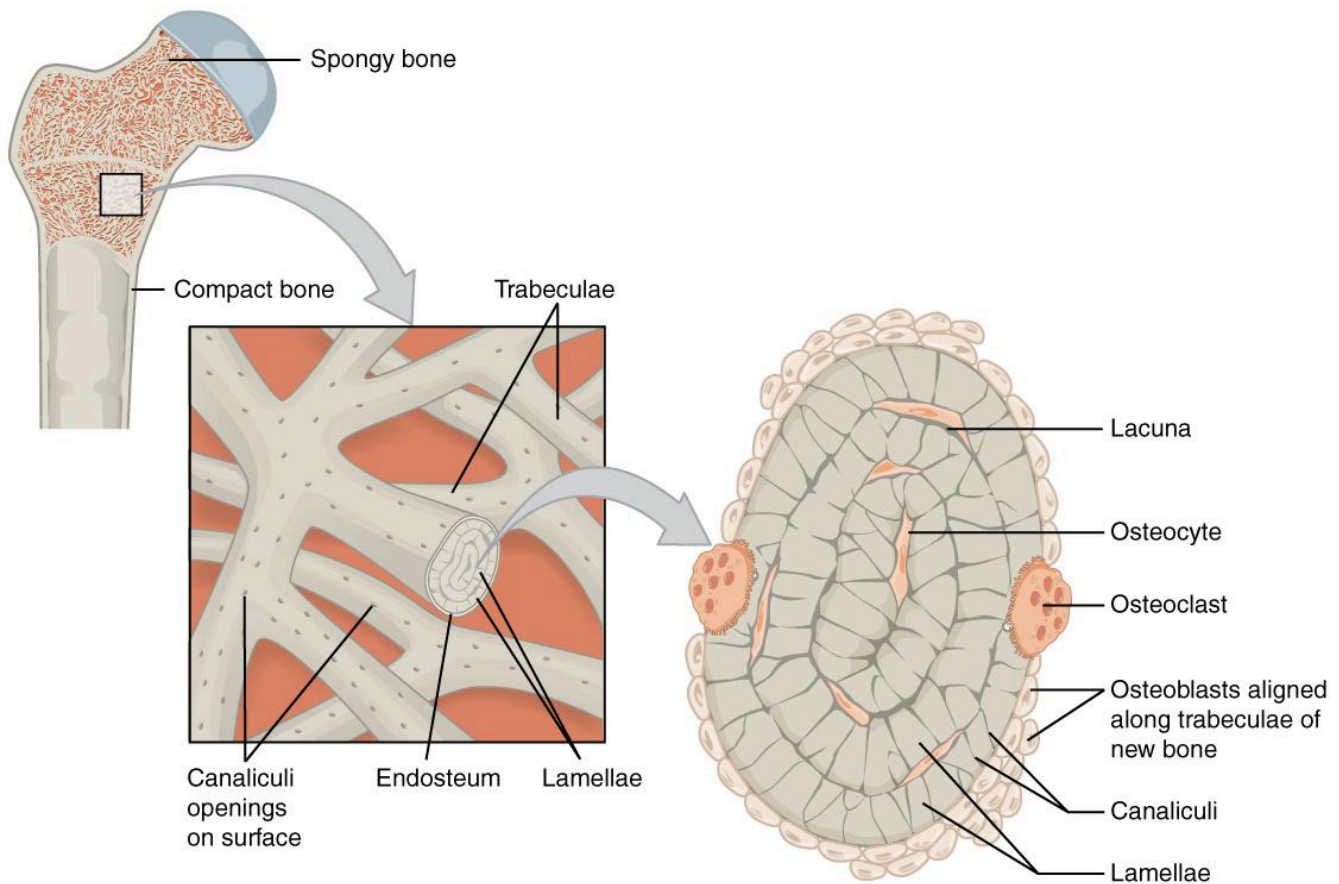
Figure 4.6 Diagram of Spongy Bone. Spongy bone is composed of trabeculae that contain the osteocytes. Red marrow fills the spaces in some bones.

How Bones Grow in Length

The **epiphyseal plate** is the area of growth in a long bone. It is a layer of hyaline cartilage where ossification occurs in immature bones. On the epiphyseal side of the epiphyseal plate, cartilage is formed. On the diaphyseal side, cartilage is ossified, and the diaphysis grows in length. The epiphyseal plate is composed of four zones of cells and activity (**Figure 4.7**). The **reserve zone (zone of resting cartilage)** is the region closest to the epiphyseal end of the plate and contains small chondrocytes within the matrix. These chondrocytes do not participate in bone growth but secure the epiphyseal plate to the osseous tissue of the epiphysis.
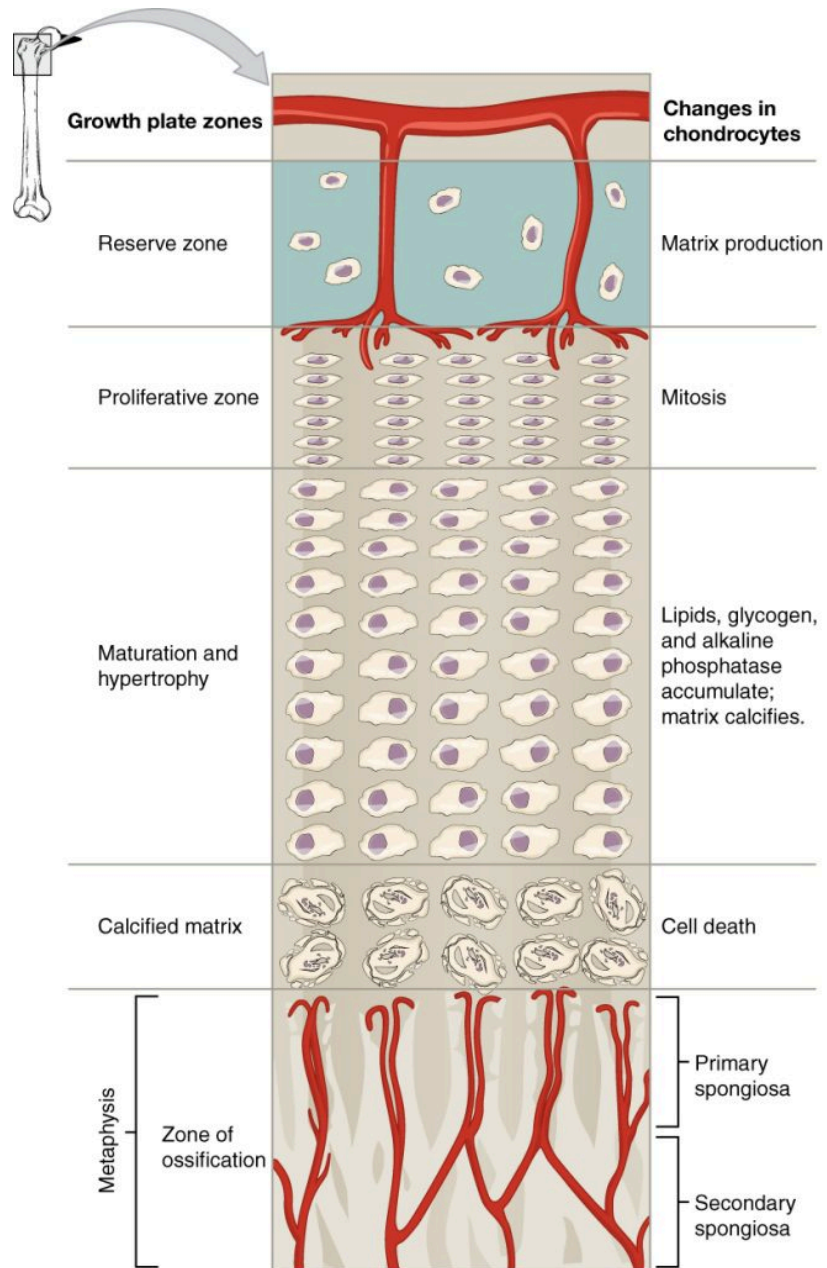
Figure 4.7 Longitudinal Bone Growth. The epiphyseal plate is responsible for longitudinal bone growth.

The **proliferative zone (zone of proliferating cartilage)** is the next layer toward the diaphysis and contains stacks of slightly larger chondrocytes. It makes new chondrocytes (via mitosis) to replace those that die at the diaphyseal end of the plate. Chondrocytes in the next layer, the **zone of maturation and hypertrophy (zone of hypertrophic cartilage)**, are older and larger than those in the proliferative zone. The more mature cells are situated closer to the diaphyseal end of the plate. The longitudinal growth of bone is a result of cellular division in the proliferative zone and the maturation of cells in the zone of maturation and hypertrophy.

Most of the chondrocytes in the **zone of calcified matrix (zone of calcified cartilage)**, the zone closest to the

diaphysis, are dead because the matrix around them has calcified. Capillaries and osteoblasts from the diaphysis penetrate this zone, and the osteoblasts secrete bone tissue on the remaining calcified cartilage. Thus, the zone of calcified matrix connects the epiphyseal plate to the diaphysis. A bone grows in length when osseous tissue is added to the diaphysis.

Bones continue to grow in length until early adulthood. The rate of growth is controlled by hormones, which will be discussed later. When the chondrocytes in the epiphyseal plate cease their proliferation and bone replaces the cartilage, longitudinal growth stops. All that remains of the epiphyseal plate is the **epiphyseal line** (**Figure 4.8**).
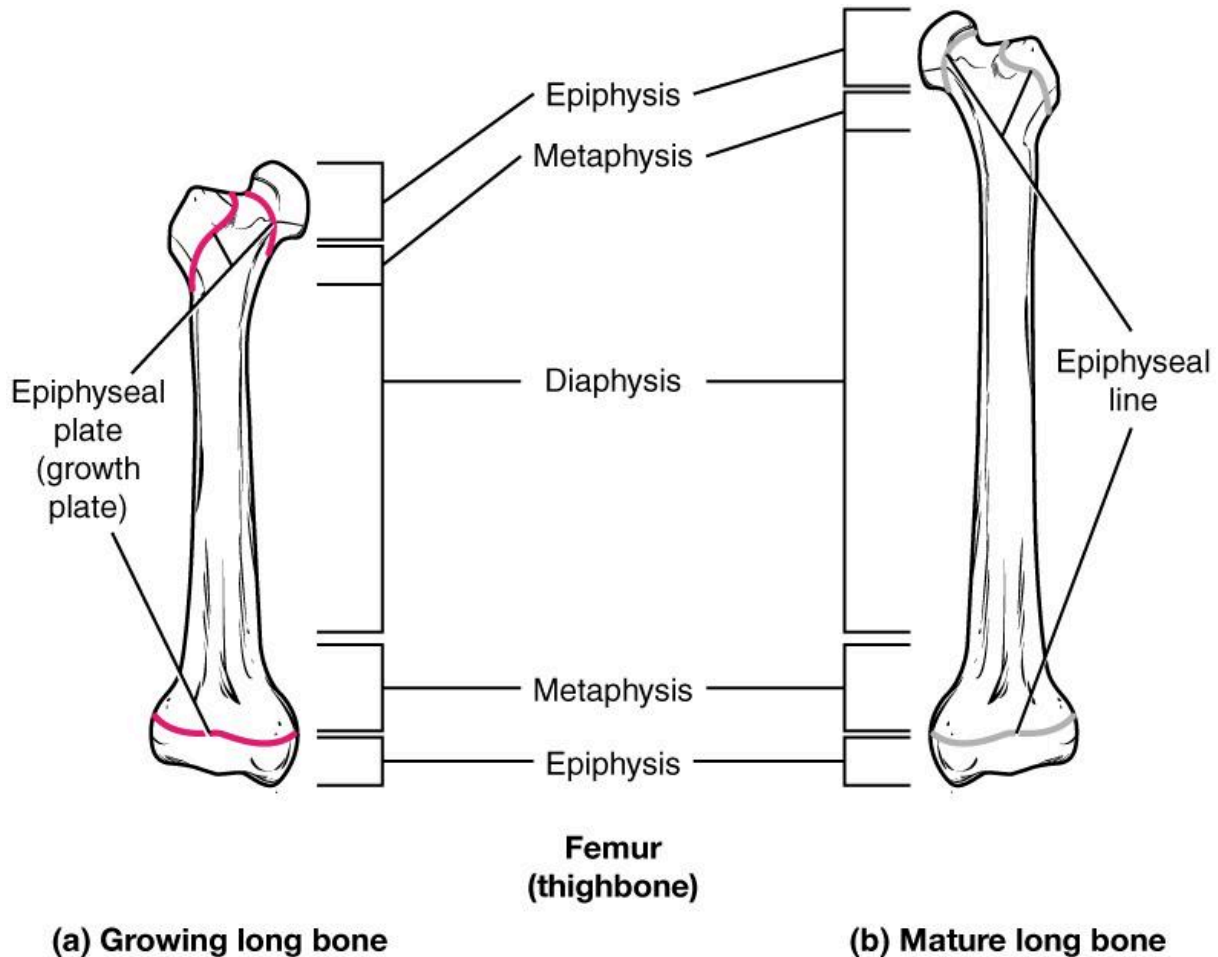
Figure 4.8 Progression from Epiphyseal Plate to Epiphyseal Line. As a bone matures, the epiphyseal plate progresses to an epiphyseal line. (a) Epiphyseal plates are visible in a growing bone. (b) Epiphyseal lines are the remnants of epiphyseal plates in a mature bone.

Divisions of the Skeletal System

The skeletal system includes all of the bones, cartilages, and ligaments of the body that support and give shape to the body and body structures. The **skeleton** consists of the bones of the body. For adults, there are 206 bones in the skeleton. Younger individuals have higher numbers of bones because some bones fuse together during childhood and adolescence to form an adult bone. The primary functions of the skeleton are to provide a rigid,

internal structure that can support the weight of the body against the force of gravity, and to provide a structure upon which muscles can act to produce movements of the body. The lower portion of the skeleton is specialized for stability during walking or running. In contrast, the upper skeleton has greater mobility and ranges of motion, features that allow you to lift and carry objects or turn your head and trunk.

In addition to providing for support and movements of the body, the skeleton has protective and storage functions. It protects the internal organs, including the brain, spinal cord, heart, lungs, and pelvic organs. The bones of the skeleton serve as the primary storage site for important minerals such as calcium and phosphate. The bone marrow found within bones stores fat and houses the blood-cell producing tissue of the body.

The skeleton is subdivided into two major divisions—the axial and appendicular.

The Axial Skeleton

The skeleton is subdivided into two major divisions—the axial and appendicular. The **axial skeleton** forms the vertical, central axis of the body and includes all bones of the head, neck, chest, and back (**Figure 4.9**). It serves to protect the brain, spinal cord, heart, and lungs. It also serves as the attachment site for muscles that move the head, neck, and back, and for muscles that act across the shoulder and hip joints to move their corresponding limbs.

The axial skeleton of the adult consists of 80 bones, including the **skull**, the **vertebral column**, and the **thoracic cage**. The skull is formed by 22 bones. Also associated with the head are an additional seven bones, including the **hyoid bone** and the **ear ossicles** (three small bones found in each middle ear). The vertebral column consists of 24 bones, each called a **vertebra**, plus the **sacrum** and **coccyx**. The thoracic cage includes the 12 pairs of **ribs**, and the **sternum**, the flattened bone of the anterior chest.

Skull
Cranial portion
Facial portion

Pectoral (shoulder) girdle
Clavicle
Scapula
Thoracic cage
Sternum
Ribs
Upper limb
Humerus

Vertebral column

Ulna
Radius
Carpals

Pelvic girdle (hip bones)

Metacarpals

Phalanges

Vertebral column

Pelvic girdle (hip bones)

Lower limb
Femur
Patella

Tibia

Fibula

Tarsals
Metatarsals
Phalanges

Key
Axial skeleton
Appendicular skeleton

Anterior view

Posterior view

Figure 4.9 Axial and Appendicular Skeleton. The axial skeleton supports the head, neck, back, and chest and thus forms the vertical axis of the body. It consists of the skull, vertebral column (including the sacrum and coccyx), and the thoracic cage, formed by the ribs and sternum. The appendicular skeleton is made up of all bones of the upper and lower limbs.

The Appendicular Skeleton

The **appendicular skeleton** includes all bones of the upper and lower limbs, plus the bones that attach each limb

to the axial skeleton. There are 126 bones in the appendicular skeleton of an adult. The bones of the appendicular skeleton are covered in the next chapter.

Bone Markings

Before we start learning the morphology of individual bones, you should familiarize yourself with the general terms used to describe bone features. The surface features of bones vary considerably, depending on the function and location in the body. There are three general classes of bone markings: (1) articulations, (2) projections, and (3) holes. As the name implies, an **articulation** is where two bone surfaces come together (articulus = "joint"). These surfaces tend to conform to one another, such as one being rounded and the other cupped, to facilitate the function of the articulation. A **projection** is an area of a bone that projects above the surface of the bone. These are the attachment points for tendons and ligaments. In general, their size and shape is an indication of the forces exerted through the attachment to the bone. A **hole** is an opening or groove in the bone that allows blood vessels and nerves to enter the bone. As with the other markings, their size and shape reflect the size of the vessels and nerves that penetrate the bone at these points.

Commonly used terms for bone markings are illustrated in **Figure 4.10** and described in **Table 4.1**.

Examples of processes formed where
tendons or ligaments attach

Fovea capitis

Head

Tubercle

Sulcus

Tuberosity

Fossa

Humerus

Tubercle   Condyle

Facet

Femur

Condyles

Examples of processes formed to
articulate with adjacent bones

Examples of an elevation or depression

Crest   Fossa

Pelvis

Examples of openings

Sinus

Foramen

Canal

Fissure

Protuberance

Skull

Figure 4.10 Bone Features. The surface features of bones depend on their function, location, attachment of ligaments and tendons, or the penetration of blood vessels and nerves.

Marking	Description	Example
Articulations	Where two bones meet	Knee joint
Head	Prominent rounded surface	Head of femur
Facet	Flat surface	Vertebrae
Condyle	Rounded surface	Occipital condyles
Projections	Raised markings	Spinous process of the vertebrae
Protuberance	Protruding	Chin
Process	Prominence feature	Transverse process of vertebra
Spine	Sharp process	Ischial spine
Tubercle	Small, rounded process	Tubercle of humerus
Tuberosity	Rough surface	Deltoid tuberosity
Line	Slight, elongated ridge	Temporal lines of the parietal bones
Crest	Ridge	Iliac crest
Holes	Holes and depressions	Foramen (holes through which blood vessels can pass through)
Fossa	Elongated basin	Mandibular fossa
Fovea	Small pit	Fovea capitis on the head of the femur
Sulcus	Groove	Sigmoid sulcus of the temporal bones
Canal	Passage in bone	Auditory canal
Fissure	Slit through bone	Auricular fissure
Foramen	Hole through bone	Foramen magnum in the occipital bone
Meatus	Opening into canal	External auditory meatus
Sinus	Air-filled space in bone	Nasal sinus

Table 4.1 Bone Markings

The Skull

The **cranium** (skull) is the skeletal structure of the head that supports the face and protects the brain. It is subdivided into the **facial bones** and the **brain case**, or neurocranium (**Figure 4.11**). The facial bones underlie the facial structures, form the nasal cavity, enclose the eyeballs, and support the teeth of the upper and lower jaws. The rounded brain case surrounds and protects the brain and houses the middle and inner ear structures.

In the adult, the skull consists of 22 individual bones, 21 of which are immobile and united into a single unit. The 22nd bone is the **mandible** (lower jaw), which is the only moveable bone of the skull.
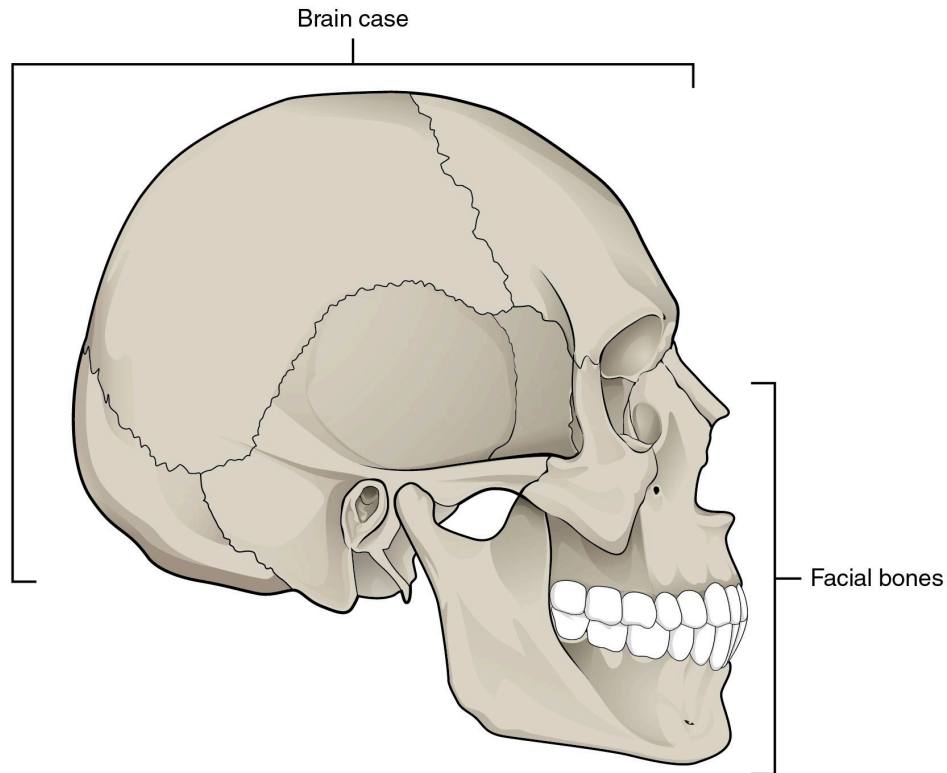
Figure 4.11 Parts of the Skull. The skull consists of the rounded brain case that houses the brain and the facial bones that form the upper and lower jaws, nose, orbits, and other facial structures.

Anterior View of Skull

The anterior skull consists of the facial bones and provides the bony support for the eyes and structures of the face. This view of the skull is dominated by the openings of the orbits and the nasal cavity. Also seen are the upper and lower jaws, with their respective teeth (**Figure 4.12**).

The **orbit** is the bony socket that houses the eyeball and muscles that move the eyeball or open the upper eyelid. The upper margin of the anterior orbit is the **supraorbital margin**. Located near the midpoint of the supraorbital margin is a small opening called the **supraorbital foramen**. This provides for passage of a sensory nerve to the skin of the forehead. Below the orbit is the **infraorbital foramen**, which is the point of emergence for a sensory nerve that supplies the anterior face below the orbit.
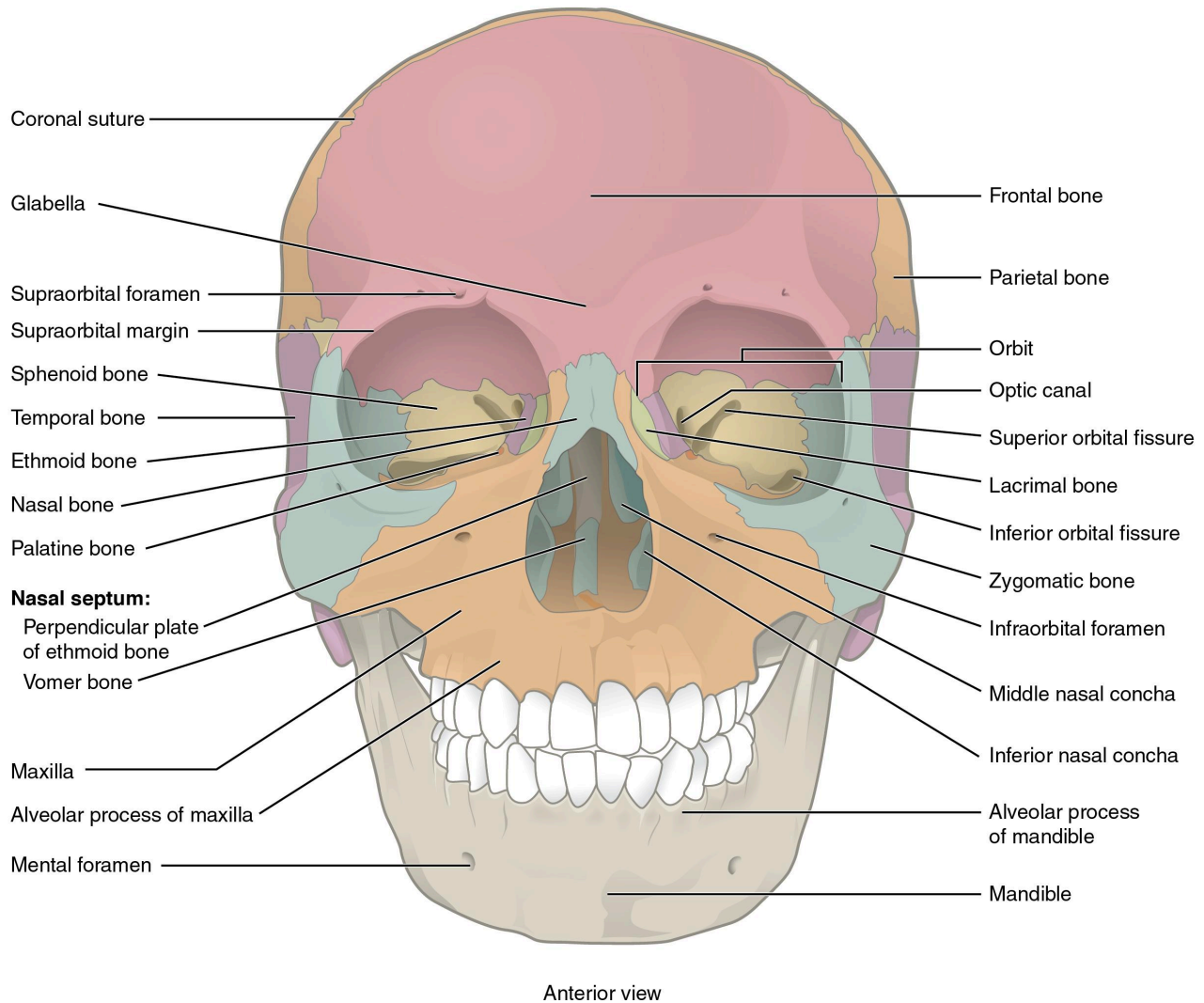
Figure 4.12 Anterior View of Skull An anterior view of the skull shows the bones that form the forehead, orbits (eye sockets), nasal cavity, nasal septum, and upper and lower jaws.

Inside the nasal area of the skull, the **nasal cavity** is divided into halves by the **nasal septum**. The upper portion of the nasal septum is formed by the **perpendicular plate of the ethmoid bone** and the lower portion is the **vomer bone**. Each side of the nasal cavity is triangular in shape, with a broad inferior space that narrows superiorly. When looking into the nasal cavity from the front of the skull, two bony plates are seen projecting from each lateral wall. The larger of these is the **inferior nasal concha**, an independent bone of the skull. Located above the inferior concha are the **middle nasal concha** and **superior nasal concha**, both of which are part of the ethmoid bone.

Lateral View of Skull

A view of the lateral skull is dominated by the large, rounded brain case above and the upper and lower jaws with their teeth below (**Figure 4.13**). Separating these areas is the bridge of bone called the zygomatic arch. The **zygomatic arch** is the bony arch on the side of the skull that spans from the area of the cheek to just above the ear canal. It is formed by the junction of processes coming from two bones: the zygomatic and temporal bones.
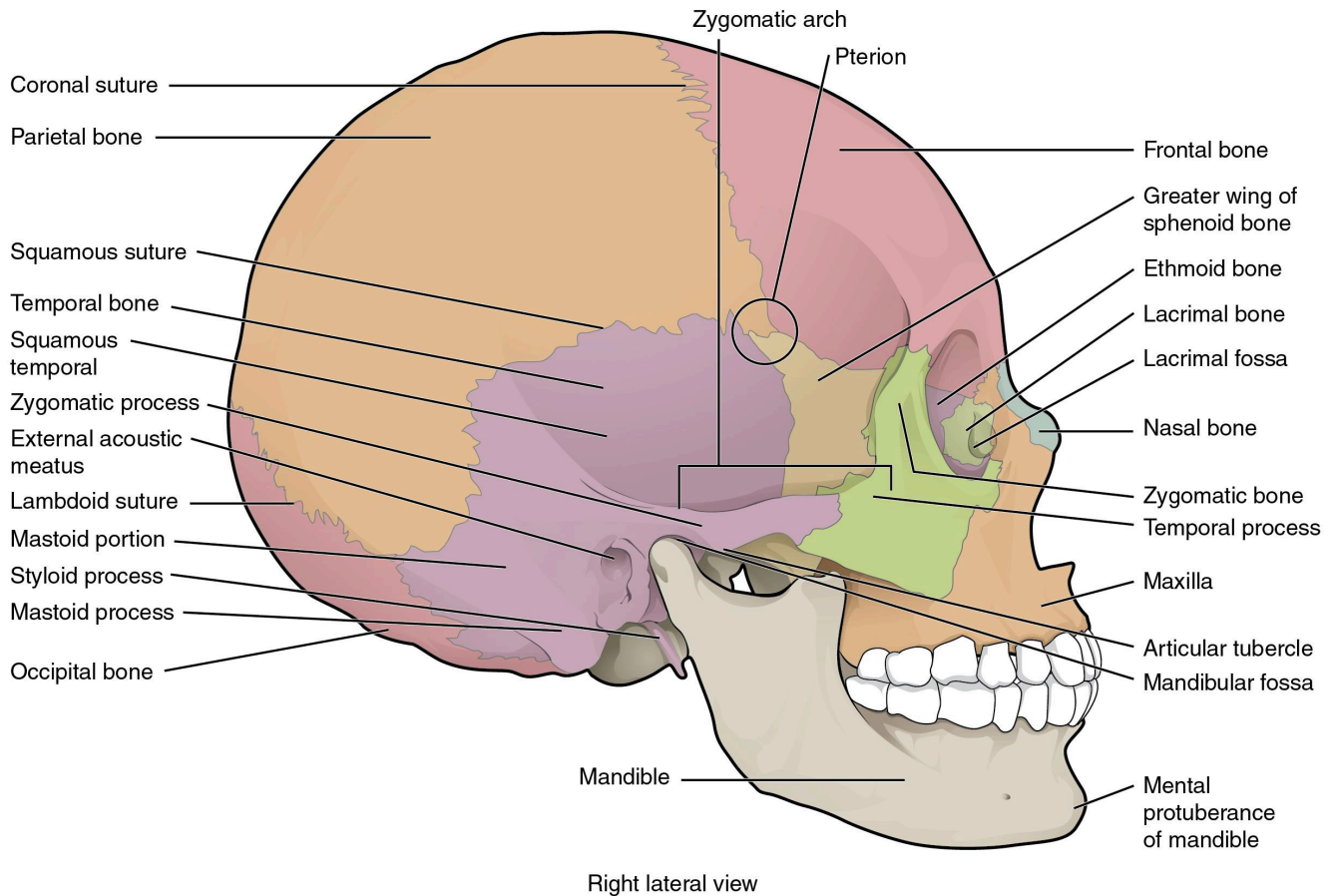
Figure 4.13 Lateral View of Skull The lateral skull shows the large rounded brain case, zygomatic arch, and the upper and lower jaws. The zygomatic arch is formed jointly by the zygomatic process of the temporal bone and the temporal process of the zygomatic bone. The shallow space above the zygomatic arch is the temporal fossa.

Bones of the Brain Case

The brain case contains and protects the brain. The interior space that is almost completely occupied by the brain is called the **cranial cavity**. This cavity is bounded superiorly by the rounded top of the skull, and the lateral and posterior sides of the skull. The bones that form the top and sides of the brain case are usually referred to as the "flat" bones of the skull. The floor of the brain case is referred to as the base of the skull. This is a complex area that varies in depth and has numerous openings for the passage of cranial nerves, blood vessels, and the spinal cord.

The brain case consists of eight bones. These include the paired parietal and temporal bones, plus the unpaired frontal, occipital, sphenoid, and ethmoid bones.

Parietal Bone

The **parietal bone** forms most of the upper lateral side of the skull (see **Figure 4.13**). These are paired bones,

with the right and left parietal bones joining together at the top of the skull. Each parietal bone is also bounded anteriorly by the frontal bone, inferiorly by the temporal bone, and posteriorly by the occipital bone.

Temporal Bone

The **temporal bone** forms the lower lateral side of the skull (see **Figure 4.13**). Common wisdom has it that the temporal bone (temporal = "time") is so named because this area of the head (the temple) is where hair typically first turns gray, indicating the passage of time.

The temporal bone has a complex morphology. Some of the important landmarks of the temporal bone, as shown in **Figures 4.13-4.14**, include the following:

- **External acoustic meatus** (ear canal)—This is the large opening on the lateral side of the skull that is associated with the ear. It leads to the interior of the temporal bone, where the middle and inner ears are housed.
- **Internal acoustic meatus**—This opening is located inside the cranial cavity, on the medial side of the petrous ridge. It connects to the middle and inner ear cavities of the temporal bone.
- **Mandibular fossa**—This is the deep, oval-shaped depression located on the external base of the skull, just in front of the external acoustic meatus. The mandible (lower jaw) joins with the skull at this site as part of the temporomandibular joint, which allows for movements of the mandible during opening and closing of the mouth.
- **Mastoid process –** This is a large prominence projecting from the posterior and inferior region of the temporal bone. It is a muscle attachment site and can easily be felt on the side of the head just behind your earlobe.
- **Styloid process**—Posterior to the mandibular fossa on the external base of the skull is an elongated, downward bony projection called the styloid process, so named because of its resemblance to a stylus (a pen or writing tool). This structure serves as an attachment site for several small muscles and for a ligament that supports the hyoid bone of the neck.
- **Carotid canal**—The carotid canal is a zig-zag shaped tunnel that provides passage through the base of the skull for one of the major arteries that supplies the brain. Its entrance is located on the outside base of the skull, anteromedial to the styloid process. The canal then runs anteromedially within the bony base of the skull, and then turns upward to its exit in the floor of the middle cranial cavity, above the foramen lacerum.

(a) Inferior view

Vomer

Zygomatic arch

View

Sphenoid bone
Foramen spinosum
Foramen lacerum
Jugular foramen
Occipital condyle
Temporal bone
Foramen magnum
Occipital bone
Superior nuchal line

Maxilla:
Palatine process
Zygomatic bone
Palatine bone (horizontal plate)
Medial and lateral pterygoid plates
Articular tubercle
Foramen ovale
Mandibular fossa
External auditory meatus
Mastoid process
Styloid process
Stylomastoid foramen
Entrance to carotid canal
External occipital protuberance

(b) Superior view

View

Transverse plane

Superior orbital fissure

Foramen rotundum
Foramen ovale
Foramen spinosum
Internal acoustic meatus
Hypoglossal canal
Foramen magnum
Occipital bone

Frontal bone

Ethmoid bone:
Crista galli
Cribriform plate

Sphenoid bone:
Lesser wing
Hypophyseal fossa — Sella turcica

Foramen lacerum and exit of carotid canal

Temporal bone

Petrous portion (petrous ridge)

Jugular foramen

Parietal bone

Figure 4.14 External and Internal Views of Base of Skull. (a) The hard palate is formed anteriorly by the palatine processes of the maxilla bones and posteriorly by the horizontal plate of the palatine bones. (b)

The complex floor of the cranial cavity is formed by the frontal, ethmoid, sphenoid, temporal, and occipital bones.

Frontal Bone

The **frontal bone** is the single bone that forms the forehead. At its anterior midline, between the eyebrows, there is a slight depression called the glabella (see **Figure 4.12**). The frontal bone also forms the **supraorbital margin** of the orbit. Near the middle of this margin, is the **supraorbital foramen**, the opening that provides passage for a sensory nerve to the forehead. The frontal bone is thickened just above each supraorbital margin, forming rounded brow ridges. These are located just behind your eyebrows and vary in size among individuals, although they are generally larger in males. Inside the cranial cavity, the frontal bone extends posteriorly. This flattened region forms both the roof of the orbit below and the floor of the anterior cranial cavity above (see **Figure 4.14**).

Occipital Bone

The **occipital bone** is the single bone that forms the posterior skull and posterior base of the cranial cavity (**Figure 4.15**; see also **Figure 4.14**). On the base of the skull, the occipital bone contains the large opening of the **foramen magnum**, which allows for passage of the spinal cord as it exits the skull. On either side of the foramen magnum is an oval-shaped **occipital condyle**. These condyles form joints with the first cervical vertebra (C1) and thus support the skull on top of the vertebral column.
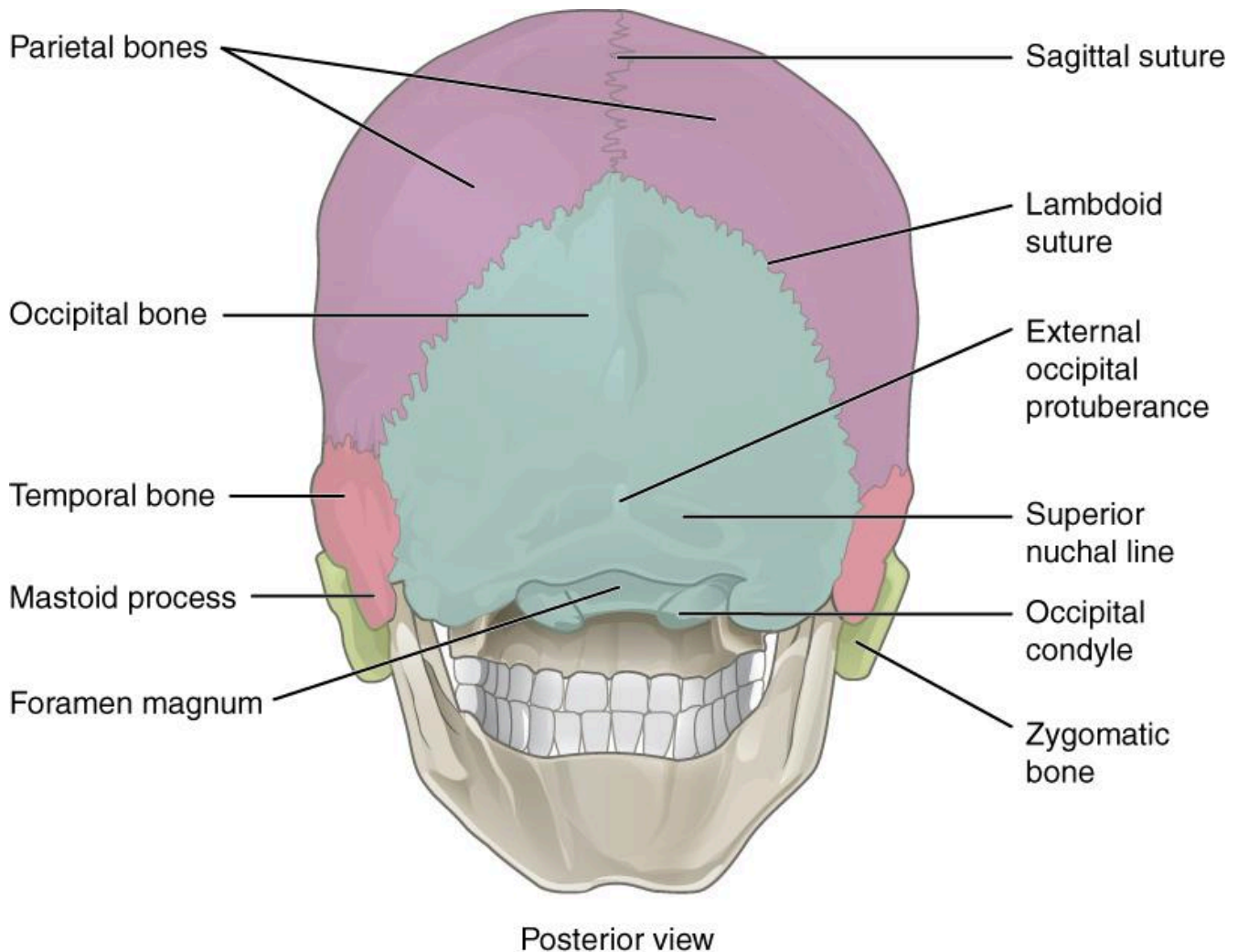
Figure 4.15 Posterior View of Skull. This view of the posterior skull shows attachment sites for muscles and joints that support the skull.

Sphenoid Bone

The **sphenoid bone** is a single, complex bone of the central skull (best seen in internal view, **Figure 4.14**). It serves as a "keystone" bone, because it joins with almost every other bone of the skull. The sphenoid forms much of the base of the central skull and also extends laterally to contribute to the sides of the skull (see **Figure 4.13**). Inside the cranial cavity, the **sella turcica** ("Turkish saddle") is located centrally. This bony region of the sphenoid bone is named for its resemblance to the horse saddles used by the Ottoman Turks, with a high back and a tall front. The rounded depression in the floor of the sella turcica houses the pea-sized pituitary (hypophyseal) gland in the hypophyseal fossa. Running through the sphenoid are two **optic canals**, which are the passageways for the optic nerves from the orbits into the internal cranial cavity.

Ethmoid Bone

The **ethmoid bone** is a single, midline bone that forms the roof and lateral walls of the upper nasal cavity, the

superior and middle nasal concha (thin, curved projections that extend into the nasal cavity), the upper portion of the nasal septum, and contributes to the medial wall of the orbit (see **Figures 4.13-4.14**). On the interior of the skull, the ethmoid also forms a portion of the floor of the anterior cranial cavity.

In the cranial cavity, the ethmoid bone forms a small area at the midline in the anterior floor, notched into the frontal bone. This portion of the ethmoid bone consists of two parts, the **crista galli** and **cribriform plates**. The crista galli ("rooster's comb or crest") is a small upward bony projection located at the midline. It functions as an anterior attachment point for one of the covering layers of the brain. To either side of the crista galli is the cribriform plate (cribrum = "sieve"), a small, flattened area with numerous small openings termed olfactory foramina. Small nerve branches from the olfactory areas of the nasal cavity pass through these openings to enter the brain.

Facial Bones of the Skull

The facial bones of the skull form the upper and lower jaws, and contribute to the nose, nasal cavity and nasal septum, and the orbit. The facial bones include 14 bones, with six paired bones and two unpaired bones. The paired bones are the maxilla, palatine, zygomatic, nasal, lacrimal, and inferior nasal conchae bones. The unpaired bones are the vomer and mandible bones.

Maxillary Bone

The **maxillary bone**, often referred to simply as the **maxilla** (plural = maxillae), is one of a pair that together form the upper jaw, much of the hard palate, the medial floor of the orbit, and the lateral base of the nose (see **Figures 4.12-4.14**). The curved, inferior margin of the maxillary bone that forms the upper jaw and contains the upper teeth is the **alveolar process of the maxilla**. Each tooth is anchored into a deep socket called an alveolus. On the anterior maxilla, just below the orbit, is the infraorbital foramen. This is the point of exit for a sensory nerve that supplies the nose, upper lip, and anterior cheek. On the inferior skull, the **palatine process** from each maxillary bone can be seen joining together at the midline to form the anterior three-quarters of the hard palate. The **hard palate** is the bony plate that forms the roof of the mouth and floor of the nasal cavity, separating the oral and nasal cavities.

Palatine Bone

The **palatine bone** is one of a pair of irregularly shaped bones that contribute small areas to the lateral walls of the nasal cavity and the medial wall of each orbit. The largest region of each of the palatine bone is the horizontal plate. The plates from the right and left palatine bones join together at the midline to form the posterior quarter of the hard palate (see **Figure 4.14**). Thus, the palatine bones are best seen in an inferior view of the skull and hard palate.

Zygomatic Bone

The **zygomatic bone** is also known as the cheekbone. Each of the paired zygomatic bones forms much of the lateral wall of the orbit and the lateral-inferior margins of the anterior orbital opening (see **Figures 4.12-4.13**). The temporal process of the zygomatic bone projects posteriorly, where it forms the anterior portion of the zygomatic arch.

Nasal Bone

The **nasal bone** is one of two small bones that articulate (join) with each other to form the bony base (bridge) of the nose. They also support the cartilages that form the lateral walls of the nose (see **Figure 4.12**). These are the bones that are damaged when the nose is broken.

Lacrimal Bone

Each **lacrimal bone** is a small, rectangular bone that forms the anterior, medial wall of the orbit (see **Figure 4.12** and **Figure 4.13**). The anterior portion of the lacrimal bone forms a shallow depression called the lacrimal fossa, and extending inferiorly from this is the nasolacrimal canal. The lacrimal fluid (tears of the eye), which serves to maintain the moist surface of the eye, drains at the medial corner of the eye into the nasolacrimal canal. This duct then extends downward to open into the nasal cavity, behind the inferior nasal concha. In the nasal cavity, the lacrimal fluid normally drains posteriorly, but with an increased flow of tears due to crying or eye irritation, some fluid will also drain anteriorly, thus causing a runny nose.

Inferior Nasal Conchae

The right and left inferior nasal conchae form a curved bony plate that projects into the nasal cavity space from the lower lateral wall (see **Figure 4.12**). The inferior concha is the largest of the nasal conchae and can easily be seen when looking into the anterior opening of the nasal cavity.

Vomer Bone

The unpaired vomer bone, often referred to simply as the vomer, is triangular-shaped and forms the posterior-inferior part of the nasal septum (see **Figure 4.12**). A small portion of the vomer can be seen when looking into the anterior opening of the nasal cavity.

Mandible

The **mandible** forms the lower jaw and is the only moveable bone of the skull. At the time of birth, the mandible consists of paired right and left bones, but these fuse together during the first year to form the single U-shaped mandible of the adult skull. Each side of the mandible consists of a horizontal body and posteriorly, a vertically oriented ramus of the mandible (ramus = "branch"). The posterior, upwardly projecting process on the ramus on each side of the mandible is the mandibular condyle, which articulates (joins) with the mandibular fossa of the temporal bone (**Figure 4.13**). Together these articulations form the temporomandibular joint, which allows for opening and closing of the mouth. Like the maxillae, the mandible contains alveoli (sockets) for teeth.

The Orbit

The orbit is the bony socket that houses the eyeball and contains the muscles that move the eyeball or open the upper eyelid. Each orbit is cone-shaped, with a narrow posterior region that widens toward the large anterior opening. To help protect the eye, the bony margins of the anterior opening are thickened and somewhat constricted. The medial walls of the two orbits are parallel to each other but each lateral wall diverges away from the midline at a 45° angle. This divergence provides greater lateral peripheral vision.

The walls of each orbit include contributions from seven skull bones (**Figure 4.16**). The frontal bone forms the roof and the zygomatic bone forms the lateral wall and lateral floor. The medial floor is primarily formed by the maxilla, with a small contribution from the palatine bone. The ethmoid bone and lacrimal bone make up much of the medial wall and the sphenoid bone forms the posterior orbit.

At the posterior apex of the orbit is the opening of the **optic canal**, which allows for passage of the optic nerve from the retina to the brain. Lateral to this is the elongated and irregularly shaped **superior orbital fissure**, which provides passage for the artery that supplies the eyeball, sensory nerves, and the nerves that supply the muscles involved in eye movements.
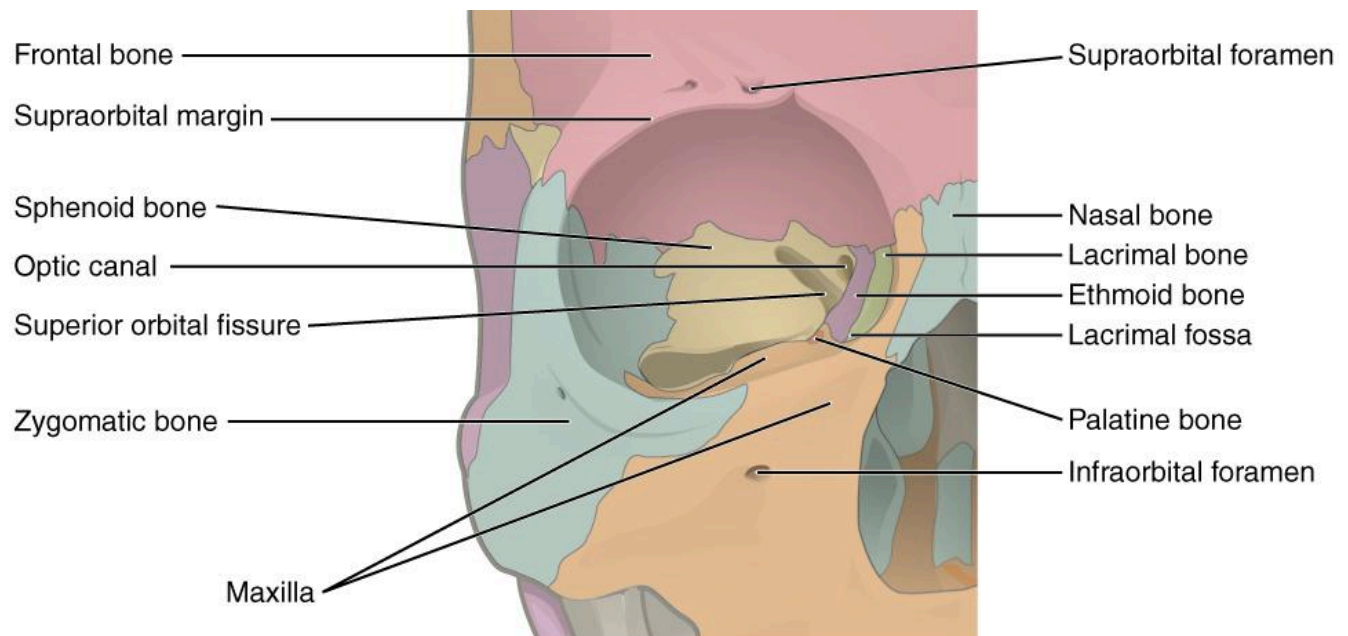
Figure 4.16 Bones of the Orbit. Seven skull bones contribute to the walls of the orbit. Opening into the posterior orbit from the cranial cavity are the optic canal and superior orbital fissure.

The Nasal Septum and Nasal Conchae

The **nasal septum** consists of both bone and cartilage components (**Figure 4.13**). The upper portion of the septum is formed by the perpendicular plate of the ethmoid bone. The lower and posterior parts of the septum are formed by the triangular-shaped vomer bone. In an anterior view of the skull, the perpendicular plate of the ethmoid bone is easily seen inside the nasal opening as the upper nasal septum, but only a small portion of the vomer is seen as the inferior septum. The anterior nasal septum is formed by the **septal cartilage**, a flexible plate that fills in the gap between the perpendicular plate of the ethmoid and vomer bones. This cartilage also extends outward into the nose where it separates the right and left nostrils. The septal cartilage is not found in the dry skull.

Attached to the lateral wall on each side of the nasal cavity are the **superior, middle, and inferior nasal conchae** (singular = concha), which are named for their positions (see **Figure 4.13**). These are bony plates that curve downward as they project into the space of the nasal cavity. They serve to swirl the incoming air, which helps

to warm and moisturize it before the air moves into the delicate air sacs of the lungs. This also allows mucus, secreted by the tissue lining the nasal cavity, to trap incoming dust, pollen, bacteria, and viruses. The largest of the conchae is the inferior nasal concha, which is an independent bone of the skull. The middle concha and the superior conchae, which is the smallest, are both formed by the ethmoid bone. When looking into the anterior nasal opening of the skull, only the inferior and middle conchae can be seen. The small superior nasal concha is well hidden above and behind the middle concha.

Paranasal Sinuses

The **paranasal sinuses** are hollow, air-filled spaces located within certain bones of the skull (**Figure 4.17**). All of the sinuses communicate with the nasal cavity (paranasal = "next to nasal cavity") and are lined with nasal mucosa. They serve to reduce bone mass and thus lighten the skull, and they also add resonance to the voice. This second feature is most obvious when you have a cold or sinus congestion. These produce swelling of the mucosa and excess mucus production, which can obstruct the narrow passageways between the sinuses and the nasal cavity, causing your voice to sound different to yourself and others. This blockage can also allow the sinuses to fill with fluid, with the resulting pressure producing pain and discomfort.

The paranasal sinuses are named for the skull bone that each occupies. The **frontal sinus** is located just above the eyebrows, within the frontal bone. The largest sinus is the **maxillary sinus**. These are paired and located within the right and left maxillary bones, where they occupy the area just below the orbits. The maxillary sinuses are most commonly involved during sinus infections. Because their connection to the nasal cavity is located high on their medial wall, they are difficult to drain. The **sphenoid sinus** is a single, midline sinus. It is located within the body of the sphenoid bone, just anterior and inferior to the sella turcica, thus making it the most posterior of the paranasal sinuses. The lateral aspects of the ethmoid bone contain multiple small spaces separated by very thin bony walls. Each of these spaces is called an **ethmoid air cell**. These are located on both sides of the ethmoid bone, between the upper nasal cavity and medial orbit, just behind the superior nasal conchae.
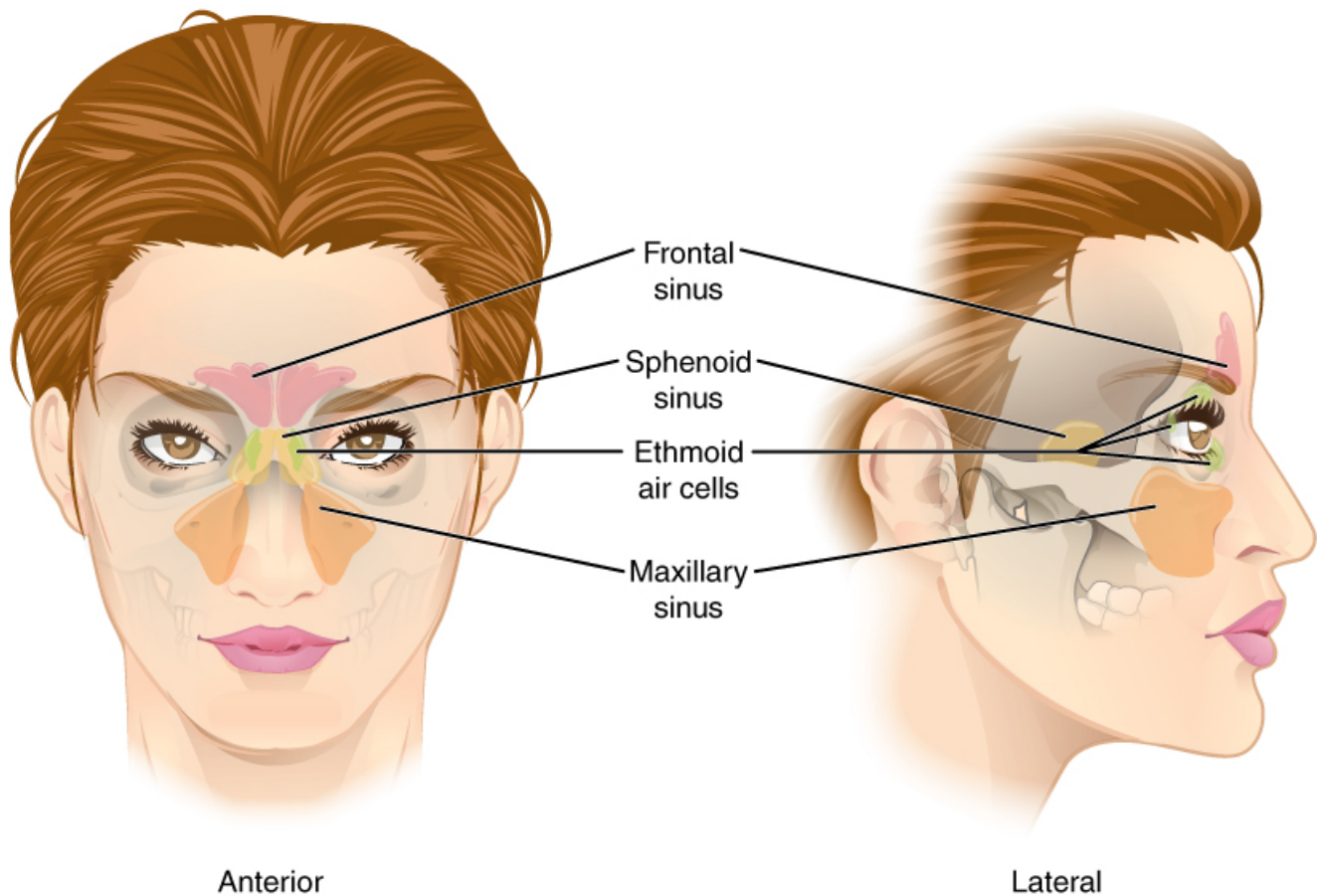
Figure 4.17 Paranasal Sinuses. The paranasal sinuses are hollow, air-filled spaces named for the skull bone that each occupies. The most anterior is the frontal sinus, located in the frontal bone above the eyebrows. The largest are the maxillary sinuses, located in the right and left maxillary bones below the orbits. The most posterior is the sphenoid sinus, located in the body of the sphenoid bone, under the sella turcica. The ethmoid air cells are multiple small spaces located in the right and left sides of the ethmoid bone, between the medial wall of the orbit and lateral wall of the upper nasal cavity.

Sutures of the Skull

A **suture** is an immobile joint between adjacent bones of the skull. The narrow gap between the bones is filled with dense, fibrous connective tissue that unites the bones. The long sutures located between the bones of the brain case are not straight, but instead follow irregular, tightly twisting paths. These twisting lines serve to tightly interlock the adjacent bones, thus adding strength to the skull for brain protection.

The two suture lines seen on the top of the skull are the coronal and sagittal sutures. The **coronal suture** runs from side to side across the skull, within the coronal plane of section (see **Figure 4.13**). It joins the frontal bone to the right and left parietal bones. The **sagittal suture** extends posteriorly from the coronal suture, running along the midline at the top of the skull in the sagittal plane of section (see **Figure 4.15**). It unites the right and left parietal bones. On the posterior skull, the sagittal suture terminates by joining the **lambdoid (lambdoidal) suture** (see **Figure 4.15**). The lambdoid suture extends downward and laterally to either side away from its junction with the sagittal suture. The lambdoid suture joins the occipital bone to the right and left parietal and temporal bones. This suture is named for its upside-down "V" shape, which resembles the capital letter version of the Greek letter

lambda (Λ). The **squamous suture** is located on the lateral skull. It unites the temporal bone with the parietal bone (see **Figure 4.13**).

Development of the Skull

The bones of the skull arise from mesenchyme during embryonic development in two different ways. The first mechanism produces the bones that form the top and sides of the brain case. This involves the local accumulation of mesenchymal cells at the site of the future bone. These cells then differentiate directly into bone producing cells, which form the skull bones through the process of intramembranous ossification. As the brain case bones grow in the fetal skull, they remain separated from each other by large areas of dense connective tissue, each of which is called a **fontanelle** (**Figure 4.18**). The fontanelles are the soft spots on an infant's head. They are important during birth because these areas allow the skull to change shape as it squeezes through the birth canal. After birth, the fontanelles allow for continued growth and expansion of the skull as the brain enlarges. The largest fontanelle is located on the anterior head, at the junction of the frontal and parietal bones. The fontanelles decrease in size and disappear by age 2. However, the skull bones remained separated from each other at the sutures, which contain dense fibrous connective tissue that unites the adjacent bones. The connective tissue of the sutures allows for continued growth of the skull bones as the brain enlarges during childhood growth.

The second mechanism for bone development in the skull produces the facial bones and floor of the brain case. This also begins with the localized accumulation of mesenchymal cells. However, these cells differentiate into cartilage cells, which produce a hyaline cartilage model of the future bone. As this cartilage model grows, it is gradually converted into bone through the process of endochondral ossification. This is a slow process and the cartilage is not completely converted to bone until the skull achieves its full adult size.
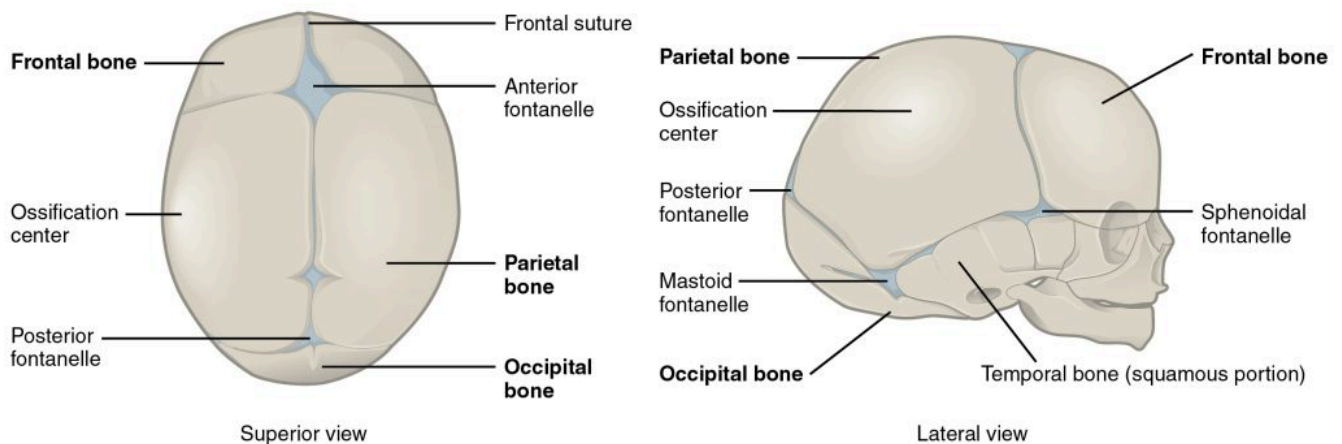
Figure 4.18 Newborn Skull. The bones of the newborn skull are not fully ossified and are separated by large areas called fontanelles, which are filled with fibrous connective tissue. The fontanelles allow for continued growth of the skull after birth. At the time of birth, the facial bones are small and underdeveloped, and the mastoid process has not yet formed.

Hyoid Bone

The **hyoid bone** is an independent bone that does not contact any other bone and thus is not part of the skull

(**Figure 4.19**). It is a small U-shaped bone located in the upper neck near the level of the inferior mandible, with the tips of the "U" pointing posteriorly. The hyoid serves as the base for the tongue above, and is attached to the larynx below and the pharynx posteriorly. The hyoid is held in position by a series of small muscles that attach to it either from above or below. These muscles act to move the hyoid up/down or forward/back. Movements of the hyoid are coordinated with movements of the tongue, larynx, and pharynx during swallowing and speaking.
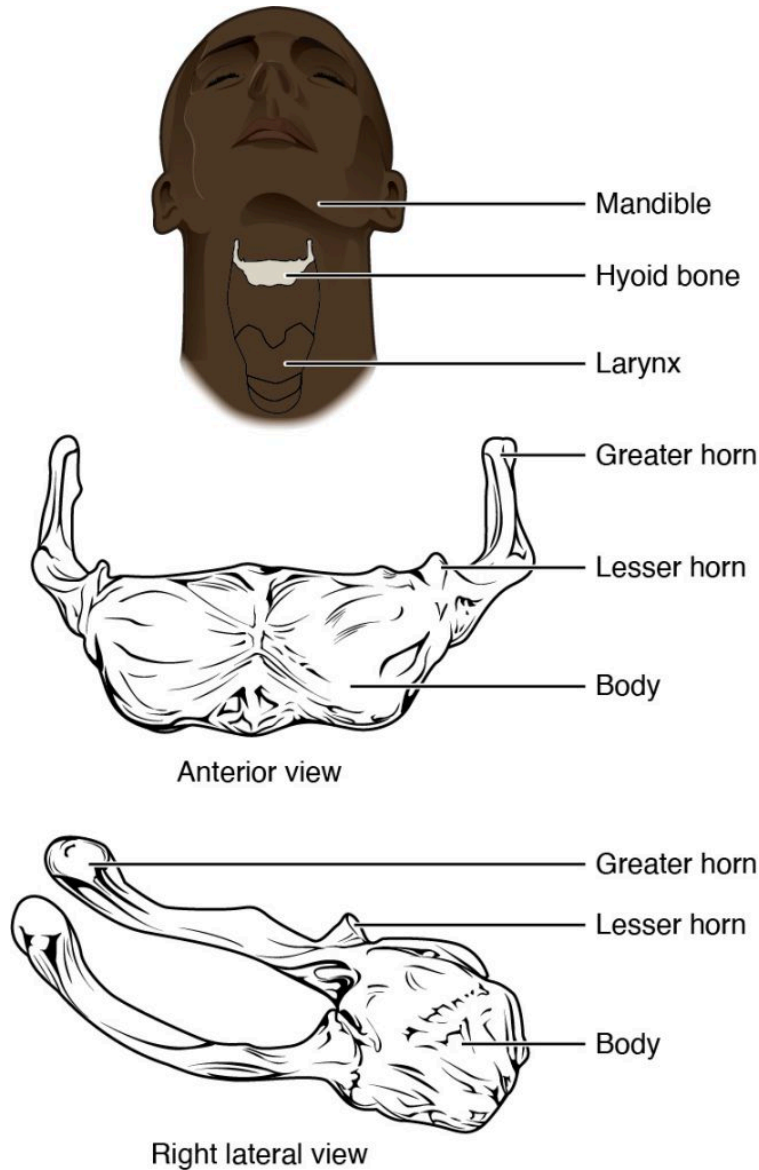
Figure 4.19 Hyoid Bone. The hyoid bone is located in the upper neck and does not join with any other bone. It provides attachments for muscles that act on the tongue, larynx, and pharynx.

The Vertebral Column

The vertebral column is also known as the spinal column or spine (**Figure 4.20**). It consists of a sequence of

vertebrae (singular = vertebra), each of which is separated and united by an **intervertebral disc**. Together, the vertebrae and intervertebral discs form the vertebral column. It is a flexible column that supports the head, neck, and body and allows for their movements. It also protects the spinal cord, which passes down the back through openings in the vertebrae.
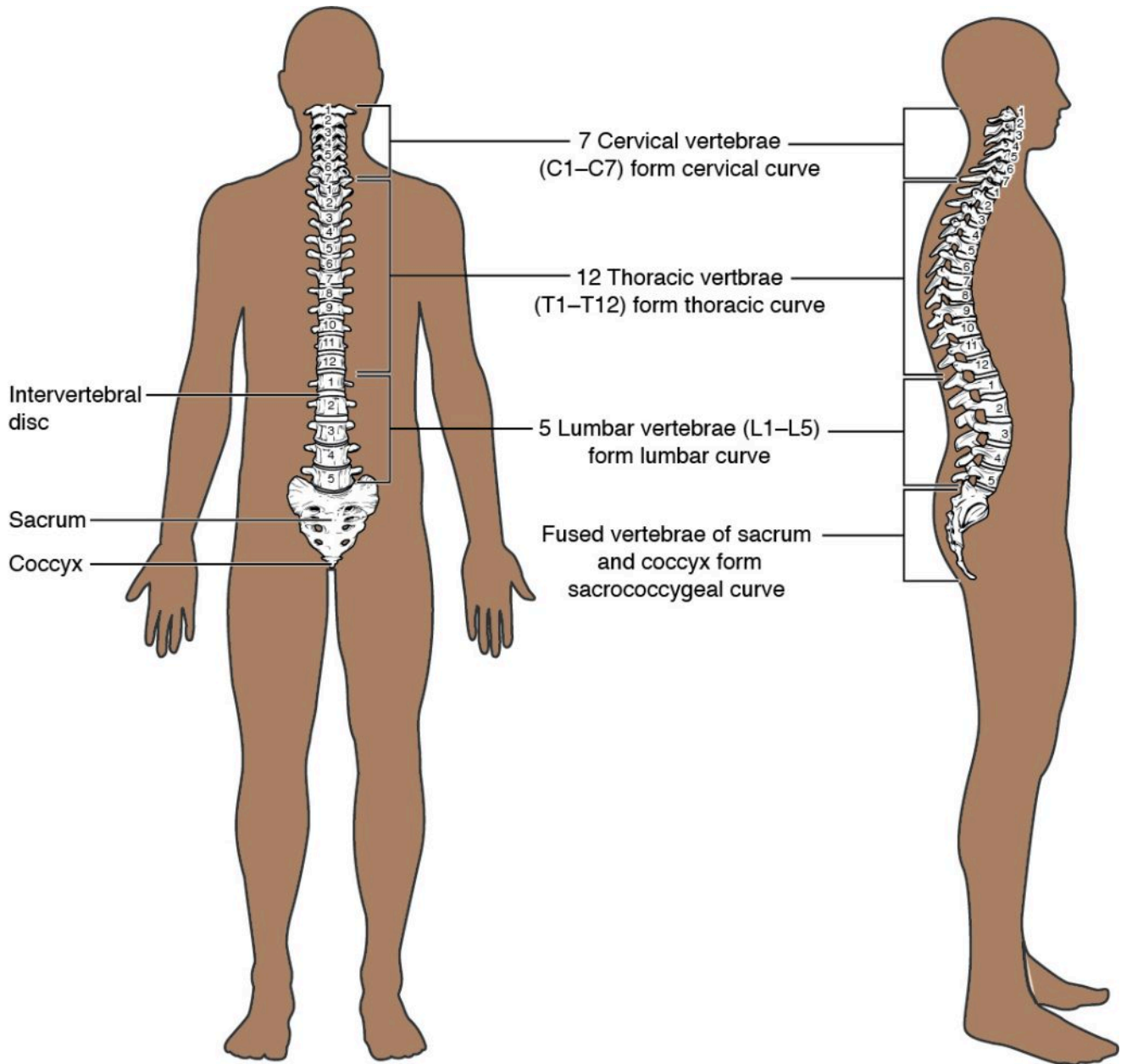
Figure 4.20 Vertebral Column. The adult vertebral column consists of 24 vertebrae, plus the sacrum and coccyx. The vertebrae are divided into three regions: cervical C1–C7 vertebrae, thoracic T1–T12 vertebrae, and lumbar L1–L5 vertebrae. The vertebral column is curved, with two primary curvatures (thoracic and sacrococcygeal curves) and two secondary curvatures (cervical and lumbar curves).

Regions of the Vertebral Column

The vertebral column originally develops as a series of 33 vertebrae, but this number is eventually reduced to 24 vertebrae, plus the sacrum and coccyx. The vertebral column is subdivided into five regions, with the vertebrae in each area named for that region and numbered in descending order. In the neck, there are seven **cervical vertebrae**, each designated with the letter "C" followed by its number. Superiorly, the C1 vertebra articulates (forms a joint) with the occipital condyles of the skull. Inferiorly, C1 articulates with the C2 vertebra, and so on. Below these are the 12 **thoracic vertebrae**, designated T1–T12. The lower back contains the L1–L5 **lumbar vertebrae**. The single **sacrum**, which is also part of the pelvis, is formed by the fusion of five sacral vertebrae. Similarly, the **coccyx**, or tailbone, results from the fusion of four small coccygeal vertebrae. However, the sacral and coccygeal fusions do not start until age 20 and are not completed until middle age.

Curvatures of the Vertebral Column

The adult vertebral column does not form a straight line, but instead has four curvatures along its length (see **Figure 4.20**). These curves increase the vertebral column's strength, flexibility, and ability to absorb shock. When the load on the spine is increased, by carrying a heavy backpack for example, the curvatures increase in depth (become more curved) to accommodate the extra weight. They then spring back when the weight is removed. The four adult curvatures are classified as either primary or secondary curvatures. Primary curves are retained from the original fetal curvature, while secondary curvatures develop after birth.

During fetal development, the body is flexed anteriorly into the fetal position, giving the entire vertebral column a single curvature that is concave anteriorly. In the adult, this fetal curvature is retained in two regions of the vertebral column as the **thoracic curve**, which involves the thoracic vertebrae, and the **sacrococcygeal curve**, formed by the sacrum and coccyx. Each of these is thus called a **primary curve** because they are retained from the original fetal curvature of the vertebral column.

A **secondary curve** develops gradually after birth as the child learns to sit upright, stand, and walk. Secondary curves are concave posteriorly, opposite in direction to the original fetal curvature. The **cervical curve** of the neck region develops as the infant begins to hold their head upright when sitting. Later, as the child begins to stand and then to walk, the **lumbar curve** of the lower back develops. In adults, the lumbar curve is generally deeper in females.

General Structure of a Vertebra

Within the different regions of the vertebral column, vertebrae vary in size and shape, but they all follow a similar structural pattern. A typical vertebra will consist of a body, a vertebral arch, and several processes (**Figure 4.21**). The **body** is the anterior portion of each vertebra and is the part that supports the body weight. Because of this, the vertebral bodies progressively increase in size and thickness going down the vertebral column. The bodies of adjacent vertebrae are separated and strongly united by an intervertebral disc. The **vertebral arch** forms the posterior portion of each vertebra. The large opening between the vertebral arch and body is the **vertebral foramen**, which contains the spinal cord. In the intact vertebral column, the vertebral foramina of all of the vertebrae align to form the **vertebral (spinal) canal**, which serves as the bony protection and passageway for the spinal cord down the back. When the vertebrae are aligned together in the vertebral column, notches in the vertebral arches of adjacent vertebrae together form an **i**ntervertebral foramen, the opening through which a spinal nerve exits from the vertebral column.

The paired **transverse processes** laterally and the single **spinous process** (vertebral spine) projecting posteriorly at the midline of the back serve as important muscle attachment sites. There are also superior and inferior articular processes that articulate with the vertebrae above and below, respectively. These junctions form slightly moveable joints between the adjacent vertebrae. The shape and orientation of the articular processes vary in different regions of the vertebral column and play a major role in determining the type and range of motion available in each region.
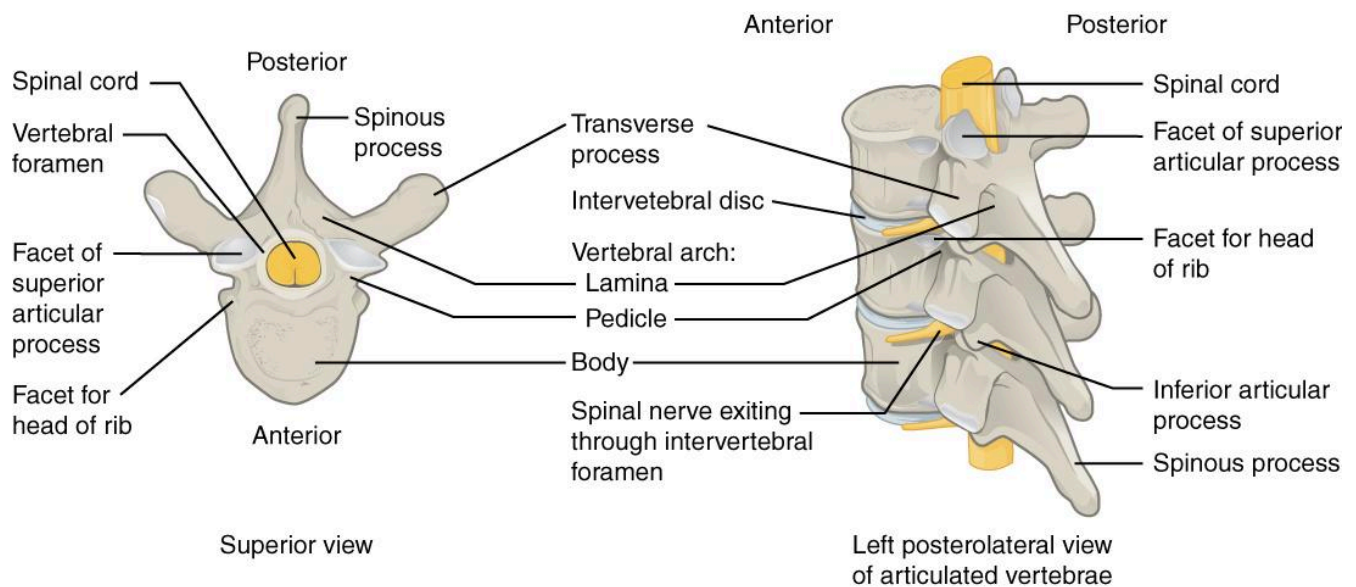
Figure 4.21 Parts of a Typical Vertebra A typical vertebra consists of a body and a vertebral arch. The arch is formed by the paired pedicles and paired laminae. Arising from the vertebral arch are the transverse, spinous, superior articular, and inferior articular processes. The vertebral foramen provides for passage of the spinal cord. Each spinal nerve exits through an intervertebral foramen, located between adjacent vertebrae. Intervertebral discs unite the bodies of adjacent vertebrae.

The Thoracic Cage

The thoracic cage (rib cage) forms the thorax (chest) portion of the body. It consists of the 12 pairs of ribs with their costal cartilages and the sternum (**Figure 4.22**). The ribs are anchored posteriorly to the 12 thoracic vertebrae (T1−T12). The thoracic cage protects the heart and lungs.

Superior

Clavicular notch

Jugular notch

Manubrium

Sternal angle

Body

Xiphoid process

Inferior

(a) Anterior view of sternum

Superior

Jugular notch

Clavicular notch

Clavicle

1

2

Sternum:
Manubrium
Body

3

4

Scapula

5

Sternal angle

6

Xiphoid process

7

T11

8

Costal cartilages

T12

11

9

12

10

Intercostal space

Inferior

(b) Anterior view of skeleton of thorax
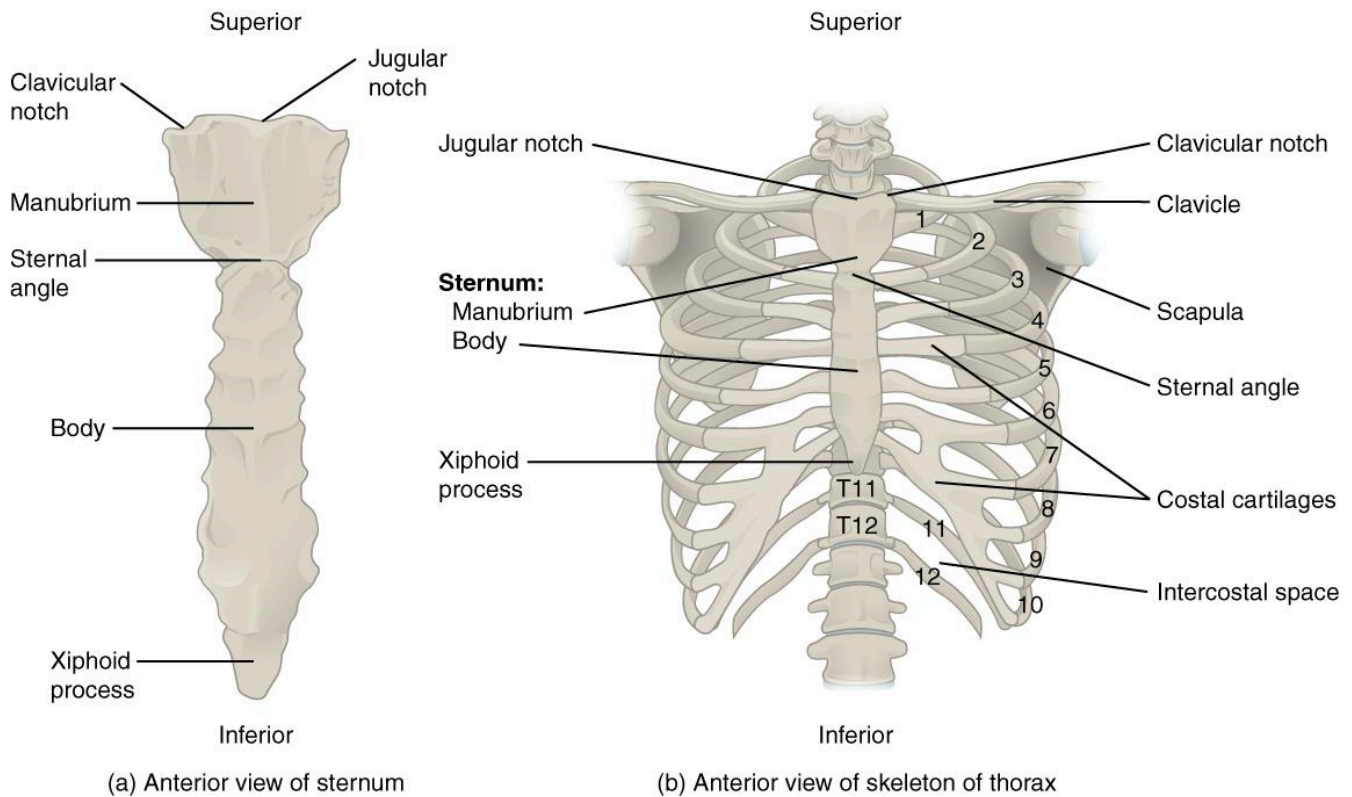
Figure 4.22 Thoracic Cage. The thoracic cage is formed by the (a) sternum and (b) 12 pairs of ribs with their costal cartilages. The ribs are anchored posteriorly to the 12 thoracic vertebrae. The sternum consists of the manubrium, body, and xiphoid process. The ribs are classified as true ribs (1–7) and false ribs (8–12). The last two pairs of false ribs are also known as floating ribs (11–12).

Sternum

The sternum is the elongated bony structure that anchors the anterior thoracic cage. It consists of three parts: the manubrium, body, and xiphoid process. The **manubrium** is the wider, superior portion of the sternum. The top of the manubrium has a shallow, U-shaped border called the jugular (suprasternal) notch. This can be easily felt at the anterior base of the neck, between the medial ends of the clavicles. The **clavicular notch** is the shallow depression located on either side at the superior-lateral margins of the manubrium. This is the site of the sternoclavicular joint, between the sternum and clavicle. The first ribs also attach to the manubrium.

The elongated, central portion of the sternum is the **body**. The manubrium and body join together at the sternal angle, so called because the junction between these two components is not flat, but forms a slight bend. The second rib attaches to the sternum at the sternal angle. Since the first rib is hidden behind the clavicle, the second rib is the highest rib that can be identified by palpation. Thus, the sternal angle and second rib are important landmarks for the identification and counting of the lower ribs. Ribs 3–7 attach to the sternal body.

The inferior tip of the sternum is the **xiphoid process**. This small structure is cartilaginous early in life, but gradually becomes ossified starting during middle age.

Ribs

Each rib is a curved, flattened bone that contributes to the wall of the thorax. The ribs articulate posteriorly with the T1−T12 thoracic vertebrae, and most attach anteriorly via their costal cartilages to the sternum. There are 12 pairs of ribs. The ribs are numbered 1−12 in accordance with the thoracic vertebrae.

The bony ribs do not extend anteriorly completely around to the sternum. Instead, each rib ends in a **costal cartilage**. These cartilages are made of hyaline cartilage and can extend for several inches. Most ribs are then attached, either directly or indirectly, to the sternum via their costal cartilage (see **Figure 4.22**). The ribs are classified into three groups based on their relationship to the sternum:

- Ribs 1−7 are classified as **true ribs** (vertebrosternal ribs). The costal cartilage from each of these ribs attaches directly to the sternum.
- Ribs 8−12 are called **false ribs** (vertebrochondral ribs). The costal cartilages from these ribs do not attach directly to the sternum. For ribs 8−10, the costal cartilages are attached to the cartilage of the next higher rib. Thus, the cartilage of rib 10 attaches to the cartilage of rib 9, rib 9 then attaches to rib 8, and rib 8 is attached to rib 7.
- The last two false ribs (11−12) are also called **floating ribs** (vertebral ribs). These are short ribs that do not attach to the sternum at all. Instead, their small costal cartilages terminate within the musculature of the lateral abdominal wall.

Lab 5: Skeletal System II - Appendicular Skeleton and Joints

Appendicular Skeleton, Articulations

The Appendicular Skeleton

Your skeleton provides the internal supporting structure of the body. The adult axial skeleton consists of 80 bones that form the head and body trunk. Attached to this are the limbs, whose 126 bones constitute the appendicular skeleton (**Figure 5.1**). These bones are divided into two groups: the bones that are located within the limbs themselves, and the girdle bones that attach the limbs to the axial skeleton. The bones of the shoulder region form the shoulder girdle, which anchors the upper limb to the thoracic cage of the axial skeleton. The lower limb is attached to the vertebral column by the pelvic girdle.
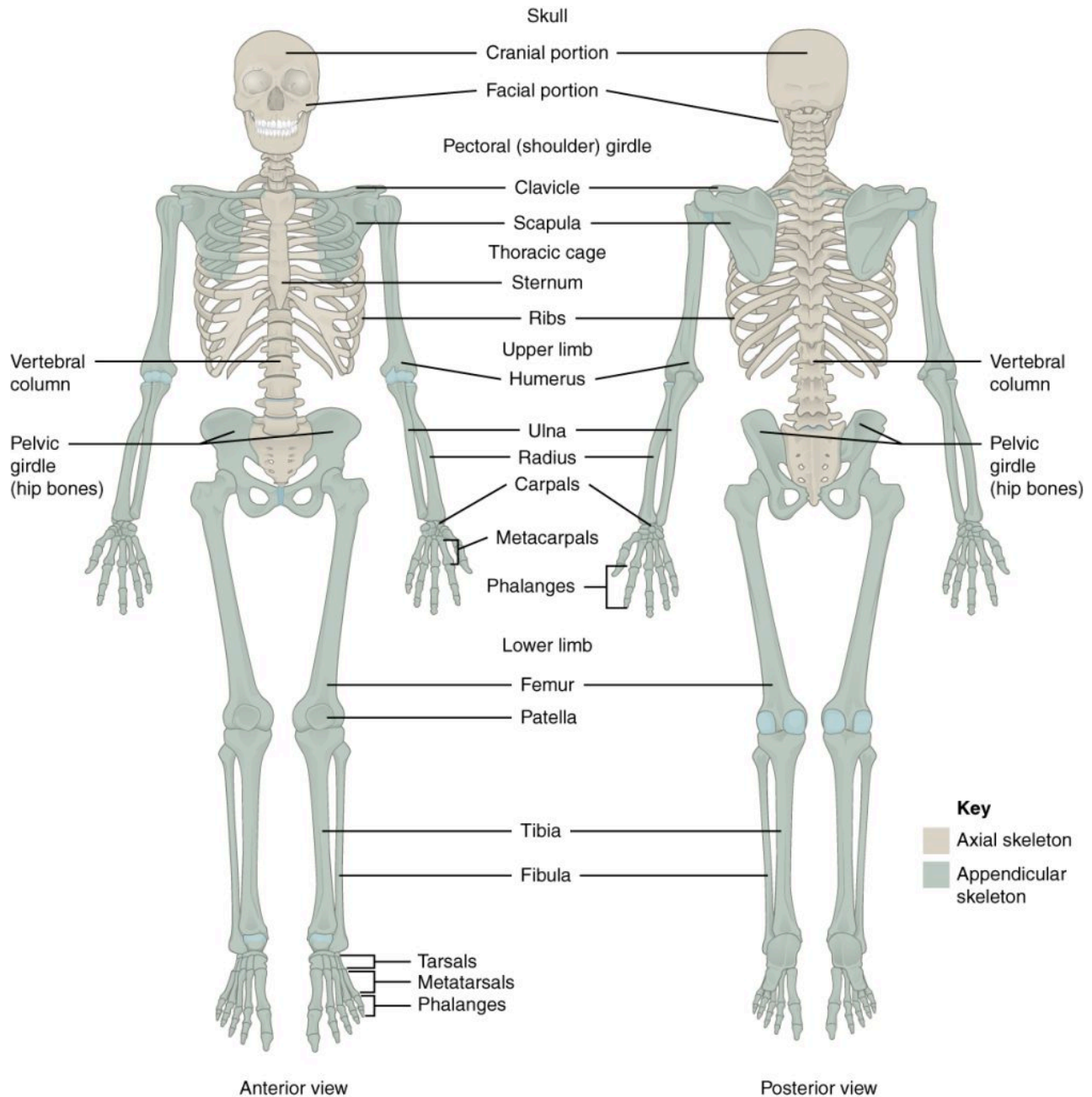
Figure 5.1 Axial and Appendicular Skeletons. The axial skeleton forms the central axis of the body and consists of the skull, vertebral column, and thoracic cage. The appendicular skeleton consists of the pectoral and pelvic girdles, the limb bones, and the bones of the hands and feet.

The Shoulder Girdle

The bones that attach each upper limb to the axial skeleton form the **shoulder girdle** (pectoral girdle). This consists of two bones, the scapula and clavicle (**Figure 5.2**). The **clavicle** (collarbone) is an S-shaped bone located on the anterior side of the shoulder. It is attached on its medial end to the sternum of the thoracic cage, which is

part of the axial skeleton. The lateral end of the clavicle articulates (joins) with the scapula just above the shoulder joint. You can easily palpate, or feel with your fingers, the entire length of your clavicle.
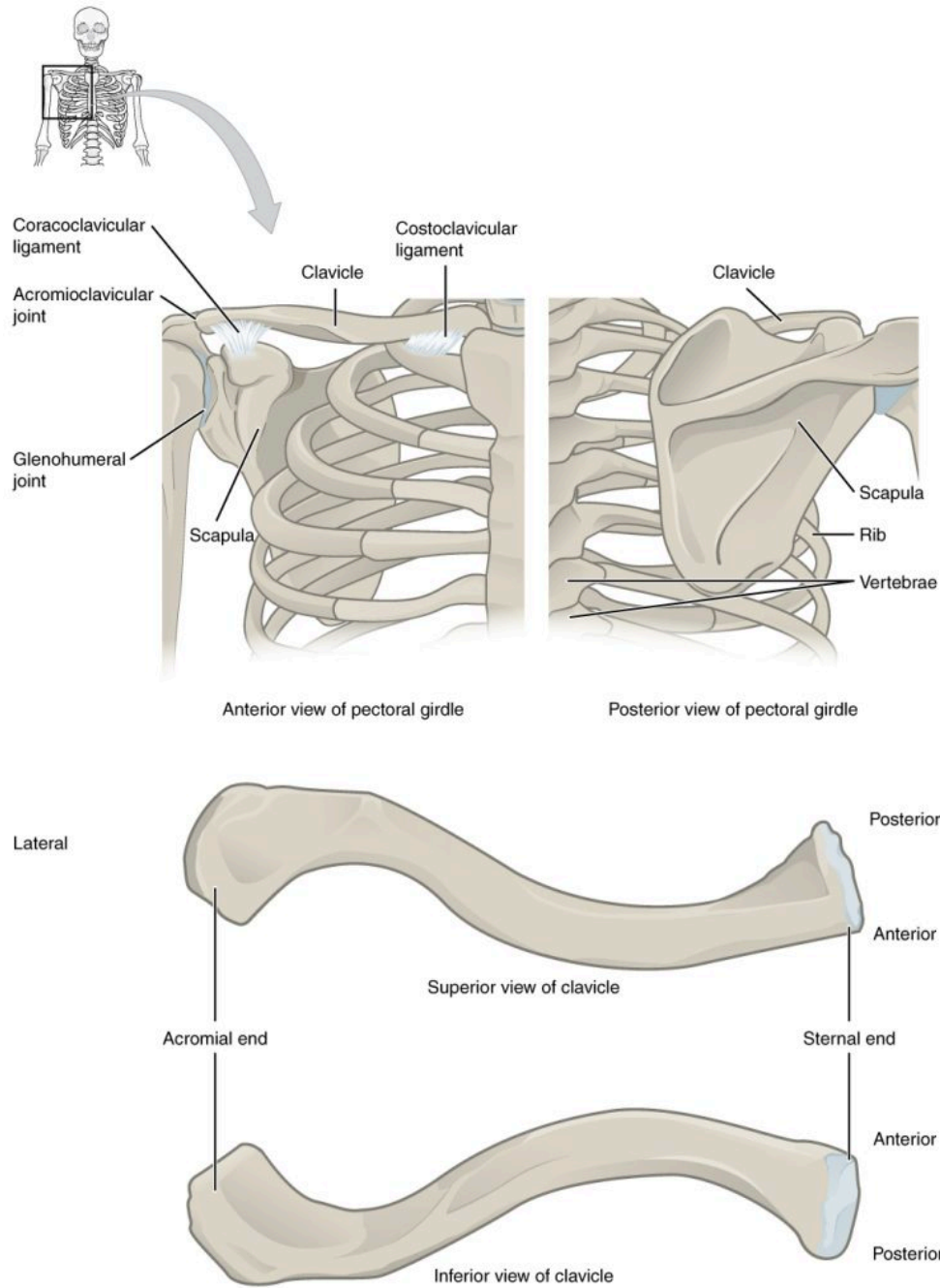
Figure 5.2 Shoulder Girdle. The shoulder girdle consists of the clavicle and the scapula, which serve to attach the upper limb to the sternum of the axial skeleton.

The **scapula** (shoulder blade) lies on the posterior aspect of the shoulder. It is supported by the clavicle, which also articulates with the humerus (arm bone) to form the shoulder joint. The scapula is a flat, triangular-shaped bone with a prominent ridge running across its posterior surface. This ridge extends out laterally, where it forms the bony tip of the shoulder and joins with the lateral end of the clavicle. By following along the clavicle, you can

palpate out to the bony tip of the shoulder, and from there, you can move back across your posterior shoulder to follow the ridge of the scapula. Move your shoulder around and feel how the clavicle and scapula move together as a unit. Both of these bones serve as important attachment sites for muscles that aid with movements of the shoulder and arm.

The right and left shoulder girdles are not joined to each other, allowing each to operate independently. In addition, the clavicle of each shoulder girdle is anchored to the axial skeleton by a single, highly mobile joint. This allows for the extensive mobility of the entire shoulder girdle, which in turn enhances movements of the shoulder and upper limb.

Clavicle

The clavicle is the only long bone that lies in a horizontal position in the body (**Figure 5.2**). The clavicle has several important functions. First, anchored by muscles from above, it serves as a strut that extends laterally to support the scapula. This in turn holds the shoulder joint superiorly and laterally from the body trunk, allowing for maximal freedom of motion for the upper limb. The clavicle also transmits forces acting on the upper limb to the sternum and axial skeleton. Finally, it serves to protect the underlying nerves and blood vessels as they pass between the trunk of the body and the upper limb.

The clavicle has three regions: the medial end, the lateral end, and the shaft. The medial end, known as the **sternal end of the clavicle**, has a triangular shape and articulates with the manubrium portion of the sternum. This forms the **sternoclavicular joint**, which is the only bony articulation between the shoulder girdle of the upper limb and the axial skeleton. This joint allows considerable mobility, enabling the clavicle and scapula to move in upward/downward and anterior/posterior directions during shoulder movements. The lateral or **acromial end of the clavicle** articulates with the acromion of the scapula, the portion of the scapula that forms the bony tip of the shoulder.

The clavicle is the most commonly fractured bone in the body. Such breaks often occur because of the force exerted on the clavicle when a person falls onto his or her outstretched arms, or when the lateral shoulder receives a strong blow. Because the sternoclavicular joint is strong and rarely dislocated, excessive force results in the breaking of the clavicle, usually between the middle and lateral portions of the bone. If the fracture is complete, the shoulder and lateral clavicle fragment will drop due to the weight of the upper limb, causing the person to support the sagging limb with their other hand. Muscles acting across the shoulder will also pull the shoulder and lateral clavicle anteriorly and medially, causing the clavicle fragments to override.

Scapula

The scapula is also part of the shoulder girdle and thus plays an important role in anchoring the upper limb to the body. The scapula is located on the posterior side of the shoulder. It is surrounded by muscles on both its anterior (deep) and posterior (superficial) sides, and thus does not articulate with the ribs of the thoracic cage.

The scapula has several important landmarks (**Figure 5.3**). The three margins or borders of the scapula, named for their positions within the body, are the **superior border of the scapula**, the **medial border of the scapula**, and the **lateral border of the scapula**. The corners of the triangular scapula, at either end of the medial border, are the superior angle of the scapula, located between the medial and superior borders, and the inferior angle of the scapula, located between the medial and lateral borders. The inferior angle is the most inferior portion of the scapula, and is particularly important because it serves as the attachment point for several powerful muscles

involved in shoulder and upper limb movements. The remaining corner of the scapula, between the superior and lateral borders, is the location of the **glenoid cavity** (glenoid fossa). This shallow depression articulates with the humerus bone of the arm to form the **glenohumeral joint** (shoulder joint).

Pectoral girdle:
Clavicle
Scapula
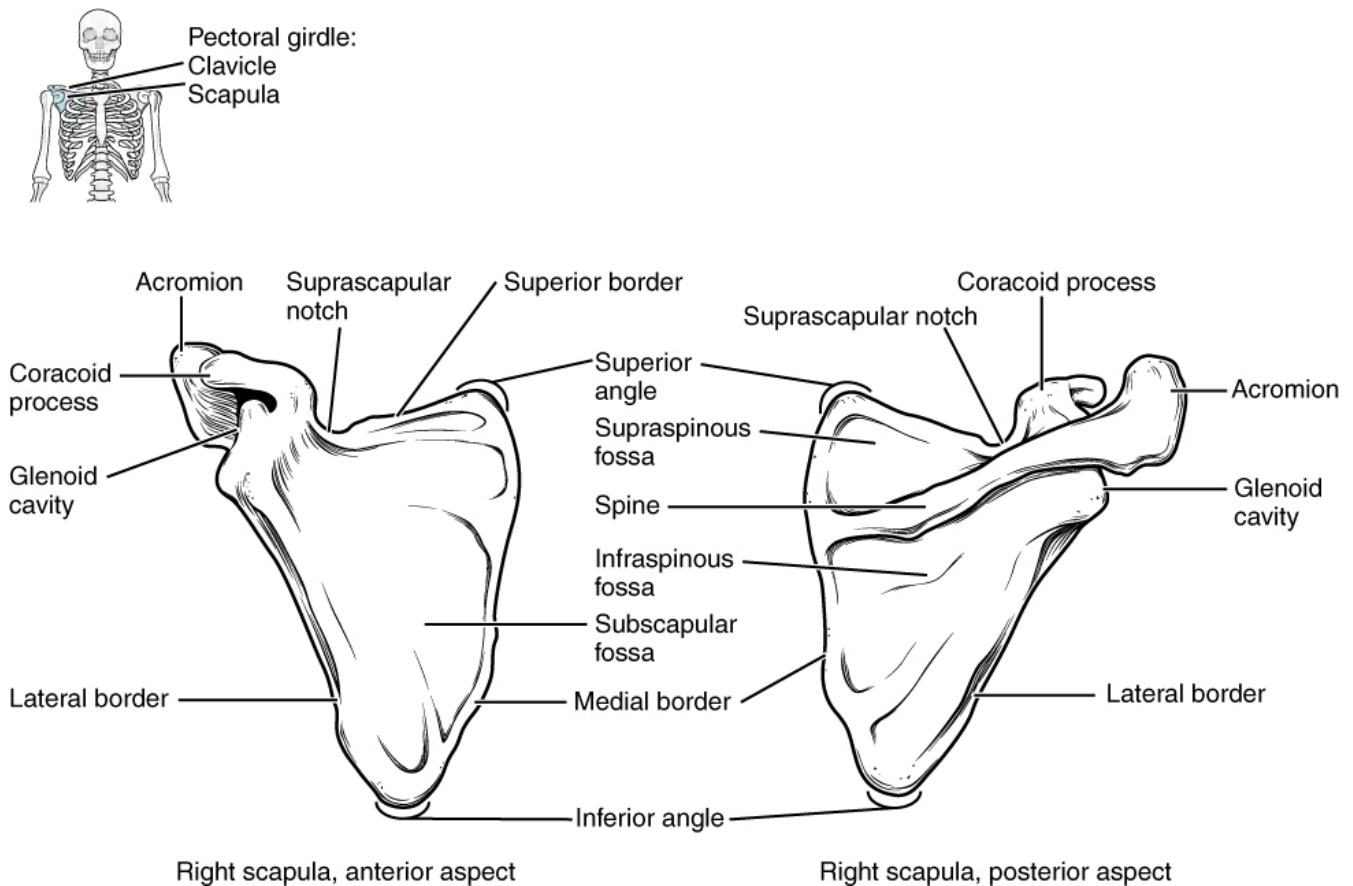
Figure 5.3 Scapula. The isolated scapula is shown here from its anterior (deep) side and its posterior (superficial) side.

The scapula also has two prominent projections. Toward the lateral end of the superior border, between the suprascapular notch and glenoid cavity, is the hook-like **coracoid process** (coracoid = "shaped like a crow's beak"), which serves as the attachment site for muscles of the anterior chest and arm. On the posterior aspect, the **spine of the scapula** is a long and prominent ridge that runs across its upper portion. Extending laterally from the spine is a flattened and expanded region called the **acromion** or **acromial process**. The acromion forms the bony tip of the superior shoulder region and articulates with the lateral end of the clavicle, forming the **acromioclavicular joint** (**Figure 5.2**). Together, the clavicle, acromion, and spine of the scapula form a V-shaped bony line that provides for the attachment of neck and back muscles that act on the shoulder, as well as muscles that pass across the shoulder joint to act on the arm.

The scapula has three depressions, each of which is called a **fossa** (plural = fossae). Two of these are found on the posterior scapula, above and below the scapular spine. Superior to the spine is the narrow **supraspinous fossa**, and inferior to the spine is the broad **infraspinous fossa**. The anterior (deep) surface of the scapula forms the broad **subscapular fossa**. All of these fossae provide large surface areas for the attachment of rotator cuff muscles that cross the shoulder joint to act on the humerus.

Bones of the Upper Limb

The upper limb is divided into three regions. These consist of the **arm**, located between the shoulder and elbow joints; the **forearm**, which is between the elbow and wrist joints; and the **hand**, which is located distal to the wrist. There are 30 bones in each upper limb (**Figure 5.1**). The **humerus** is the single bone of the upper arm, and the **ulna** (medially) and the **radius** (laterally) are the paired bones of the forearm. The base of the hand contains eight bones, each called a **carpal bone**, and the palm of the hand is formed by five bones, each called a **metacarpal bone**. The fingers and thumb contain a total of 14 bones, each of which is a **phalanx bone of the hand**.

Humerus

The humerus is the single bone of the upper arm region (**Figure 5.4**). At its proximal end is the **head of the humerus**. This is the large, round, smooth region that faces medially. The head articulates with the glenoid cavity of the scapula to form the glenohumeral (shoulder) joint. Located on the lateral side of the proximal humerus is an expanded bony area called the **greater tubercle**. The smaller **lesser tubercle** of the humerus is found on the anterior aspect of the humerus. Both the greater and lesser tubercles serve as attachment sites for rotator cuff muscles that act across the shoulder joint.
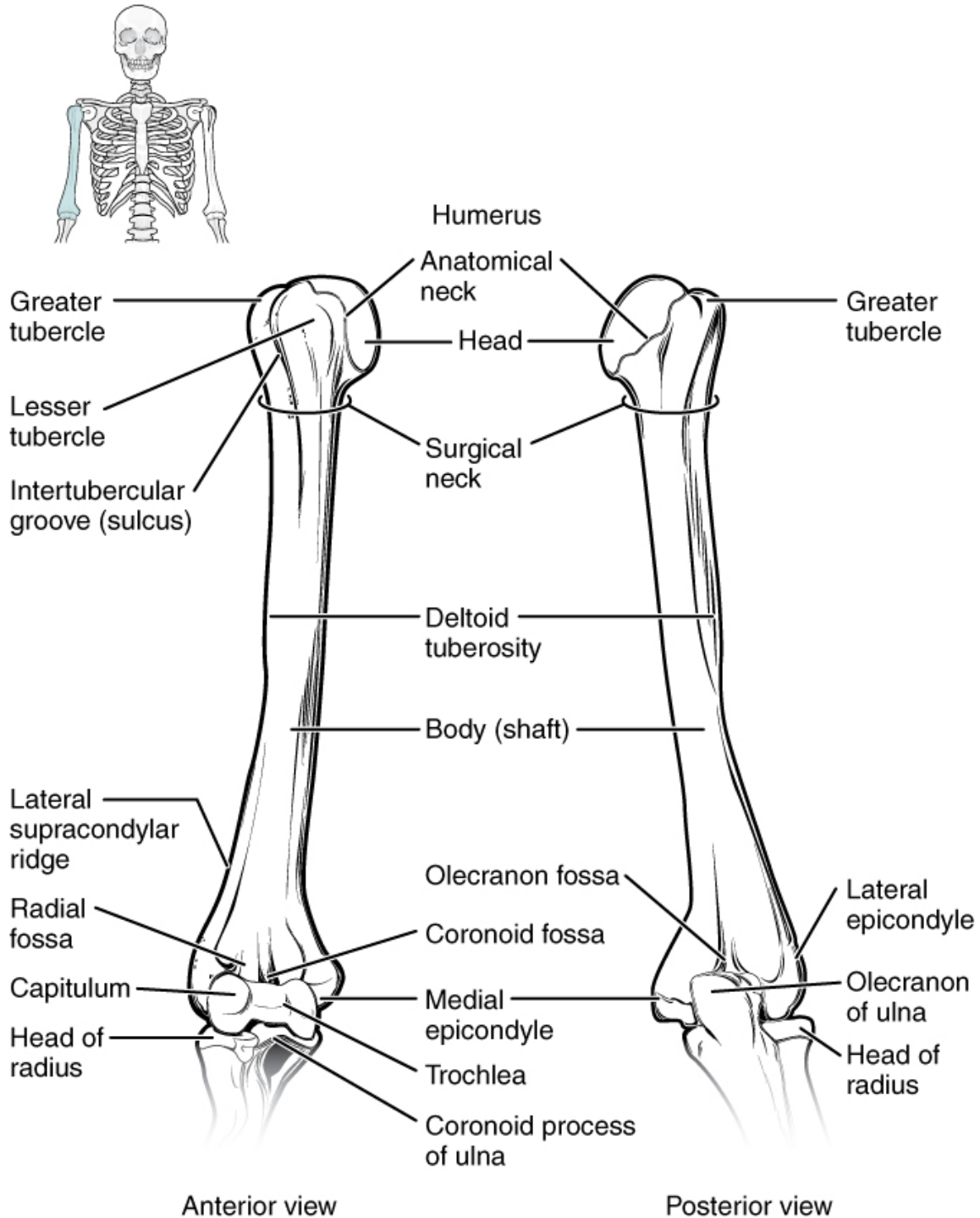
Figure 5.4 **Humerus and Elbow Joint.** The humerus is the single bone of the upper arm region. It articulates with the radius and ulna bones of the forearm to form the elbow joint.

Distally, the humerus becomes flattened. The prominent bony projection on the medial side is the **medial epicondyle of the humerus**. The much smaller **lateral epicondyle of the humerus** is found on the lateral side of the distal humerus. These areas are attachment points for muscles that act on the forearm, wrist, and hand. The

powerful grasping muscles of the anterior forearm arise from the medial epicondyle, which is thus larger and more robust than the lateral epicondyle that gives rise to the weaker posterior forearm muscles.

The distal end of the humerus has two articulation areas, which join the ulna and radius bones of the forearm to form the **elbow joint**. The more medial of these areas is the **trochlea**, a spindle- or pulley-shaped region (trochlea = "pulley"), which articulates with the ulna bone. Immediately lateral to the trochlea is the **capitulum** ("small head"), a knob-like structure located on the anterior surface of the distal humerus. The capitulum articulates with the radius bone of the forearm. Just above these bony areas are two small depressions. These spaces accommodate the forearm bones when the elbow is fully bent (flexed). Superior to the trochlea is the **coronoid fossa**, which receives the coronoid process of the ulna, and above the capitulum is the **radial fossa**, which receives the head of the radius when the elbow is flexed. Similarly, the posterior humerus has the **olecranon fossa**, a larger depression that receives the olecranon process of the ulna when the forearm is fully extended.

Ulna

The ulna is the medial bone of the forearm. It runs parallel to the radius, which is the lateral bone of the forearm (**Figure 5.5**). The proximal end of the ulna resembles a crescent wrench with its large, C-shaped **trochlear notch**. This region articulates with the trochlea of the humerus as part of the elbow joint. The inferior margin of the trochlear notch is formed by a prominent lip of bone called the **coronoid process of the ulna**. To the lateral side and slightly inferior to the trochlear notch is a small, smooth area called the **radial notch of the ulna**. This area is the site of articulation between the proximal radius and the ulna, forming the proximal radioulnar joint. The posterior and superior portions of the proximal ulna make up the **olecranon process**, which forms the bony tip of the elbow.
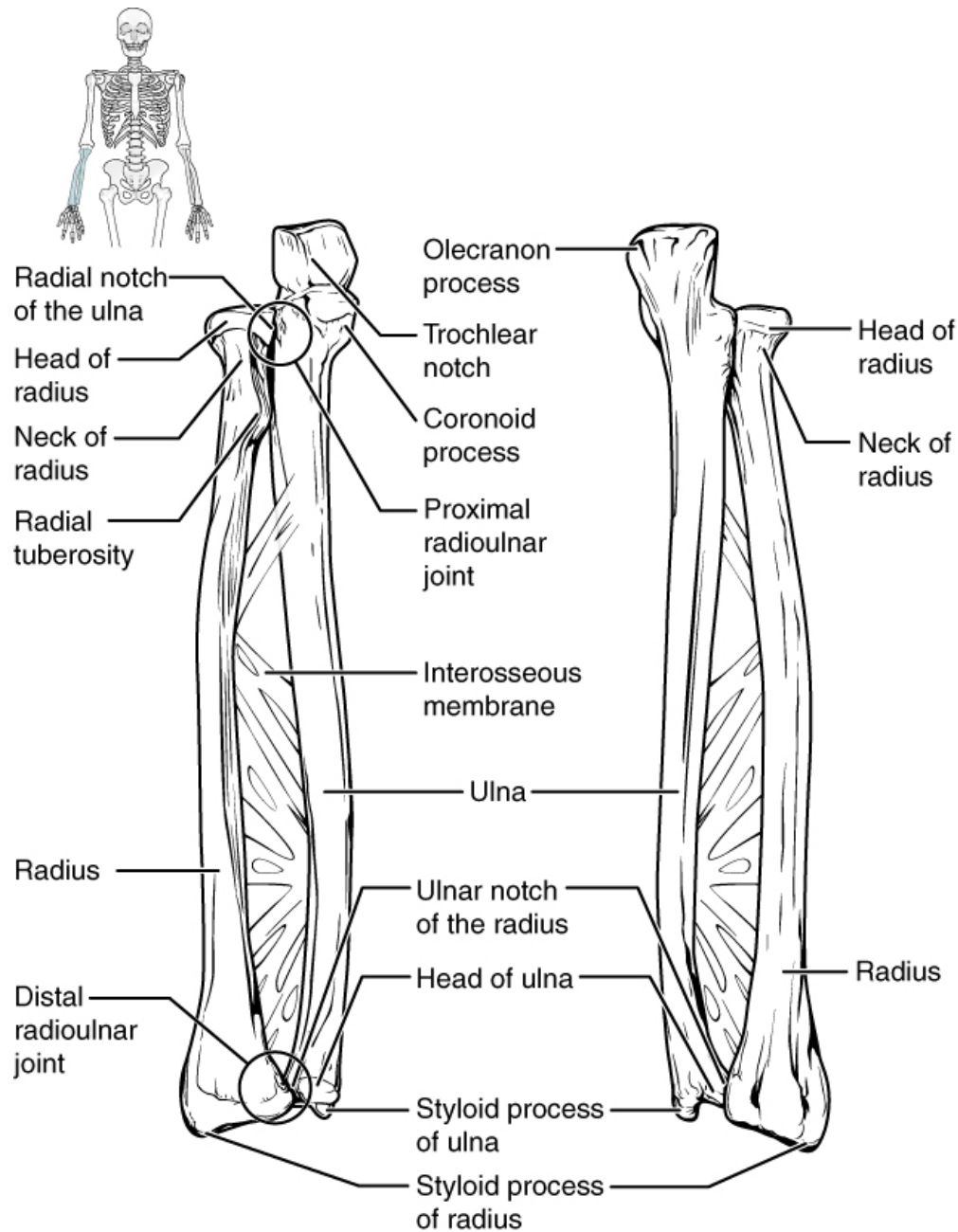
Figure 5.5 Ulna and Radius. The ulna is located on the medial side of the forearm, and the radius is on the lateral side. These bones are attached to each other by an interosseous membrane.

More distal is the shaft of the ulna. The lateral side of the shaft forms a ridge called the **interosseous border of the ulna**. This is the line of attachment for the **interosseous membrane of the forearm**, a sheet of dense connective tissue that unites the ulna and radius bones. The small, rounded area that forms the distal end is the **head of the ulna**. Projecting from the posterior side of the ulnar head is the **styloid process of the ulna**, a short bony projection. This serves as an attachment point for a connective tissue structure that unites the distal ends of the ulna and radius.

Radius

The radius runs parallel to the ulna, on the lateral (thumb) side of the forearm (**Figure 5.5**). The **head of the radius** is a disc-shaped structure that forms the proximal end. The small depression on the surface of the head articulates with the capitulum of the humerus as part of the elbow joint, whereas the smooth, outer margin of the head articulates with the radial notch of the ulna at the proximal radioulnar joint. The shaft of the radius is slightly curved and has a small ridge along its medial side. This ridge forms the **interosseous border of the radius**, which, like the similar border of the ulna, is the line of attachment for the interosseous membrane that unites the two forearm bones. The distal end of the radius has a smooth surface for articulation with two carpal bones to form the **radiocarpal joint** or wrist joint (**Figure 5.6**). On the medial side of the distal radius is the **ulnar notch of the radius**. This shallow depression articulates with the head of the ulna, which together form the **distal radioulnar joint**. The lateral end of the radius has a pointed projection called the **styloid process of the radius**. This provides attachment for ligaments that support the lateral side of the wrist joint. Compared to the styloid process of the ulna, the styloid process of the radius projects more distally, thereby limiting the range of movement for lateral deviations of the hand at the wrist joint.

Carpal Bones

The wrist and base of the hand are formed by a series of eight small carpal bones (**Figure 5.6**). The carpal bones are arranged in two rows, forming a proximal row of four carpal bones and a distal row of four carpal bones. The bones in the proximal row, running from the lateral (thumb) side to the medial side, are the **scaphoid** ("boat-shaped"), **lunate** ("moon-shaped"), **triquetrum** ("three-cornered"), and **pisiform** ("pea-shaped") bones. The small, rounded pisiform bone articulates with the anterior surface of the triquetrum bone. The pisiform thus projects anteriorly, where it forms the bony bump that can be felt at the medial base of your hand. The distal bones (lateral to medial) are the **trapezium** ("table"), **trapezoid** ("resembles a table"), **capitate** ("head-shaped"), and **hamate** ("hooked bone") bones. The hamate bone is characterized by a prominent bony extension on its anterior side called the **hook of the hamate bone**.

A helpful mnemonic for remembering the arrangement of the carpal bones is "So Long To Pinky, Here Comes The Thumb." This mnemonic starts on the lateral side and names the proximal bones from lateral to medial (scaphoid, lunate, triquetrum, pisiform), then makes a U-turn to name the distal bones from medial to lateral (hamate, capitate, trapezoid, trapezium). Thus, it starts and finishes on the lateral side.
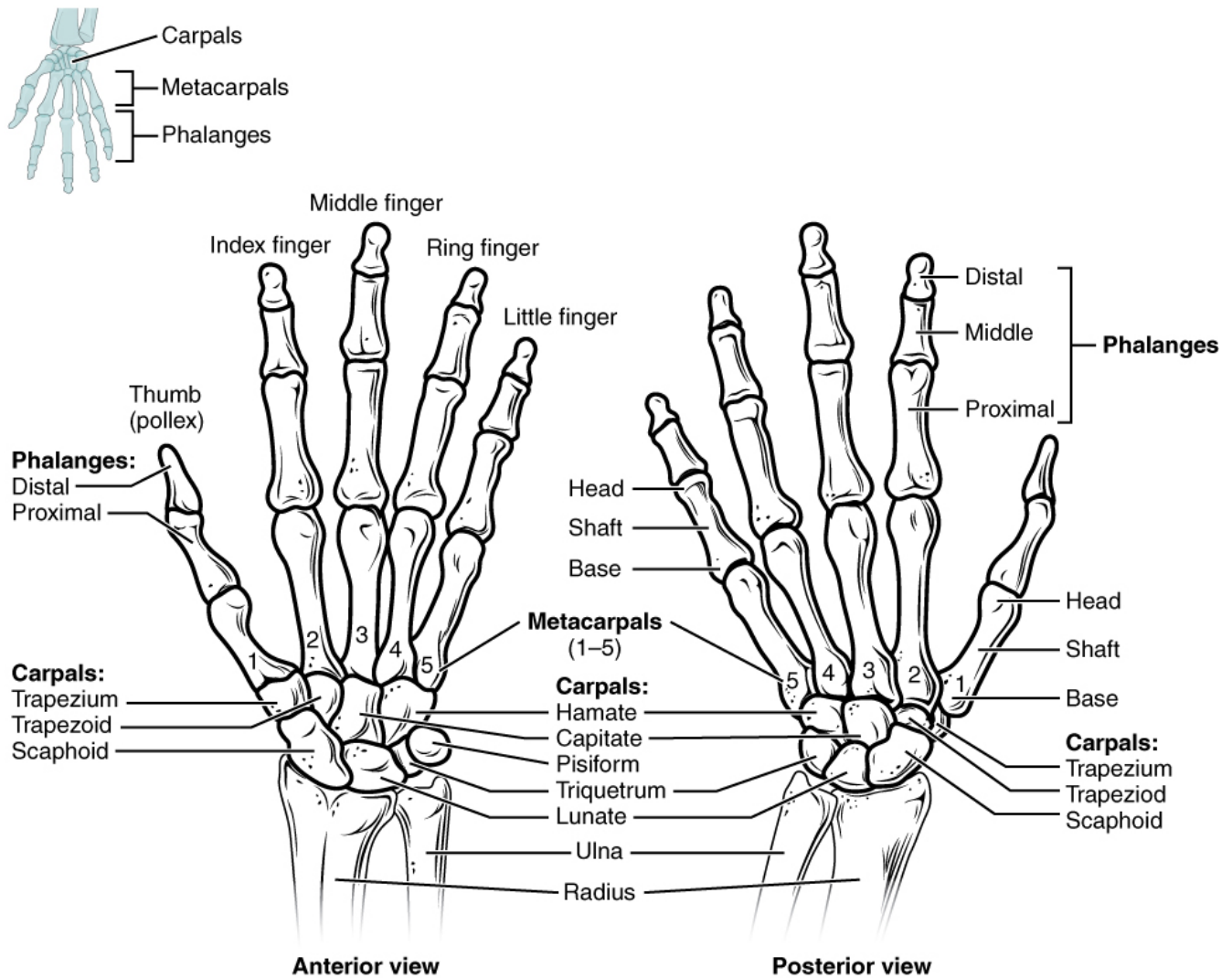
Figure 5.6 Bones of the Wrist and Hand. The eight carpal bones form the base of the hand. These are arranged into proximal and distal rows of four bones each. The metacarpal bones form the palm of the hand. The thumb and fingers consist of the phalanx bones.

In the articulated hand, the carpal bones form a U-shaped grouping. A strong ligament called the **flexor retinaculum** spans the top of this U-shaped area to maintain this grouping of the carpal bones. The flexor retinaculum is attached laterally to the trapezium and scaphoid bones, and medially to the hamate and pisiform bones. Together, the carpal bones and the flexor retinaculum form a passageway called the **carpal tunnel**, with the carpal bones forming the walls and floor, and the flexor retinaculum forming the roof of this space. The tendons of nine muscles of the anterior forearm and an important nerve pass through this narrow tunnel to enter the hand. Overuse of the muscle tendons or wrist injury can produce inflammation and swelling within this space. This produces compression of the nerve, resulting in carpal tunnel syndrome, which is characterized by pain or numbness, and muscle weakness in those areas of the hand supplied by this nerve.

Metacarpal Bones

The palm of the hand contains five elongated metacarpal bones. These bones lie between the carpal bones of the wrist and the bones of the fingers and thumb. The proximal end of each metacarpal bone articulates with one of the distal carpal bones (**Figure 5.6**). The expanded distal end of each metacarpal bone articulates with the proximal phalanx bone of the thumb or one of the fingers. The distal end also forms the knuckles of the hand, at the base of the fingers. The metacarpal bones are numbered 1–5, beginning at the thumb. The first metacarpal bone, at the base of the thumb, is separated from the other metacarpal bones. This allows it a freedom of motion that is independent of the other metacarpal bones, which is very important for thumb mobility. The remaining metacarpal bones are united together to form the palm of the hand.

Phalanx Bones

The fingers and thumb contain 14 bones, each of which is called a phalanx bone (plural = phalanges), named after the ancient Greek phalanx (a rectangular block of soldiers). The thumb (**pollex**) is digit number 1 and has two phalanges, a proximal phalanx, and a distal phalanx bone. Digits 2 (index finger) through 5 (little finger) have three phalanges each, called the proximal, middle, and distal phalanx bones.

The Pelvic Girdle and Pelvis

The **pelvic girdle** (hip girdle) is formed by a single bone, the **hip bone** or **os coxa** (coxal = "hip"), which serves as the attachment point for each lower limb. Each hip bone, in turn, is firmly joined to the axial skeleton via its attachment to the sacrum of the vertebral column. The right and left hip bones also converge anteriorly to attach to each other. The bony **pelvis** is the entire structure formed by the two hip bones, the sacrum, and, attached inferiorly to the sacrum, the coccyx (**Figure 5.7**).

The pelvis has several important functions. Its primary role is to support the weight of the upper body when sitting and to transfer this weight to the lower limbs when standing. It serves as an attachment point for trunk and lower limb muscles, and also protects the internal pelvic organs. Unlike the bones of the pectoral girdle, which are highly mobile to enhance the range of upper limb movements, the bones of the pelvis are strongly united to each other to form a largely immobile, weight-bearing structure. This is important for stability because it enables the weight of the body to be easily transferred laterally from the vertebral column, through the pelvic girdle and hip joints, and into either lower limb whenever the other limb is not bearing weight. Thus, the immobility of the pelvis provides a strong foundation for the upper body as it rests on top of the mobile lower limbs.
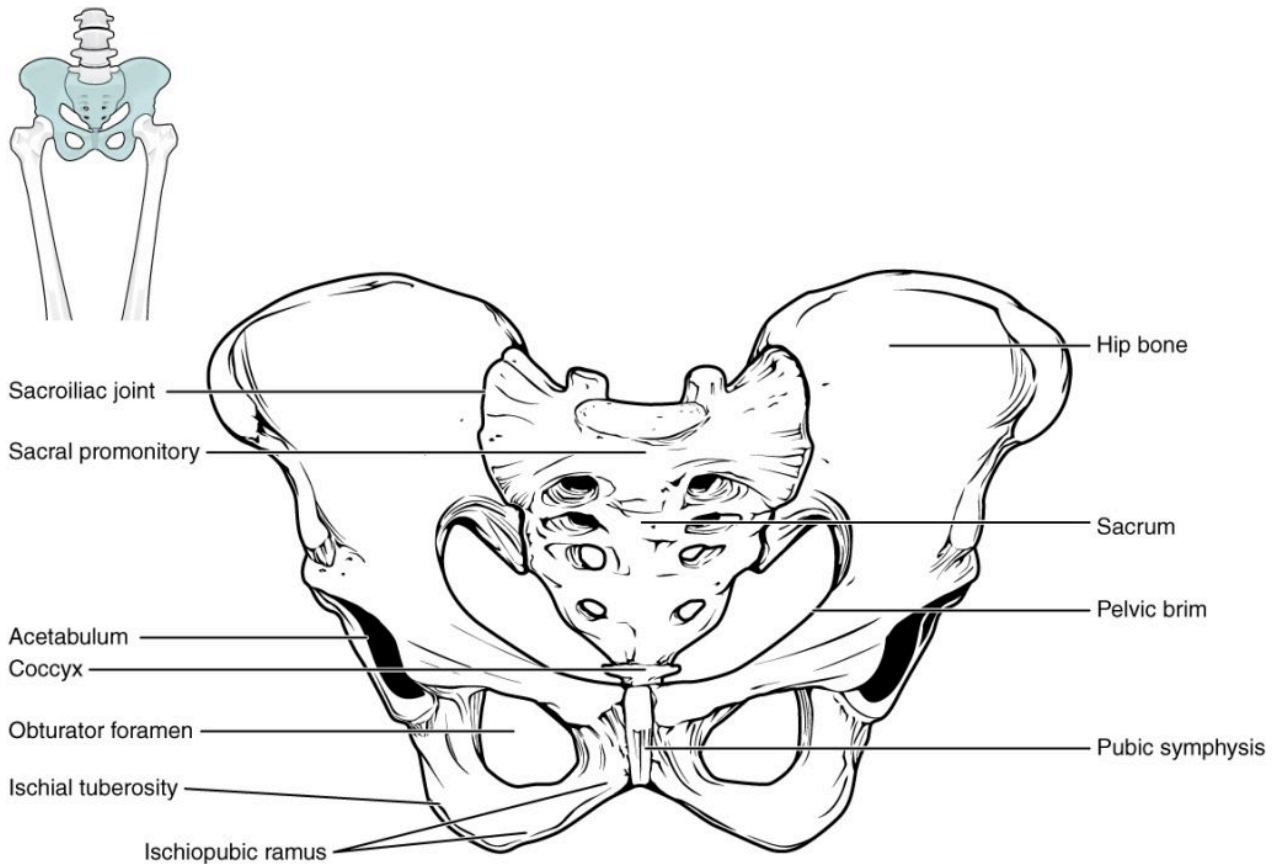
Figure 5.7 Pelvis. The pelvic girdle is formed by a single hip bone. The hip bone attaches the lower limb to the axial skeleton through its articulation with the sacrum. The right and left hip bones, plus the sacrum and the coccyx, together form the pelvis.

The hip bone, or os coxa, forms the pelvic girdle portion of the pelvis. The paired hip bones are the large, curved bones that form the lateral and anterior aspects of the pelvis. Each adult hip bone is formed by three separate bones that fuse together during the late teenage years. These bony components are the ilium, ischium, and pubis (**Figure 5.8**). These names are retained and used to define the three regions of the adult hip bone.

The **ilium** is the fan-like, superior region that forms the largest part of the hip bone. It is firmly united to the sacrum at the largely immobile sacroiliac joint (**Figure 5.7**). The **ischium** forms the posteroinferior region of each hip bone. It supports the body when sitting. The **pubis** forms the anterior portion of the hip bone. The pubis curves medially, where it joins to the pubis of the opposite hip bone at a specialized joint called the **pubic symphysis**.

The three areas of each hip bone, the ilium, pubis, and ischium, converge centrally to form a deep, cup-shaped cavity called the **acetabulum**. This is located on the lateral side of the hip bone and is part of the hip joint. The large opening in the anteroinferior hip bone between the ischium and pubis is the **obturator foramen**. This space is largely filled in by a layer of connective tissue and serves for the attachment of muscles on both its internal and external surfaces.
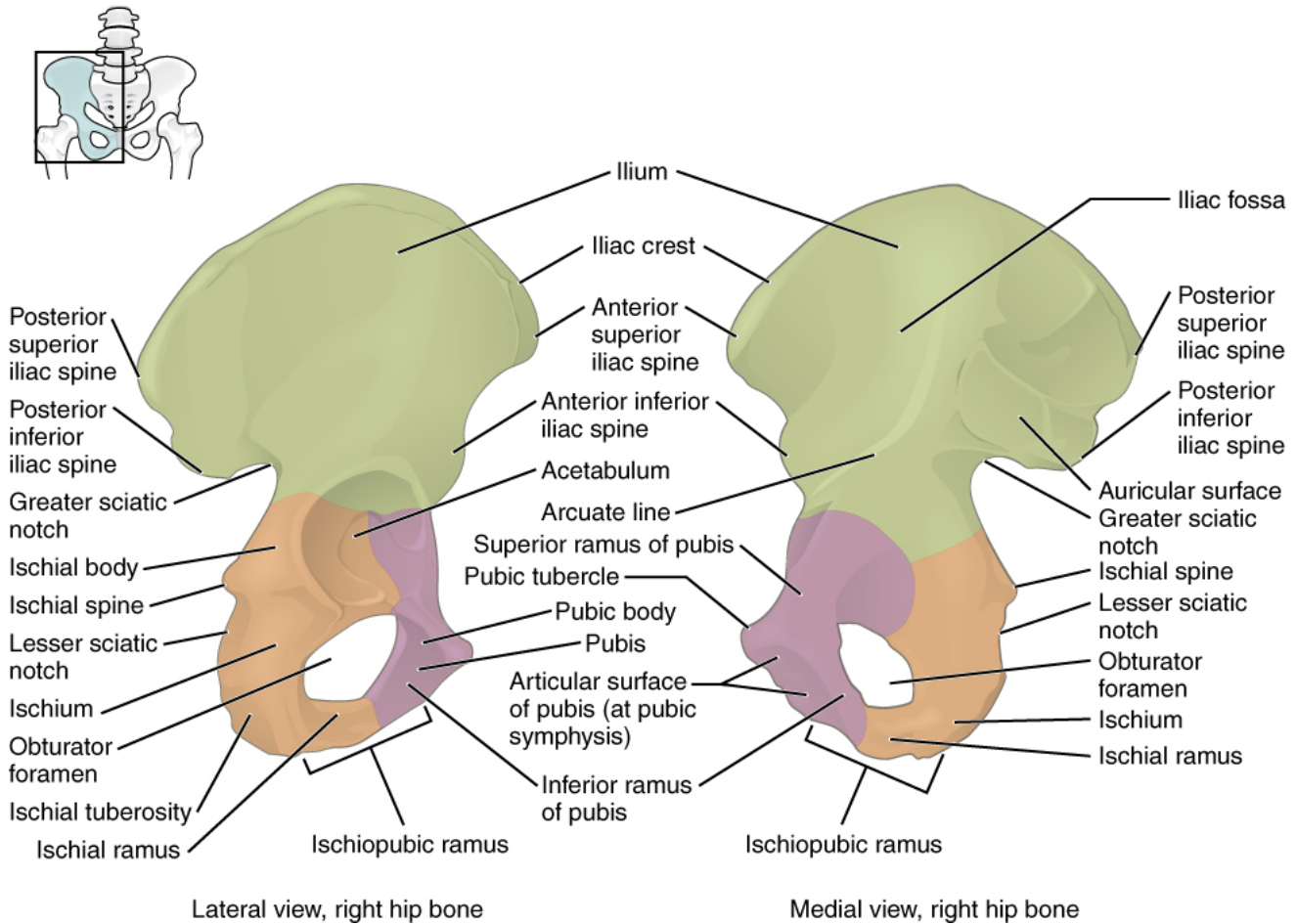
Figure 5.8 The Ilium, Ischium, and Pubis. The adult hip bone consists of three regions. The ilium forms the large, fan-shaped superior portion, the ischium forms the posteroinferior portion, and the pubis forms the anteromedial portion.

Ilium

When you place your hands on your waist, you can feel the arching, superior margin of the ilium along your waistline (**Figure 5.8**). This curved, superior margin of the ilium is the **iliac crest**. The rounded, anterior termination of the iliac crest is the **anterior superior iliac spine**. This important bony landmark can be felt at your anterolateral hip. Inferior to the anterior superior iliac spine is a rounded protuberance called the **anterior inferior iliac spine**. Both of these iliac spines serve as attachment points for muscles of the thigh. Posteriorly, the iliac crest curves downward to terminate as the **posterior superior iliac spine**. Muscles and ligaments surround but do not cover this bony landmark, thus sometimes producing a depression seen as a "dimple" located on the lower back. More inferiorly is the **posterior inferior iliac spine**. This is located at the inferior end of a large, roughened area called the **auricular surface of the ilium**. The auricular surface articulates with the auricular surface of the sacrum to form the sacroiliac joint. Both the posterior superior and posterior inferior iliac spines serve as attachment points for the muscles and very strong ligaments that support the sacroiliac joint. The large, inverted U-shaped indentation located on the posterior margin of the lower ilium is called the **greater sciatic notch**.

Ischium

The ischium forms the posterolateral portion of the hip bone (**Figure 5.8**). The large, roughened area of the inferior ischium is the **ischial tuberosity**. This serves as the attachment for the posterior thigh muscles and also carries the weight of the body when sitting. You can feel the ischial tuberosity if you wiggle your pelvis against the seat of a chair. Projecting superiorly and anteriorly from the ischial tuberosity is a narrow segment of bone called the **ischial ramus**. The slightly curved posterior margin of the ischium above the ischial tuberosity is the **lesser sciatic notch**. The bony projection separating the lesser sciatic notch and greater sciatic notch is the **ischial spine**.

Pubis

The pubis forms the anterior portion of the hip bone (**Figure 5.8**). The enlarged medial portion of the pubis is the pubic body. The pubic body is joined to the pubic body of the opposite hip bone by the **pubic symphysis**. Extending downward and laterally from the body is the **inferior pubic ramus**. The **pubic arch** is the bony structure formed by the pubic symphysis, and the bodies and inferior pubic rami of the adjacent pubic bones. The inferior pubic ramus extends downward to join the ischial ramus. Together, these form the single **ischiopubic ramus**, which extends from the pubic body to the ischial tuberosity. The inverted V-shape formed as the ischiopubic rami from both sides come together at the pubic symphysis is called the **subpubic angle**.

Bones of the Lower Limb

Like the upper limb, the lower limb is divided into three regions. The **thigh** is that portion of the lower limb located between the hip joint and knee joint. The **leg** is specifically the region between the knee joint and the ankle joint. Distal to the ankle is the **foot**. The lower limb contains 30 bones. These are the femur, patella, tibia, fibula, tarsal bones, metatarsal bones, and phalanges (**Figure 5.1**). The **femur** is the single bone of the thigh. The **patella** is the kneecap and articulates with the distal femur. The **tibia** is the larger, weight-bearing bone located on the medial side of the leg, and the **fibula** is the thin bone of the lateral leg. The bones of the foot are divided into three groups. The posterior portion of the foot is formed by a group of seven bones, each of which is known as a **tarsal bone**, whereas the mid-foot contains five elongated bones, each of which is a **metatarsal bone**. The toes contain 14 small bones, each of which is a **phalanx bone of the foot**.

Femur

The femur, or thigh bone, is the single bone of the thigh region (**Figure 5.9**). It is the longest and strongest bone of the body, and accounts for approximately one-quarter of a person's total height. The rounded, proximal end is the **head of the femur**, which articulates with the acetabulum of the hip bone to form the **hip joint**. The narrowed region below the head is the **neck of the femur**. This is a common area for fractures of the femur. The **greater trochanter** is the large, upward, bony projection located above the base of the neck. Multiple muscles that act across the hip joint attach to the greater trochanter, which, because of its projection from the femur, gives additional leverage to these muscles. The greater trochanter can be felt just under the skin on the lateral side of your upper thigh. The **lesser trochanter** is a small, bony prominence that lies on the medial aspect of the femur, just below the neck. A single, powerful muscle attaches to the lesser trochanter.
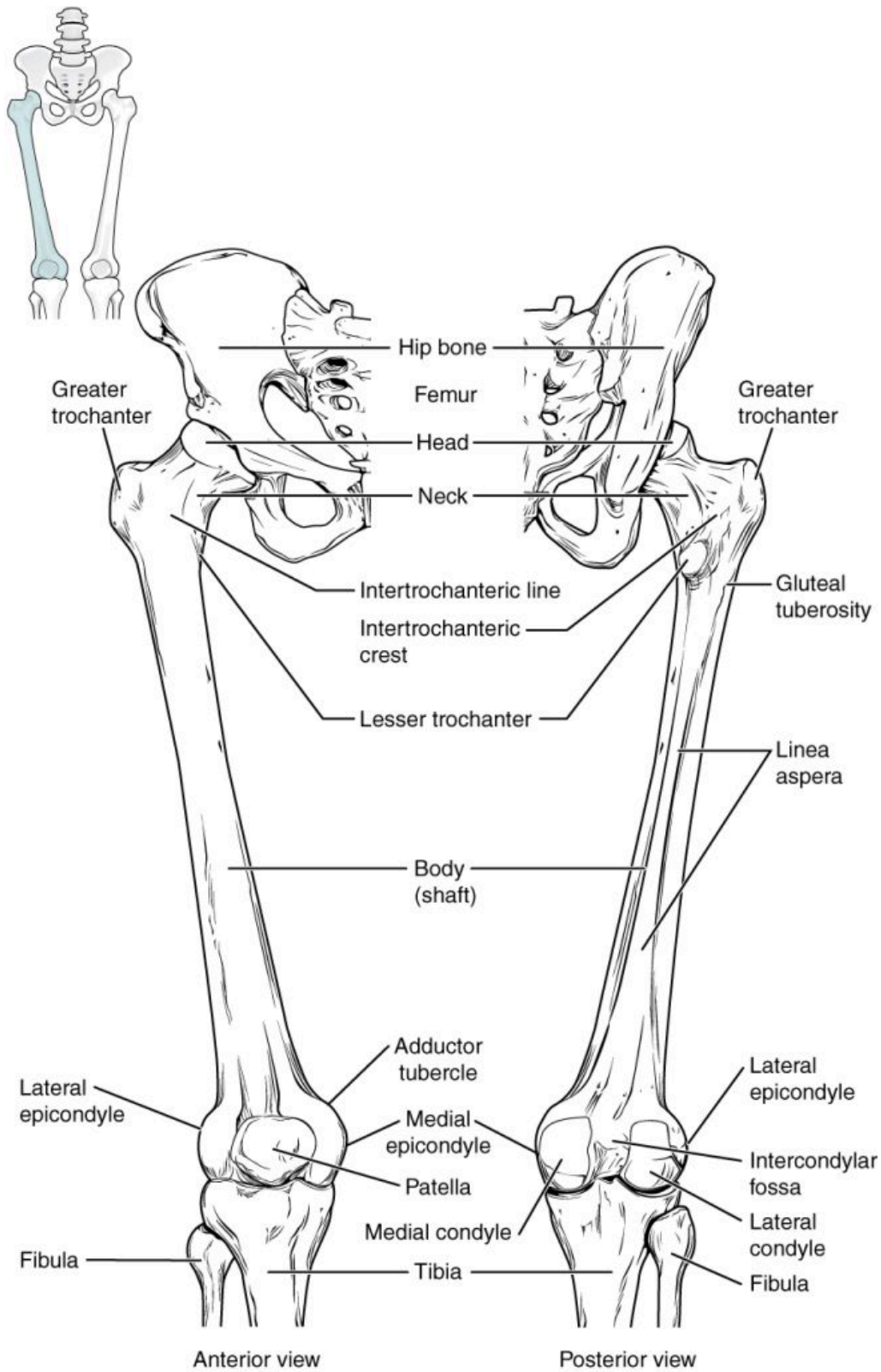
Figure 5.9 Femur and Patella. The femur is the single bone of the thigh region. It articulates superiorly with the hip bone at the hip joint, and inferiorly with the tibia at the knee joint. The patella only articulates with the distal end of the femur.

The elongated shaft of the femur has a slight anterior bowing or curvature. At its proximal end, the posterior shaft has the gluteal tuberosity, a roughened area extending inferiorly from the greater trochanter. More inferiorly, the **gluteal tuberosity** becomes continuous with the **linea aspera** ("rough line"). This is the roughened ridge that passes distally along the posterior side of the mid-femur. Multiple muscles of the hip and thigh regions make long, thin attachments to the femur along the linea aspera.

The distal end of the femur has medial and lateral bony expansions. On the lateral side, the smooth portion that covers the distal and posterior aspects of the lateral expansion is the **lateral condyle of the femur**. The roughened area on the outer, lateral side of the condyle is the **lateral epicondyle of the femur**. Similarly, the smooth region of the distal and posterior medial femur is the **medial condyle of the femur**, and the irregular outer, medial side of this is the **medial epicondyle of the femur**. The lateral and medial condyles articulate with the tibia to form the knee joint. The epicondyles provide attachment for muscles and supporting ligaments of the knee. Anteriorly, the smooth surfaces of the condyles join together to form a wide groove called the **patellar surface**, which provides for articulation with the patella bone. The combination of the medial and lateral condyles with the patellar surface gives the distal end of the femur a horseshoe (U) shape.

Patella

The patella (kneecap) is the largest sesamoid bone of the body (**Figure 5.9**). A sesamoid bone is a bone that is incorporated into the tendon of a muscle where that tendon crosses a joint. The sesamoid bone articulates with the underlying bones to prevent damage to the muscle tendon due to rubbing against the bones during movements of the joint. The patella is found in the tendon of the quadriceps femoris muscle, the large muscle of the anterior thigh that passes across the anterior knee to attach to the tibia. The patella articulates with the patellar surface of the femur and thus prevents rubbing of the muscle tendon against the distal femur. The patella also lifts the tendon away from the knee joint, which increases the leverage power of the quadriceps femoris muscle as it acts across the knee. The patella does not articulate with the tibia.

Tibia

The tibia (shin bone) is the medial bone of the leg and is larger than the fibula, with which it is paired (**Figure 5.10**). The tibia is the main weight-bearing bone of the lower leg and the second longest bone of the body, after the femur. The medial side of the tibia is located immediately under the skin, allowing it to be easily palpated down the entire length of the medial leg.
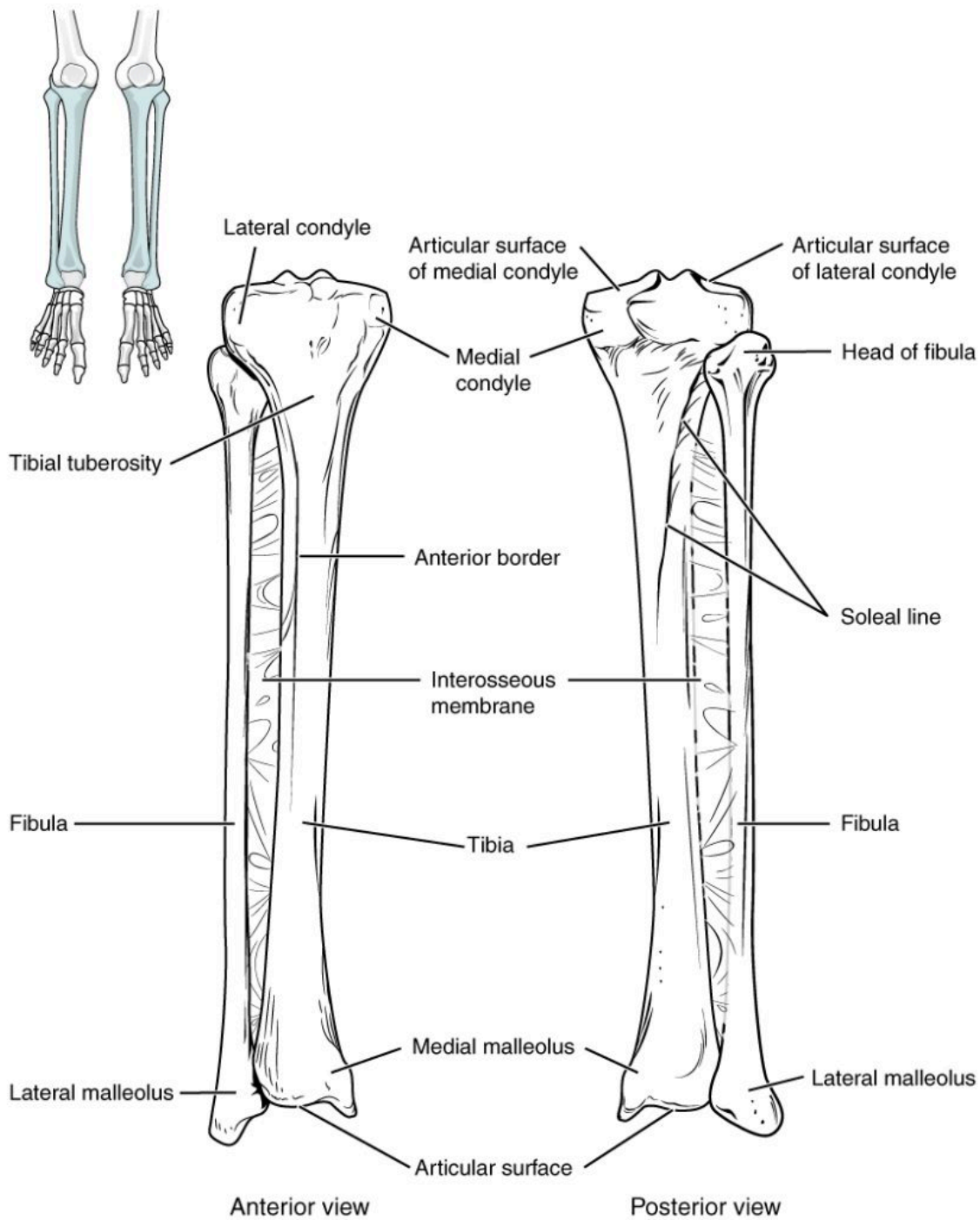
Figure 5.10 Tibia and Fibula. The tibia is the larger, weight-bearing bone located on the medial side of the leg. The fibula is the slender bone of the lateral side of the leg and does not bear weight.

The proximal end of the tibia is greatly expanded. The two sides of this expansion form the **medial condyle of the tibia** and the **lateral condyle of the tibia**. The tibia does not have epicondyles. The top surface of each condyle is smooth and flattened. These areas articulate with the medial and lateral condyles of the femur to form the **knee**

joint. Between the articulating surfaces of the tibial condyles is the **intercondylar eminence**, an irregular, elevated area that serves as the inferior attachment point for two supporting ligaments of the knee.

The **tibial tuberosity** is an elevated area on the anterior side of the tibia, near its proximal end. It is the final site of attachment for the muscle tendon associated with the patella. More inferiorly, the shaft of the tibia becomes triangular in shape. A small ridge running down the lateral side of the tibial shaft is the **interosseous border of the tibia**. This is for the attachment of the **interosseous membrane of the leg**, the sheet of dense connective tissue that unites the tibia and fibula bones.

The large expansion found on the medial side of the distal tibia is the **medial malleolus** ("little hammer"). This forms the large bony bump found on the medial side of the ankle region. Both the smooth surface on the inside of the medial malleolus and the smooth area at the distal end of the tibia articulate with the talus bone of the foot as part of the ankle joint. On the lateral side of the distal tibia is a wide groove called the **fibular notch**. This area articulates with the distal end of the fibula, forming the distal tibiofibular joint.

Fibula

The fibula is the slender bone located on the lateral side of the leg (**Figure 5.10**). The fibula does not bear weight. It serves primarily for muscle attachments and thus is largely surrounded by muscles. Only the proximal and distal ends of the fibula can be palpated.

The **head of the fibula** is the small, knob-like, proximal end of the fibula. It articulates with the inferior aspect of the lateral tibial condyle, forming the proximal tibiofibular joint. The thin shaft of the fibula has the **interosseous border of the fibula**, a narrow ridge running down its medial side for the attachment of the interosseous membrane that spans the fibula and tibia. The distal end of the fibula forms the **lateral malleolus**, which forms the easily palpated bony bump on the lateral side of the ankle. The deep (medial) side of the lateral malleolus articulates with the talus bone of the foot as part of the ankle joint. The distal fibula also articulates with the fibular notch of the tibia.

Tarsal Bones

The posterior half of the foot is formed by seven tarsal bones (**Figure 5.11**). The most superior bone is the **talus**. This has a relatively square-shaped, upper surface that articulates with the tibia and fibula to form the **ankle joint**. Three areas of articulation form the ankle joint: The superomedial surface of the talus bone articulates with the medial malleolus of the tibia, the top of the talus articulates with the distal end of the tibia, and the lateral side of the talus articulates with the lateral malleolus of the fibula. Inferiorly, the talus articulates with the **calcaneus** (heel bone), the largest bone of the foot, which forms the heel. Body weight is transferred from the tibia to the talus to the calcaneus, which rests on the ground.
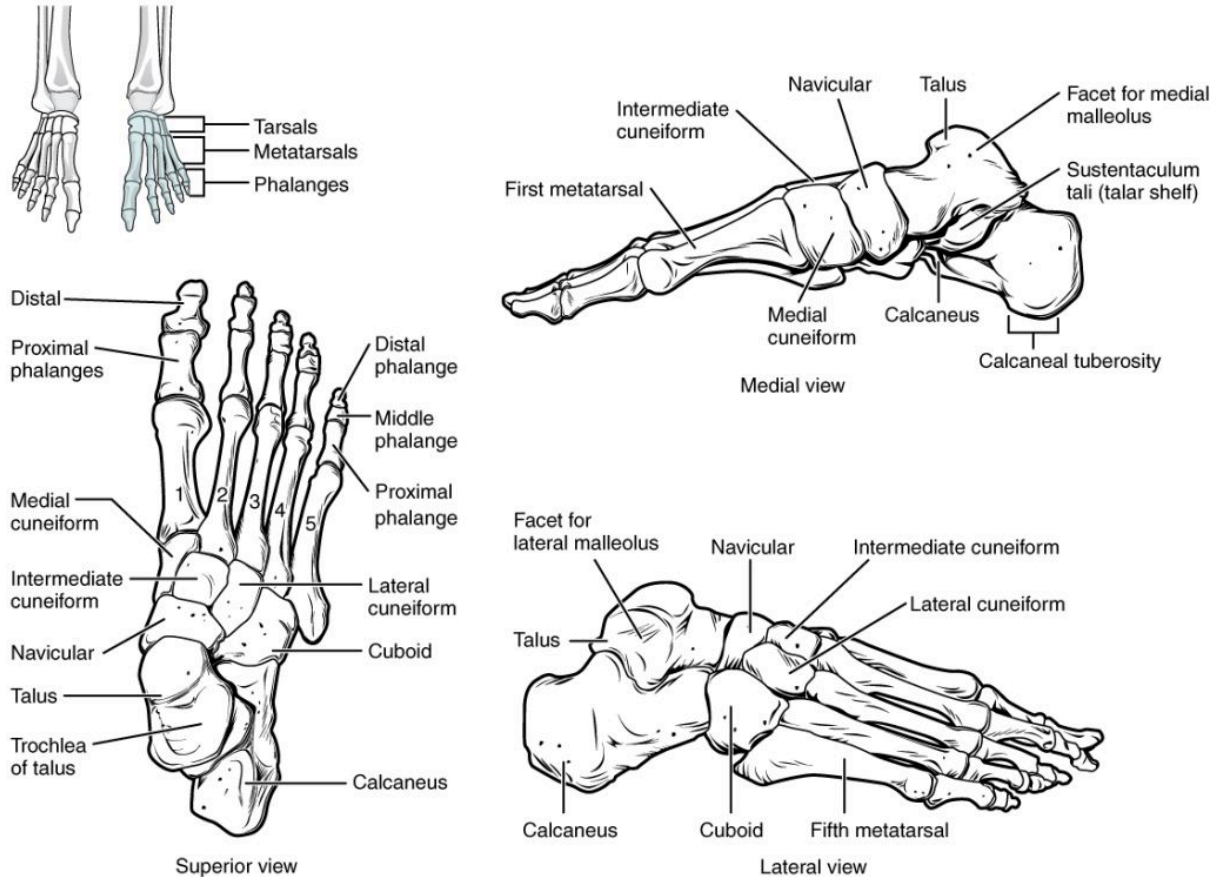
Figure 5.11 Bones of the Foot. The bones of the foot are divided into three groups. The posterior foot is formed by the seven tarsal bones. The mid-foot has the five metatarsal bones. The toes contain the phalanges.

The **cuboid** bone articulates with the anterior end of the calcaneus bone. The talus bone articulates anteriorly with the **navicular** bone, which in turn articulates anteriorly with the three cuneiform ("wedge-shaped") bones. These bones are the **medial cuneiform**, the **intermediate cuneiform**, and the **lateral cuneiform**. Each of these bones has a broad superior surface and a narrow inferior surface, which together produce the transverse (medial-lateral) curvature of the foot. The navicular and lateral cuneiform bones also articulate with the medial side of the cuboid bone.

Metatarsal Bones

The anterior half of the foot is formed by the five metatarsal bones, which are located between the tarsal bones of the posterior foot and the phalanges of the toes (**Figure 5.11**). These elongated bones are numbered 1–5, starting with the medial side of the foot. The first metatarsal bone is shorter and thicker than the others. The second metatarsal is the longest. The **base of the metatarsal bone** is the proximal end of each metatarsal bone. These articulate with the cuboid or cuneiform bones. The expanded distal end of each metatarsal is the **head of the metatarsal bone**. Each metatarsal bone articulates with the proximal phalanx of a toe to form a metatarsophalangeal joint. The heads of the metatarsal bones also rest on the ground and form the ball (anterior end) of the foot.

Phalanges

The toes contain a total of 14 phalanx bones (phalanges), arranged in a similar manner as the phalanges of the fingers (**Figure 5.11**). The toes are numbered 1–5, starting with the big toe (**hallux**). The big toe has two phalanx bones, the proximal and distal phalanges. The remaining toes all have proximal, middle, and distal phalanges.

Joints

Classification of Joints

A **joint**, also called an **articulation**, is any place where adjacent bones or bone and cartilage come together (articulate with each other) to form a connection. Joints are classified both structurally and functionally. **Structural classifications of joints** take into account whether the adjacent bones are strongly anchored to each other by fibrous connective tissue or cartilage, or whether the adjacent bones articulate with each other within a fluid-filled space called a joint cavity. **Functional classifications** describe the degree of movement available between the bones, ranging from immobile, to slightly mobile, to freely moveable joints. The amount of movement available at a particular joint of the body is related to the functional requirements for that joint. Thus immobile or slightly moveable joints serve to protect internal organs, give stability to the body, and allow for limited body movement. In contrast, freely moveable joints allow for much more extensive movements of the body and limbs.

Functional Classification of Joints

The functional classification of joints is determined by the amount of mobility found between the adjacent bones. Joints are thus functionally classified as a **synarthrosis** or immobile joint, an **amphiarthrosis** or slightly moveable joint, or as a **diarthrosis**, which is a freely moveable joint (arthroun = "to fasten by a joint").

Synarthrosis

An immobile or nearly immobile joint is called a **synarthrosis**. The immobile nature of these joints provide for a strong union between the articulating bones. This is important at locations where the bones provide protection for internal organs. Examples include sutures, the fibrous joints between the bones of the skull that surround and protect the brain (**Figure 5.12**), and the manubriosternal joint, the cartilaginous joint that unites the manubrium and body of the sternum for protection of the heart.
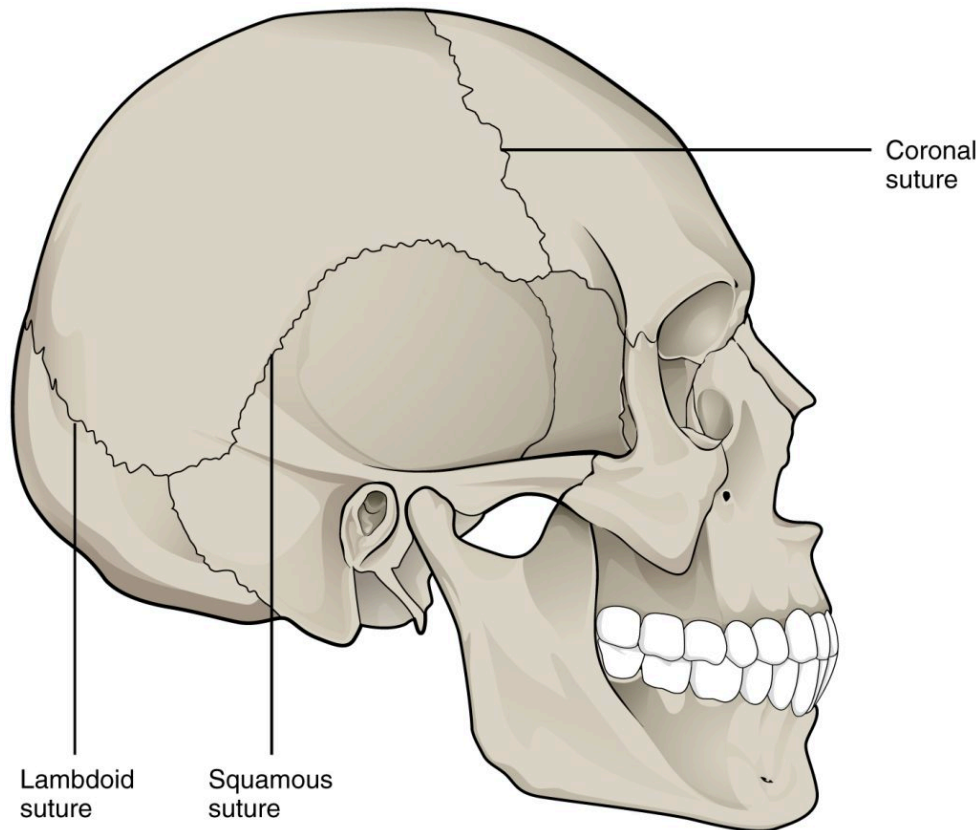
Figure 5.12 Suture Joints of Skull. The suture joints of the skull are an example of a synarthrosis, an immobile or essentially immobile joint.

Amphiarthrosis

An **amphiarthrosis** is a joint that has limited mobility. An example of this type of joint is the cartilaginous joint that unites the bodies of adjacent vertebrae. Filling the gap between the vertebrae is a thick pad of fibrocartilage called an intervertebral disc (**Figure 5.13**). Each intervertebral disc strongly unites the vertebrae but still allows for a limited amount of movement between them. However, the small movements available between adjacent vertebrae can sum together along the length of the vertebral column to provide for large ranges of body movements. Another example of an amphiarthrosis is the pubic symphysis of the pelvis. This is a cartilaginous joint in which the pubic regions of the right and left hip bones are strongly anchored to each other by fibrocartilage. This joint normally has very little mobility. The strength of the pubic symphysis is important in conferring weight-bearing stability to the pelvis.
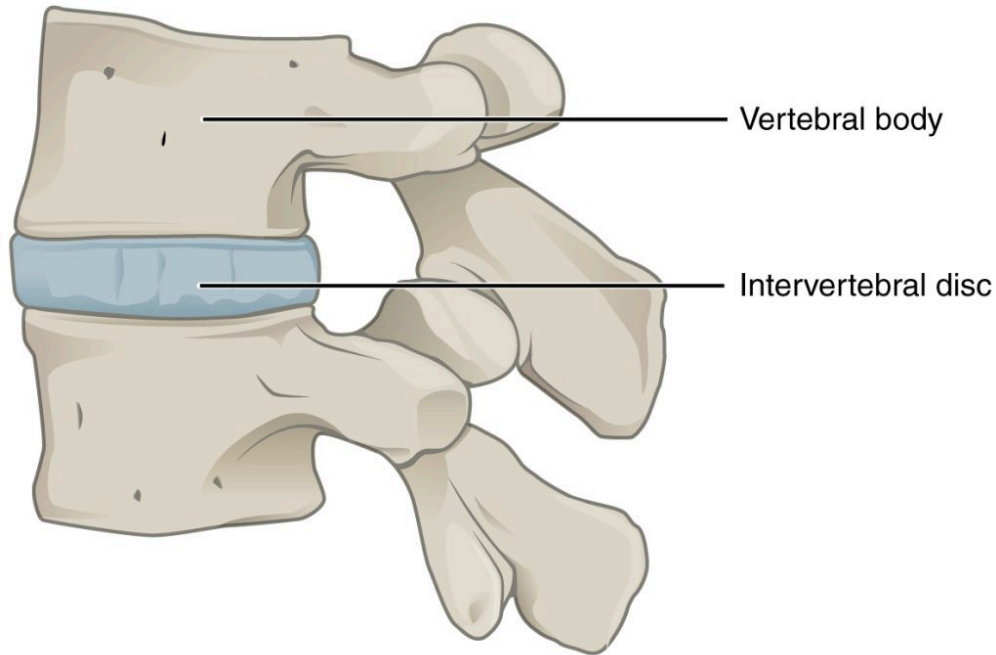
Lateral view

Figure 5.13 Intervertebral Disc. An intervertebral disc unites the bodies of adjacent vertebrae within the vertebral column. Each disc allows for limited movement between the vertebrae and thus functionally forms an amphiarthrosis type of joint. Intervertebral discs are made of fibrocartilage and thereby structurally form a symphysis type of cartilaginous joint.

Diarthrosis

A freely mobile joint is classified as a **diarthrosis**. These types of joints include all synovial joints of the body, which provide the majority of body movements. Most diarthrotic joints are found in the appendicular skeleton and thus give the limbs a wide range of motion. These joints are divided into three categories, based on the number of axes of motion provided by each. An axis in anatomy is described as the movements in reference to the three anatomical planes: transverse, frontal, and sagittal. Thus, diarthroses are classified as uniaxial (for movement in one plane), biaxial (for movement in two planes), or multiaxial joints (for movement in all three anatomical planes) (**Figure 5.14**).
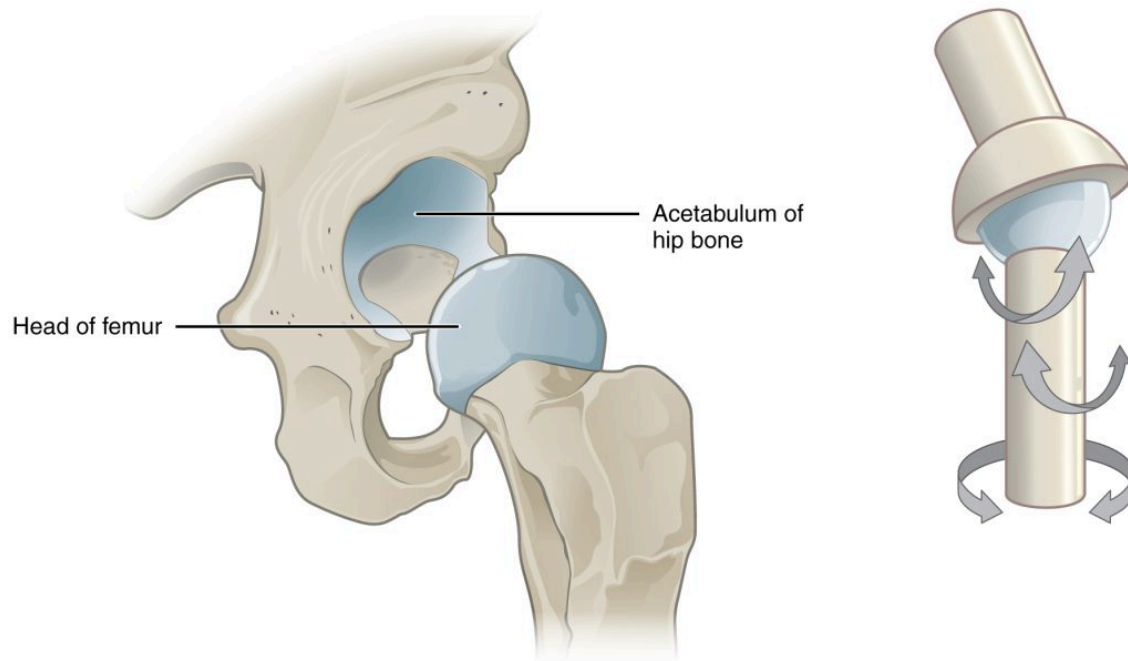
Figure 5.14 Multiaxial Joint. A multiaxial joint, such as the hip joint, allows for three types of movement: anterior-posterior, medial-lateral, and rotational.

Structural Classification of Joints

The structural classification of joints is based on whether the articulating surfaces of the adjacent bones are directly connected by fibrous connective tissue or cartilage, or whether the articulating surfaces contact each other within a fluid-filled joint cavity. These differences serve to divide the joints of the body into three structural classifications. A **fibrous joint** is where the adjacent bones are united by fibrous connective tissue. At a **cartilaginous joint**, the bones are joined by hyaline cartilage or fibrocartilage. At a **synovial joint**, the articulating surfaces of the bones are not directly connected, but instead come into contact with each other within a joint cavity that is filled with a lubricating fluid. Synovial joints allow for free movement between the bones and are the most common joints of the body.

Depending on their location, fibrous joints may be functionally classified as a synarthrosis (immobile joint) or an amphiarthrosis (slightly mobile joint). Cartilaginous joints are also functionally classified as either a synarthrosis or an amphiarthrosis joint. All synovial joints are functionally classified as a diarthrosis joint.

Fibrous Joints

At a fibrous joint, the adjacent bones are directly connected to each other by fibrous connective tissue, and thus the bones do not have a joint cavity between them (**Figure 5.15**). The gap between the bones may be narrow or wide. There are three types of fibrous joints. A suture is the narrow fibrous joint found between most bones of the skull. At a syndesmosis joint, the bones are more widely separated but are held together by a narrow band of fibrous connective tissue called a ligament or a wide sheet of connective tissue called an interosseous membrane. This type of fibrous joint is found between the shaft regions of the long bones in the forearm and in

the leg. Lastly, a gomphosis is the narrow fibrous joint between the roots of a tooth and the bony socket in the jaw into which the tooth fits.
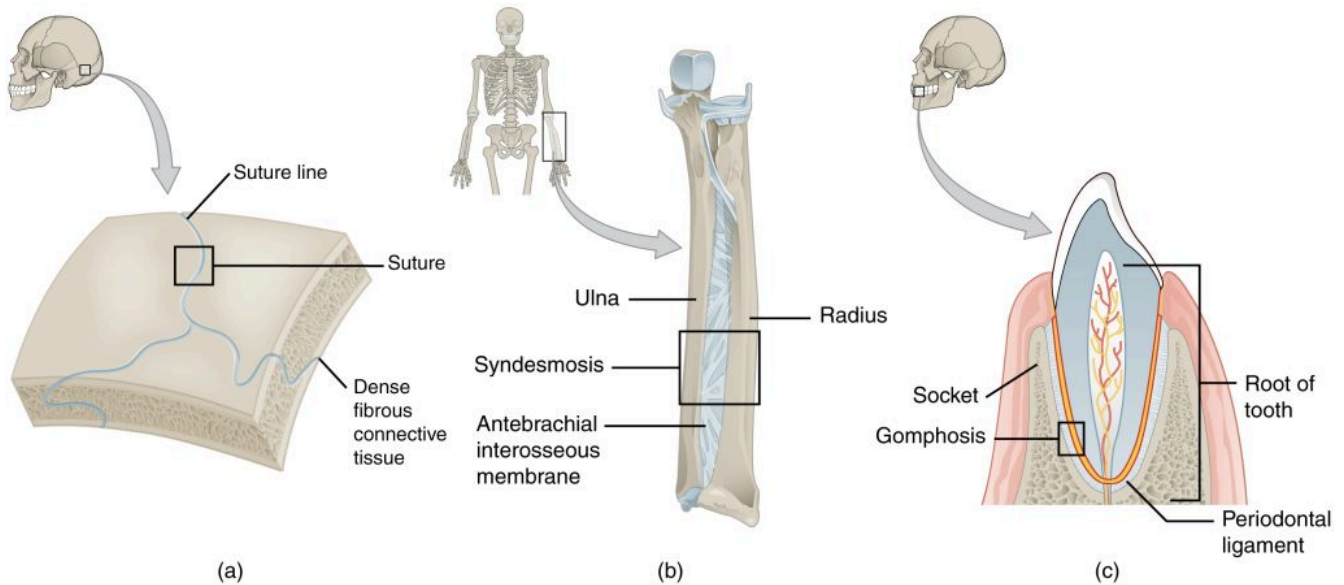
Figure 5.15 Fibrous Joints. Fibrous joints form strong connections between bones. (a) Sutures join most bones of the skull. (b) An interosseous membrane forms a syndesmosis between the radius and ulna bones of the forearm. (c) A gomphosis is a specialized fibrous joint that anchors a tooth to its socket in the jaw.

Cartilaginous Joints

As the name indicates, at a cartilaginous joint, the adjacent bones are united by cartilage, a tough but flexible type of connective tissue. These types of joints lack a joint cavity and involve bones that are joined together by either hyaline cartilage or fibrocartilage (**Figure 5.16**). There are two types of cartilaginous joints. A synchondrosis is a cartilaginous joint where the bones are joined by hyaline cartilage. Also classified as a synchondrosis are places where bone is united to a cartilage structure, such as between the anterior end of a rib and the costal cartilage of the thoracic cage. The second type of cartilaginous joint is a symphysis, where the bones are joined by fibrocartilage.
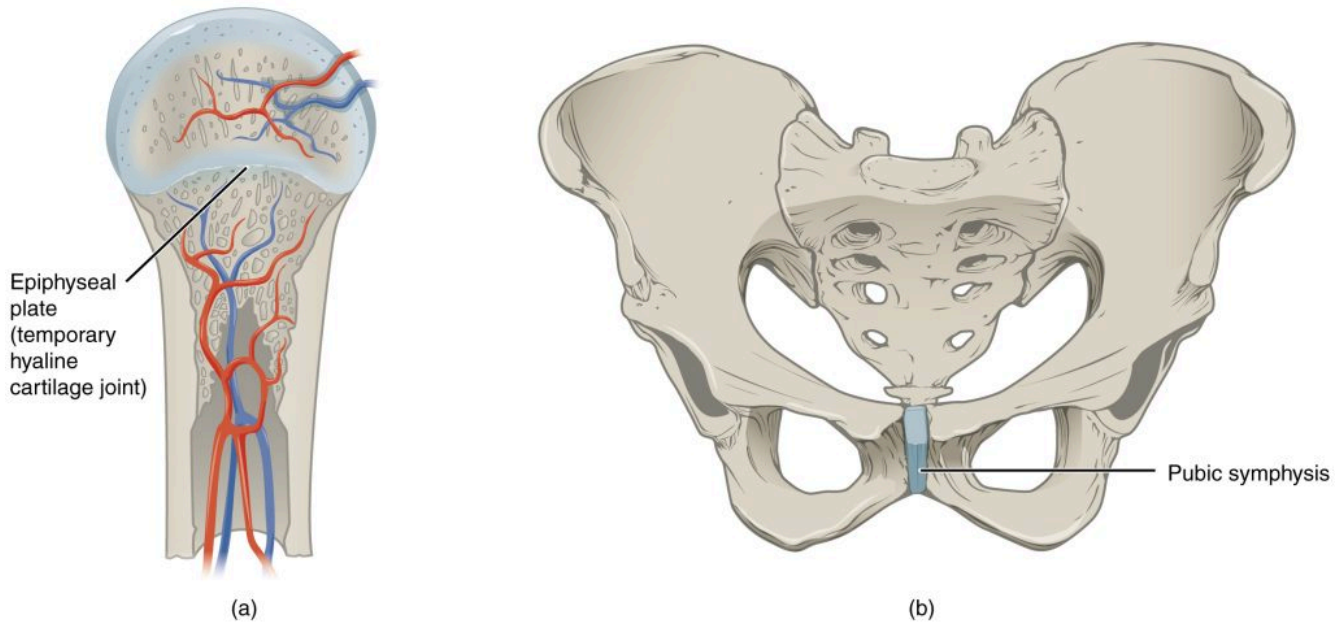
Figure 5.16 Cartilaginous Joints. At cartilaginous joints, bones are united by hyaline cartilage to form a synchondrosis or by fibrocartilage to form a symphysis. (a) The hyaline cartilage of the epiphyseal plate (growth plate) forms a synchondrosis that unites the shaft (diaphysis) and end (epiphysis) of a long bone and allows the bone to grow in length. (b) The pubic portions of the right and left hip bones of the pelvis are joined together by fibrocartilage, forming the pubic symphysis.

Synovial Joints

Synovial joints are the most common type of joint in the body. A key structural characteristic for a synovial joint that is not seen at fibrous or cartilaginous joints is the presence of a **joint cavity** (**Figure 5.17**). This fluid-filled space is the site at which the articulating surfaces of the bones contact each other. Also unlike fibrous or cartilaginous joints, the articulating bone surfaces at a synovial joint are not directly connected to each other with fibrous connective tissue or cartilage. This gives the bones of a synovial joint the ability to move smoothly against each other, allowing for increased joint mobility.
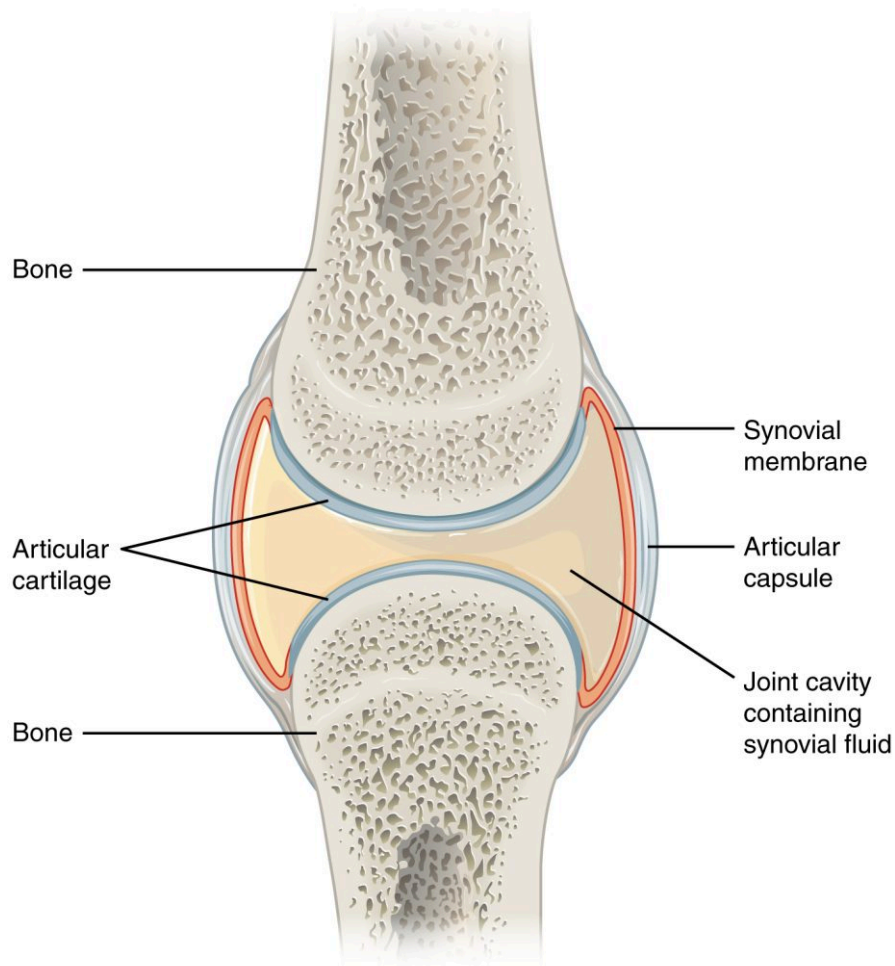
Figure 5.17 Synovial Joints. Synovial joints allow for smooth movements between the adjacent bones. The joint is surrounded by an articular capsule that defines a joint cavity filled with synovial fluid. The articulating surfaces of the bones are covered by a thin layer of articular cartilage. Ligaments support the joint by holding the bones together and resisting excess or abnormal joint motions.

Synovial joints are characterized by the presence of a joint cavity. The walls of this space are formed by the **articular capsule**, a fibrous connective tissue structure that is attached to each bone just outside the area of the bone's articulating surface. The bones of the joint articulate with each other within the joint cavity.

Friction between the bones at a synovial joint is prevented by the presence of the **articular cartilage**, a thin layer of hyaline cartilage that covers the entire articulating surface of each bone. However, unlike at a cartilaginous joint, the articular cartilages of each bone are not continuous with each other. Instead, the articular cartilage acts like a Teflon® coating over the bone surface, allowing the articulating bones to move smoothly against each other without damaging the underlying bone tissue. Lining the inner surface of the articular capsule is a thin **synovial membrane**. The cells of this membrane secrete **synovial fluid** (synovia = "a thick fluid"), a thick, slimy fluid that provides lubrication to further reduce friction between the bones of the joint. This fluid also provides nourishment to the articular cartilage, which does not contain blood vessels. The ability of the bones to move smoothly against

each other within the joint cavity, and the freedom of joint movement this provides, means that each synovial joint is functionally classified as a diarthrosis.

Outside of their articulating surfaces, the bones are connected together by **ligaments**, which are strong bands of fibrous connective tissue. These strengthen and support the joint by anchoring the bones together and preventing their separation. Ligaments allow for normal movements at a joint, but limit the range of these motions, thus preventing excessive or abnormal joint movements. At many synovial joints, additional support is provided by the muscles and their tendons that act across the joint. A **tendon** is the dense connective tissue structure that attaches a muscle to bone. As forces acting on a joint increase, the body will automatically increase the overall strength of contraction of the muscles crossing that joint, thus allowing the muscle and its tendon to serve as a "dynamic ligament" to resist forces and support the joint. This type of indirect support by muscles is very important at the shoulder joint, for example, where the ligaments are relatively weak.

Classification of Synovial Joints

Synovial joints are subdivided based on the shapes of the articulating surfaces of the bones that form each joint. The six types of synovial joints are pivot, hinge, condyloid, saddle, plane, and ball-and socket-joints (**Figure 5.18**). Each synovial joint of the body is specialized to perform certain movements. The movements that are allowed are determined by the structural classification for each joint. For example, a multiaxial ball-and-socket joint has much more mobility than a uniaxial hinge joint. However, the ligaments and muscles that support a joint may place restrictions on the total range of motion available. Thus, the ball-and-socket joint of the shoulder has little in the way of ligament support, which gives the shoulder a very large range of motion. In contrast, movements at the hip joint are restricted by strong ligaments, which reduce its range of motion but confer stability during standing and weight bearing.
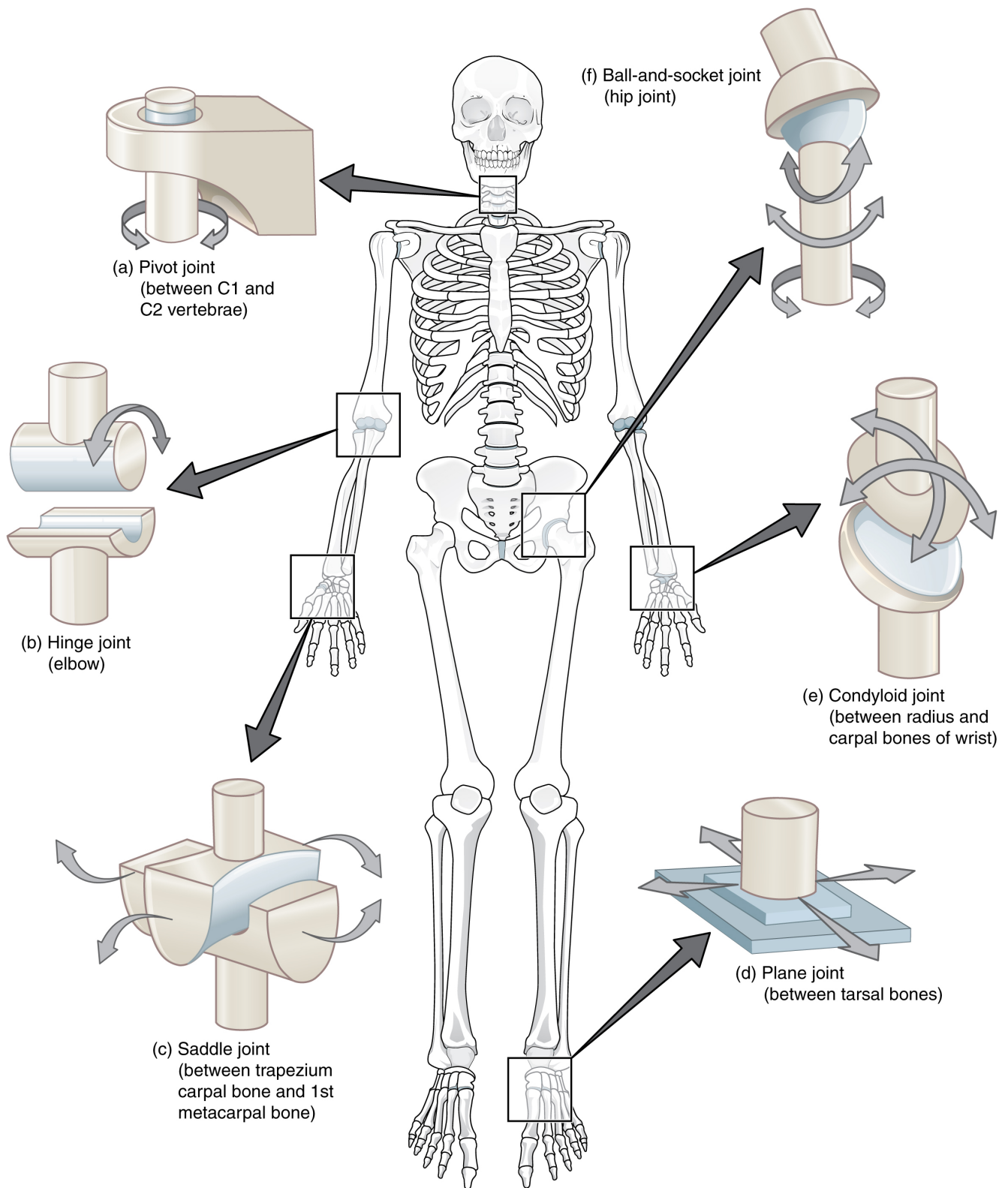
Figure 5.18 Types of Synovial Joints. The six types of synovial joints allow the body to move in a variety of ways. (a) Pivot joints allow for rotation around an axis, such as between the first and second cervical vertebrae, which allows for side-to-side rotation of the head. (b) The hinge joint of the elbow works like a door hinge. (c) The articulation between

Synovial joint example: The Knee Joint

The knee joint is the largest joint of the body (**Figure 5.19**). It actually consists of three articulations. The **femoropatellar joint** is found between the patella and the distal femur. The **medial tibiofemoral joint** and **lateral tibiofemoral joint** are located between the medial and lateral condyles of the femur and the medial and lateral condyles of the tibia. All of these articulations are enclosed within a single articular capsule. The knee functions as a hinge joint, allowing flexion and extension of the leg. In addition, some rotation of the leg is available when the knee is flexed, but not when extended. The knee is well constructed for weight bearing in its extended position, but is vulnerable to injuries associated with hyperextension, twisting, or blows to the medial or lateral side of the joint, particularly while weight bearing.

At the femoropatellar joint, the patella slides vertically within a groove on the distal femur. Continuing from the patella to the anterior tibia just below the knee is the **patellar ligament**. Acting via the patella and patellar ligament, the quadriceps femoris is a powerful muscle that acts to extend the leg at the knee. It also serves as a "dynamic ligament" to provide very important support and stabilization for the knee joint.

The medial and lateral tibiofemoral joints are the articulations between the rounded condyles of the femur and the relatively flat condyles of the tibia. During flexion and extension motions, the condyles of the femur both roll and glide over the surfaces of the tibia. The rolling action produces flexion or extension, while the gliding action serves to maintain the femoral condyles centered over the tibial condyles, thus ensuring maximal bony, weight-bearing support for the femur in all knee positions. As the knee comes into full extension, the femur undergoes a slight medial rotation in relation to tibia. The rotation results because the lateral condyle of the femur is slightly smaller than the medial condyle. Thus, the lateral condyle finishes its rolling motion first, followed by the medial condyle. The resulting small medial rotation of the femur serves to "lock" the knee into its fully extended and most stable position. Flexion of the knee is initiated by a slight lateral rotation of the femur on the tibia, which "unlocks" the knee.

Femur

Articular capsule

Posterior cruciate ligament

Lateral meniscus

Anterior cruciate ligament

Tibia

Tendon of quadriceps femoris

Suprapatellar bursa

Patella

Prepatellar bursa

Synovial cavity

Lateral meniscus

Infrapatellar fat pad

Infrapatellar bursa

Patellar ligament

(a) Sagittal section through the right knee joint

Anterior cruciate ligament

Articular cartilage on medial tibial condyle

Medial meniscus

Anterior

Articular cartilage on lateral tibial condyle

Lateral meniscus

Posterior cruciate ligament

(b) Superior view of the right tibia in the knee joint, showing the menisci and cruciate ligaments

Quadriceps femoris muscle

Tendon of quadriceps femoris muscle

Lateral patellar retinaculum

Fibular collateral ligament

Fibula

Patella

Medial patellar retinaculum

Tibial collateral ligament

Patellar ligament

Tibia

(c) Anterior view of right knee

Figure 5.19 Knee Joint. (a) The knee joint is the largest joint of the body. (b)–(c) It is supported by the tibial and fibular collateral ligaments located on the sides of the knee outside of the articular capsule, and the anterior and posterior cruciate ligaments found inside the capsule. The medial and lateral menisci provide padding and support between the femoral condyles and tibial condyles.

Located between the articulating surfaces of the femur and tibia are two articular discs, the **medial meniscus** and **lateral meniscus** (**Figure 5.19b**). Each is a C-shaped fibrocartilage structure that is thin along its inside margin and thick along the outer margin. They are attached to their tibial condyles, but do not attach to the femur. While both menisci are free to move during knee motions, the medial meniscus shows less movement because it is anchored at its outer margin to the articular capsule and tibial collateral ligament. The menisci provide padding between the bones and help to fill the gap between the round femoral condyles and flattened tibial condyles. Some areas of each meniscus lack an arterial blood supply and thus these areas heal poorly if damaged.

The knee joint has multiple ligaments that provide support, particularly in the extended position (**Figure 5.19c**). Outside of the articular capsule, located at the sides of the knee, are two extrinsic ligaments. The **fibular collateral ligament** (lateral collateral ligament) is on the lateral side and spans from the lateral epicondyle of the femur to the head of the fibula. The **tibial collateral ligament** (medial collateral ligament) of the medial knee runs from the medial epicondyle of the femur to the medial tibia. As it crosses the knee, the tibial collateral ligament is

firmly attached on its deep side to the articular capsule and to the medial meniscus, an important factor when considering knee injuries. In the fully extended knee position, both collateral ligaments are taut (tight), thus serving to stabilize and support the extended knee and preventing side-to-side or rotational motions between the femur and tibia.

Inside the knee are two intracapsular ligaments, the **anterior cruciate ligament** and **posterior cruciate ligament**. These ligaments are anchored inferiorly to the tibia at the intercondylar eminence, the roughened area between the tibial condyles. The cruciate ligaments are named for whether they are attached anteriorly or posteriorly to this tibial region. Each ligament runs diagonally upward to attach to the inner aspect of a femoral condyle. The cruciate ligaments are named for the X-shape formed as they pass each other (cruciate means "cross"). The posterior cruciate ligament is the stronger ligament. It serves to support the knee when it is flexed and weight bearing, as when walking downhill. In this position, the posterior cruciate ligament prevents the femur from sliding anteriorly off the top of the tibia. The anterior cruciate ligament becomes tight when the knee is extended, and thus resists hyperextension.

Lab 6: Muscular System I - Muscle Tissue and Hindlimb Muscles

Skeletal muscle cells and tissues, Muscles of the hindlimb

Muscle Tissue

When most people think of muscles, they think of the muscles that are visible just under the skin, particularly of the limbs. These are **skeletal muscles**, so-named because most of them move the skeleton. But as we learned in Week 3, there are two other types of muscle tissue in the body, with distinctly different jobs (**Figure 6.1**). **Cardiac muscle**, found in the heart, is concerned with pumping blood through the circulatory system. **Smooth muscle** is concerned with various involuntary movements, such as having one's hair stand on end when cold or frightened, or moving food through the digestive system. In the next two weeks, we will focus on the structure and function of skeletal muscle tissue, and how it works with the skeletal system to move and stabilize the framework of the body. We will revisit cardiac and smooth muscle tissue later in the semester when looking at their roles in other organ systems.
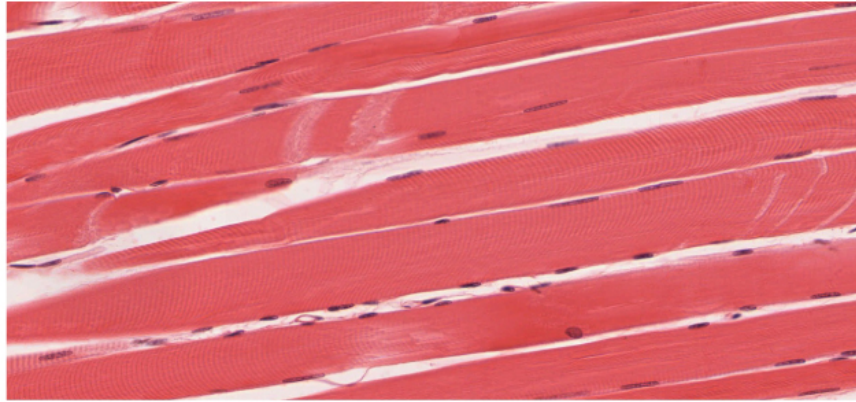
(a)
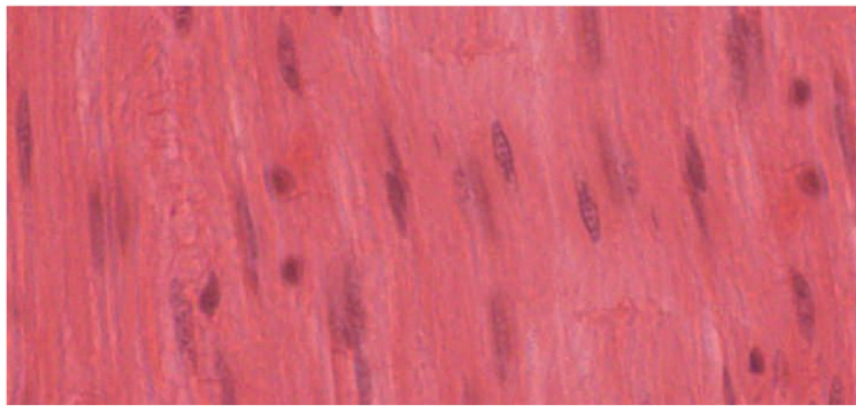
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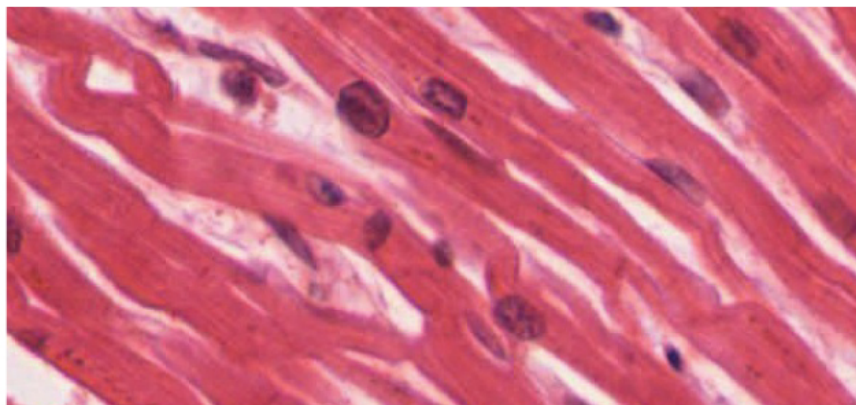
(c)

Figure 6.1 The Three Types of Muscle Tissue. The body contains three types of muscle tissue: (a) skeletal muscle, (b) smooth muscle, and (c) cardiac muscle. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Skeletal Muscle

The best-known feature of skeletal muscle is its ability to contract and cause movement. Skeletal muscles act not only to produce movement but also to stop movement, such as resisting gravity to maintain posture. Small, constant adjustments of the skeletal muscles are needed to hold a body upright or balanced in any position. Muscles also prevent excess movement of the bones and joints, maintaining skeletal stability and preventing skeletal structure damage or deformation. Joints can become misaligned or dislocated entirely by pulling on the associated bones; muscles work to keep joints stable. Skeletal muscles are located throughout the body at the openings of internal tracts to control the movement of various substances. These muscles allow functions, such as swallowing, urination, and defecation, to be under voluntary control. Skeletal muscles also protect internal organs (particularly abdominal and pelvic organs) by acting as an external barrier or shield to external trauma and by supporting the weight of the organs.

Skeletal muscles contribute to the maintenance of homeostasis in the body by generating heat. Muscle contraction requires energy, and when ATP is broken down, heat is produced. This heat is very noticeable during exercise, when sustained muscle movement causes body temperature to rise, and in cases of extreme cold, when shivering is caused by random skeletal muscle contractions to generate heat.

Each skeletal muscle is an organ that consists of various integrated tissues. These tissues include the skeletal muscle fibers, blood vessels, nerve fibers, and connective tissue. Skeletal muscles have three layers of connective tissue (called "mysia", singular: "mysium") that enclose it and provide structure to the muscle as a whole, and also compartmentalize the muscle fibers within the muscle (**Figure 6.2**). Each muscle is wrapped in connective tissue called the **epimysium**, which separates the muscle from other tissues and organs in the area, allowing the muscle to move independently.
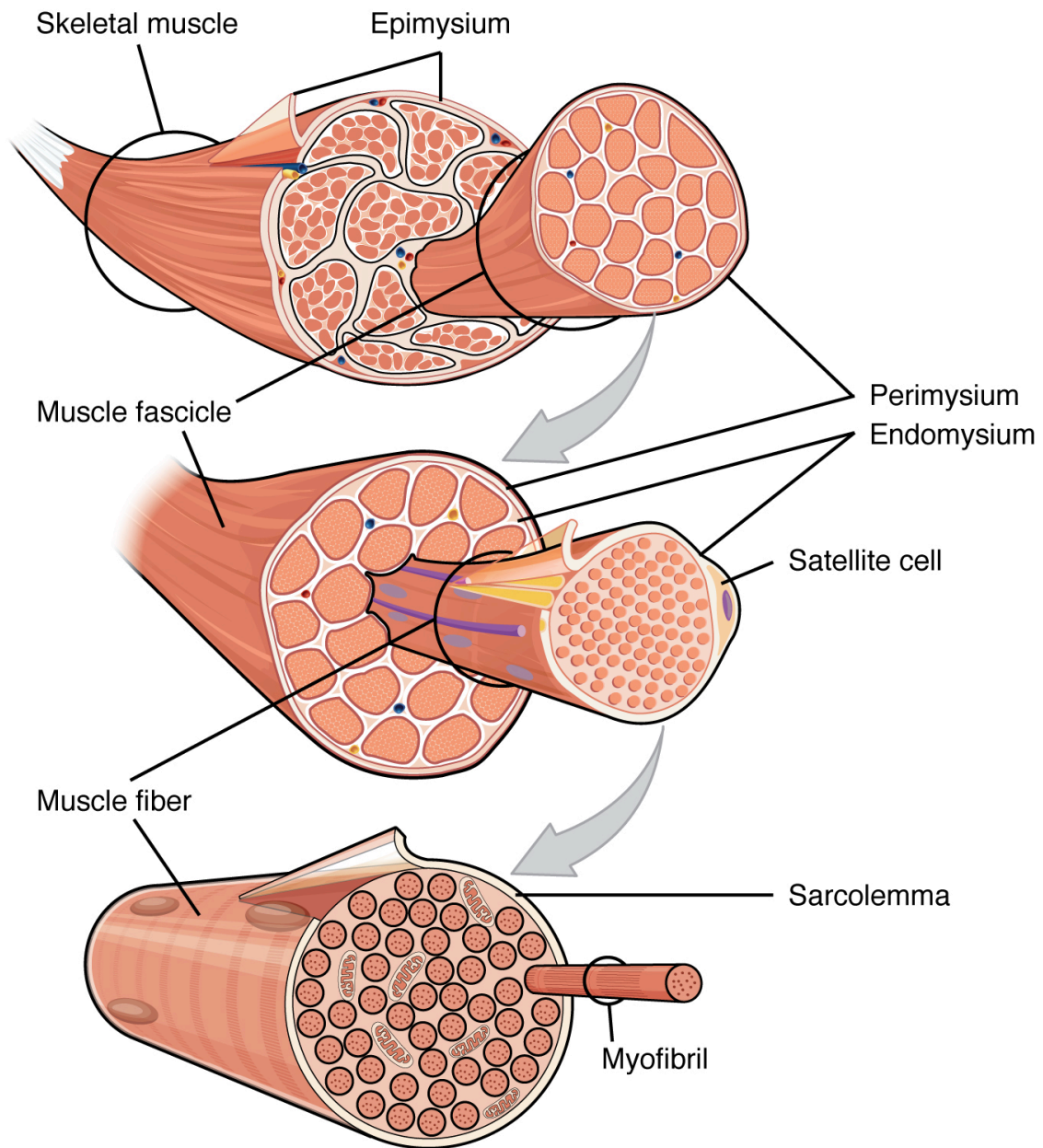
Figure 6.2: The Three Connective Tissue Layers. Bundles of muscle fibers, called fascicles, are covered by the perimysium. Muscle fibers are covered by the endomysium.

Inside each skeletal muscle, muscle fibers are organized into individual bundles, each called a **fascicle**, by a middle layer of connective tissue called the **perimysium**. This fascicular organization is common in muscles of the limbs; it allows the nervous system to trigger a specific movement of a muscle by activating a subset of muscle fibers within a bundle, or fascicle of the muscle. Inside each fascicle, each muscle fiber is encased in a thin connective tissue layer of collagen and reticular fibers called the **endomysium**. The endomysium contains the extracellular fluid and nutrients to support the muscle fiber. These nutrients are supplied via blood to the muscle tissue.

In skeletal muscles that work with tendons to pull on bones, the collagen in the three tissue layers (the mysia)

intertwines with the collagen of a tendon. At the other end of the tendon, it fuses with the periosteum coating the bone. The tension created by contraction of the muscle fibers is then transferred though the mysia, to the tendon, and then to the periosteum to pull on the bone for movement of the skeleton. In other places, the mysia may fuse with a broad, tendon-like sheet called an **aponeurosis**, or to fascia, the connective tissue between skin and bones. The broad sheet of connective tissue in the lower back that the latissimus dorsi muscles (the "lats") fuse into is an example of an aponeurosis.

Every skeletal muscle is also richly supplied by blood vessels for nourishment, oxygen delivery, and waste removal. In addition, every muscle fiber in a skeletal muscle is supplied by the axon branch of a somatic motor neuron, which signals the fiber to contract. Unlike cardiac and smooth muscle, the only way to functionally contract a skeletal muscle is through signaling from the nervous system.

Skeletal Muscle Fibers

Because skeletal muscle cells are long and cylindrical, they are commonly referred to as muscle fibers. **Skeletal muscle fibers** can be quite large for human cells, with diameters up to 100 μm and lengths up to 30 cm (11.8 in) in the Sartorius of the upper leg. During early development, embryonic myoblasts, each with its own nucleus, fuse with up to hundreds of other myoblasts to form the multinucleated skeletal muscle fibers. Multiple nuclei mean multiple copies of genes, permitting the production of the large amounts of proteins and enzymes needed for muscle contraction.

Some other terminology associated with muscle fibers is rooted in the Greek sarco, which means "flesh." The plasma membrane of muscle fibers is called the **sarcolemma**, the cytoplasm is referred to as **sarcoplasm**, and the specialized smooth endoplasmic reticulum, which stores, releases, and retrieves calcium ions (Ca++) is called the **sarcoplasmic reticulum (SR)** (**Figure 6.3**). As will soon be described, the functional unit of a skeletal muscle fiber is the sarcomere, a highly organized arrangement of the contractile myofilaments **actin** (thin filament) and **myosin** (thick filament), along with other support proteins.
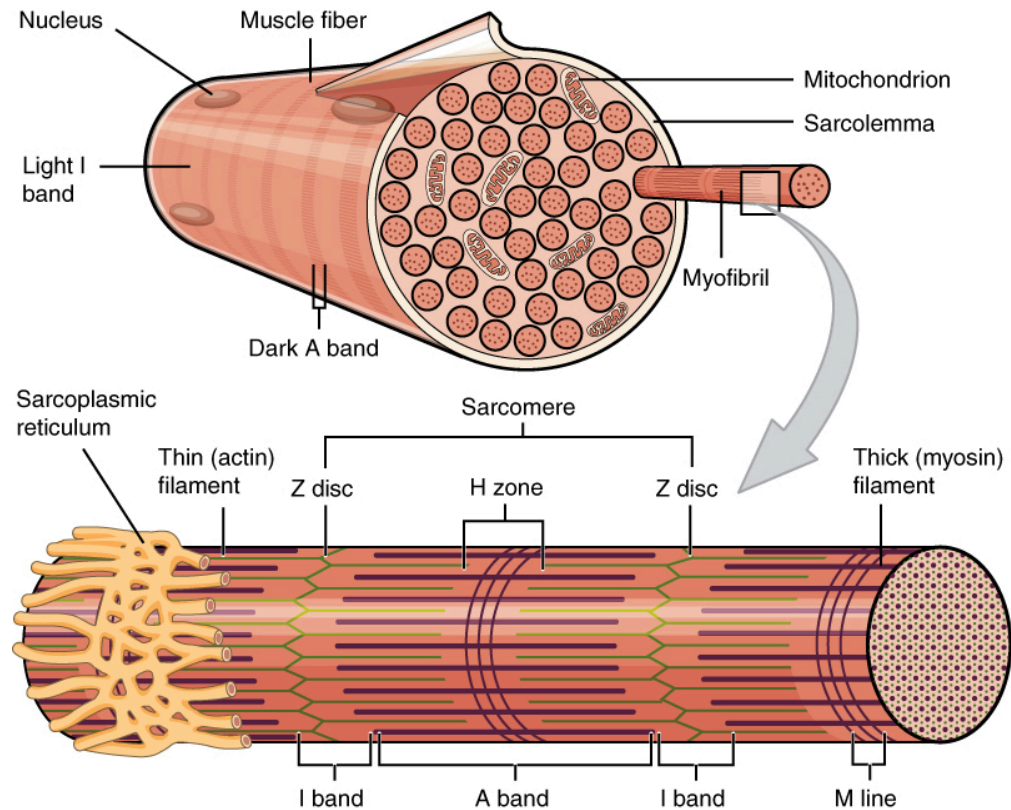
Figure 6.3: Muscle Fiber A skeletal muscle fiber is surrounded by a plasma membrane called the sarcolemma, which contains sarcoplasm, the cytoplasm of muscle cells. A muscle fiber is composed of many fibrils, which give the cell its striated appearance.

The Sarcomere

The striated appearance of skeletal muscle fibers is due to the arrangement of the myofilaments of actin and myosin in sequential order from one end of the muscle fiber to the other. Each packet of these microfilaments and their regulatory proteins, **troponin** and **tropomyosin** (along with other proteins) is called a **sarcomere**.

The sarcomere is the functional unit of the muscle fiber. The sarcomere itself is bundled within the myofibril that runs the entire length of the muscle fiber and attaches to the sarcolemma at its end. As myofibrils contract, the entire muscle cell contracts. Because myofibrils are only approximately 1.2 μm in diameter, hundreds to thousands (each with thousands of sarcomeres) can be found inside one muscle fiber. Each sarcomere is approximately 2 μm in length with a three-dimensional cylinder-like arrangement and is bordered by structures called Z-discs (also called Z-lines, because pictures are two-dimensional), to which the actin myofilaments are anchored (**Figure 6.4**). Because the actin form strands that are thinner than the myosin, it is called the **thin filament** of the sarcomere. Likewise, because the myosin strands and their multiple heads (projecting from the center of the sarcomere, toward but not all to way to, the Z-discs) have more mass and are thicker, they are called the **thick filament** of the sarcomere.
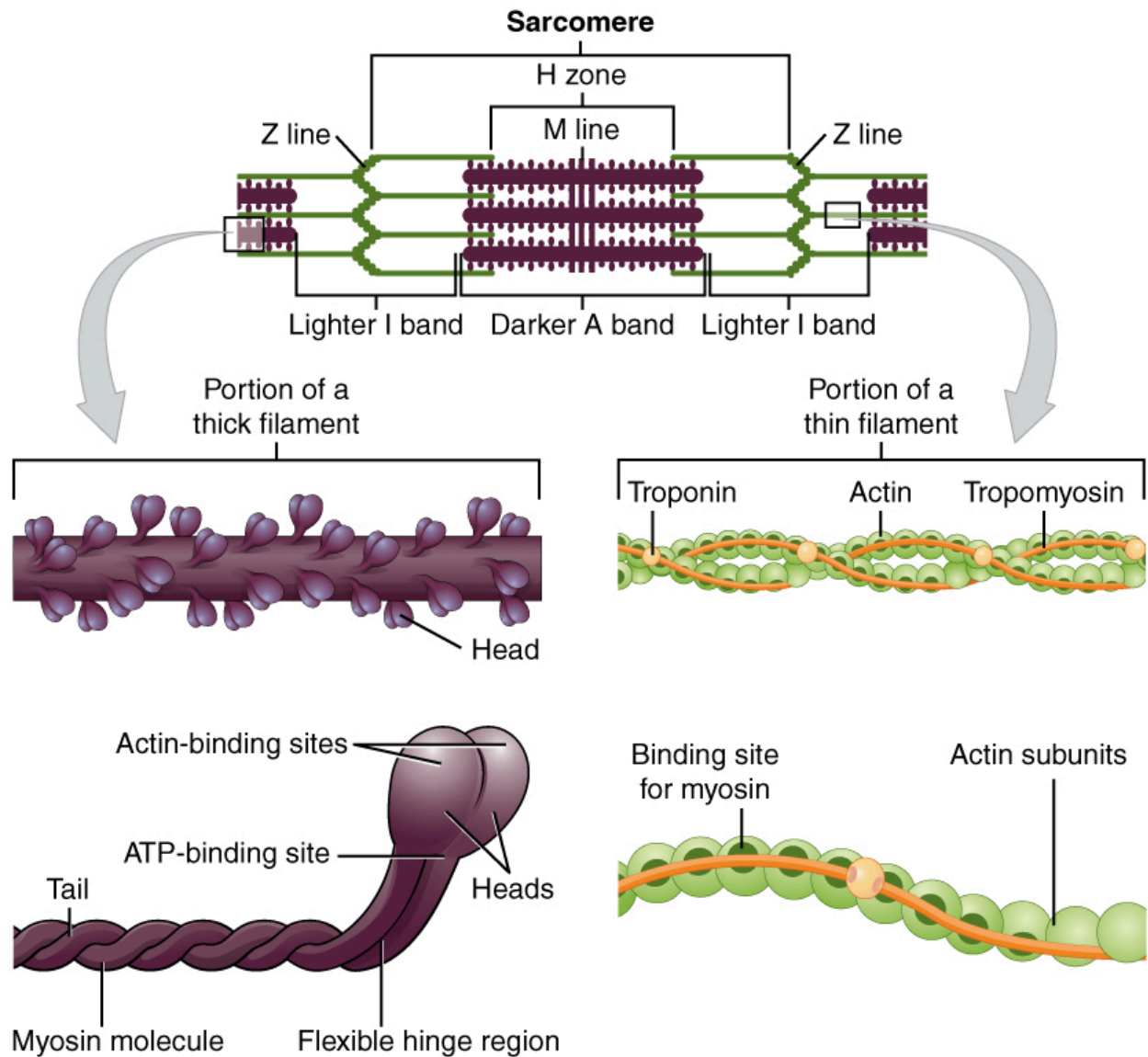
Figure 6.4: The Sarcomere The sarcomere, the region from one Z-line to the next Z-line, is the functional unit of a skeletal muscle fiber.

The Neuromuscular Junction and Muscle Contraction

Another specialization of the skeletal muscle is the site where a motor neuron's terminal meets the muscle fiber — called the **neuromuscular junction (NMJ)**. This is where the muscle fiber first responds to signaling by the motor neuron. Every skeletal muscle fiber in every skeletal muscle is innervated by a motor neuron at the NMJ. Excitation signals from the neuron are the only way to functionally activate the fiber to contract.

All living cells have membrane potentials, or electrical gradients across their membranes. The inside of the membrane is usually around -60 to -90 mV, relative to the outside. This is referred to as a cell's membrane potential. Neurons and muscle cells can use their membrane potentials to generate electrical signals. They do

this by controlling the movement of charged particles, called ions, across their membranes to create electrical currents. This is achieved by opening and closing specialized proteins in the membrane called ion channels. Although the currents generated by ions moving through these channel proteins are very small, they form the basis of both neural signaling and muscle contraction.

Both neurons and skeletal muscle cells are electrically excitable, meaning that they are able to generate action potentials. An action potential is a special type of electrical signal that can travel along a cell membrane as a wave. This allows a signal to be transmitted quickly and faithfully over long distances.

For a skeletal muscle fiber to contract, its membrane must first be stimulated to fire an action potential. The muscle fiber action potential, which sweeps along the sarcolemma as a wave, causes contraction through the release of calcium ions (Ca++) from the SR. Once released, the Ca++ interacts with the shielding proteins, forcing them to move aside so that the actin-binding sites are available for attachment by myosin heads. The myosin then pulls the actin filaments toward the center, shortening the muscle fiber. In skeletal muscle, this sequence begins with signals from the somatic motor division of the nervous system. In other words, the "excitation" step in skeletal muscles is always triggered by signaling from the nervous system (**Figure 6.5**).
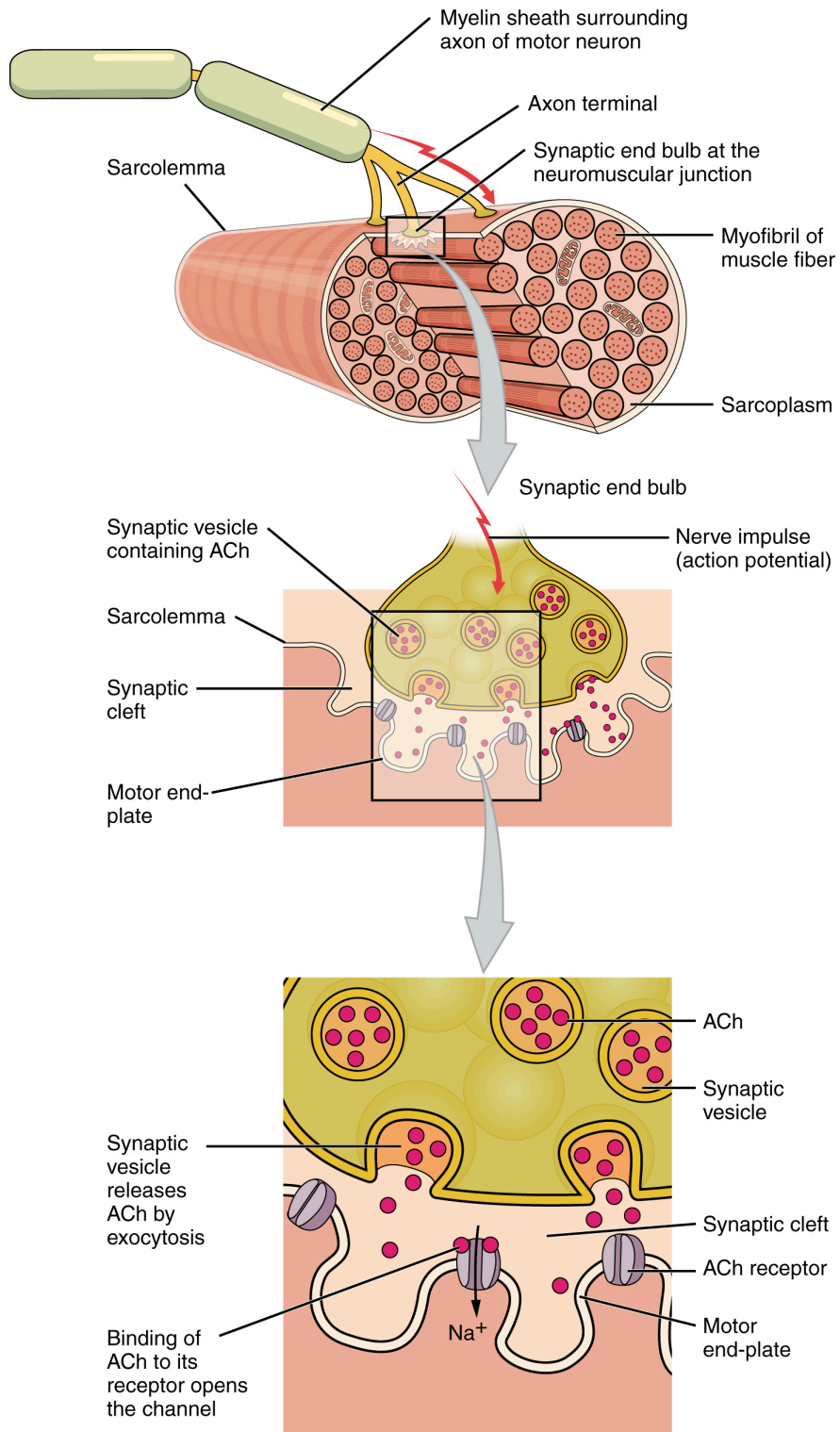
Figure 6.5: Motor End-Plate and Innervation. At the NMJ, the axon terminal releases ACh. The motor end-plate is the location of the ACh-receptors in the muscle fiber sarcolemma. When ACh molecules are released, they diffuse across a minute space called the synaptic cleft and bind to the receptors.

The motor neurons that tell the skeletal muscle fibers to contract originate in the spinal cord, with a smaller number located in the brainstem for activation of skeletal muscles of the face, head, and neck. These neurons have long processes, called axons, which are specialized to transmit action potentials long distances — in this case, all the way from the spinal cord to the muscle itself (which may be up to three feet away). The axons of multiple neurons bundle together to form nerves, like wires bundled together in a cable.

Signaling begins when a neuronal **action potential** travels along the axon of a motor neuron, and then along the individual branches to terminate at the NMJ. At the NMJ, the axon terminal releases a chemical messenger, or **neurotransmitter**, called **acetylcholine (ACh)**. The ACh molecules diffuse across a minute space called the **synaptic cleft** and bind to ACh receptors located within the **motor end-plate** of the sarcolemma on the other side of the synapse. Once ACh binds, a channel in the ACh receptor opens and positively charged ions can pass through into the muscle fiber, causing it to **depolarize**, meaning that the membrane potential of the muscle fiber becomes less negative (closer to zero.)

As the membrane depolarizes, another set of ion channels called **voltage-gated sodium channels** are triggered to open. Sodium ions enter the muscle fiber, and an action potential rapidly spreads (or "fires") along the entire membrane to initiate excitation-contraction coupling. Things happen very quickly in the world of excitable membranes (just think about how quickly you can snap your fingers as soon as you decide to do it). Immediately following depolarization of the membrane, it repolarizes, re- establishing the negative membrane potential. Meanwhile, the ACh in the synaptic cleft is degraded by the enzyme acetylcholinesterase (AChE) so that the ACh cannot rebind to a receptor and reopen its channel, which would cause unwanted extended muscle excitation and contraction.

Propagation of an action potential along the sarcolemma triggers the release of calcium ions (Ca^{2+}) from its storage in the cell's SR. For the action potential to reach the membrane of the SR, there are periodic invaginations in the sarcolemma, called **T- tubules** ("T" stands for "transverse"). You will recall that the diameter of a muscle fiber can be up to 100 μm, so these T-tubules ensure that the membrane can get close to the SR in the sarcoplasm. The arrangement of a T-tubule with the membranes of SR on either side is called a **triad** (**Figure 6.6**). The triad surrounds the cylindrical structure called a **myofibril**, which contains actin and myosin.
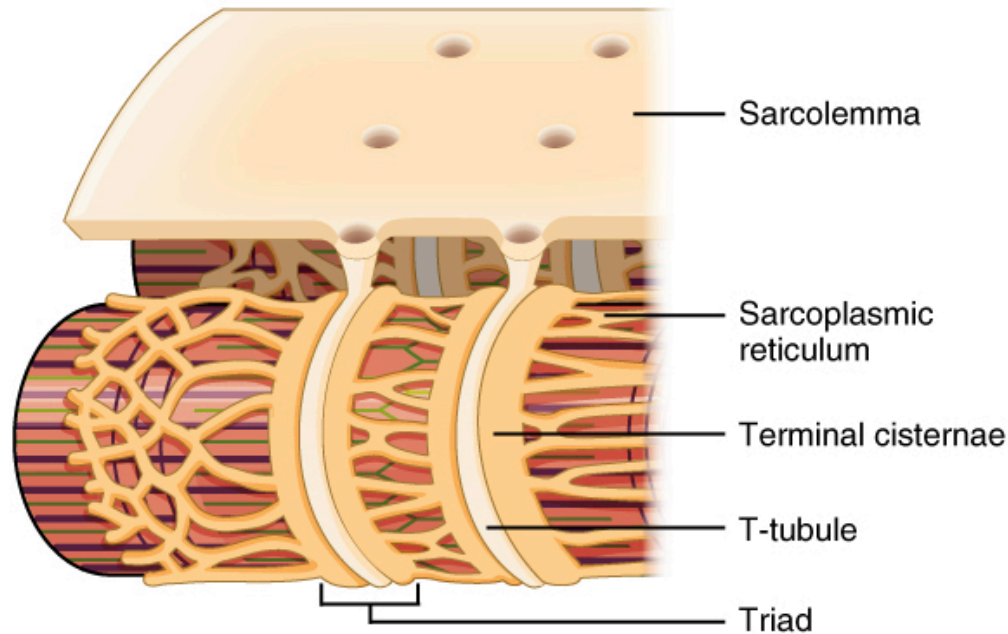
Figure 6.6. The T-tubule. Narrow T-tubules permit the conduction of electrical impulses. The SR functions to regulate intracellular levels of calcium. Two terminal cisternae (where enlarged SR connects to the T-tubule) and one T-tubule comprise a triad — a "threesome" of membranes, with those of SR on two sides and the T-tubule sandwiched between them.

The T-tubules carry the action potential into the interior of the cell, which triggers the opening of calcium channels in the membrane of the adjacent SR, causing Ca++ to diffuse out of the SR and into the sarcoplasm. It is the arrival of Ca++ in the sarcoplasm that initiates contraction of the muscle fiber by its contractile units, or sarcomeres.

The Muscular System

Naming Skeletal Muscles

The Greeks and Romans conducted the first studies done on the human body in Western culture. The educated class of subsequent societies studied Latin and Greek, and therefore the early pioneers of anatomy continued to apply Latin and Greek terminology or roots when they named the skeletal muscles. The large number of muscles in the body and unfamiliar words can make learning the names of the muscles in the body seem daunting, but understanding the etymology can help. Etymology is the study of how the root of a particular word entered a language and how the use of the word evolved over time. Taking the time to learn the root of the words is crucial to understanding the vocabulary of anatomy and physiology. When you understand the names of muscles it will help you remember where the muscles are located and what they do (**Figure 6.7** and **Table 6.1**). Pronunciation of words and terms will take a bit of time to master, but after you have some basic information; the correct names and pronunciations will become easier.
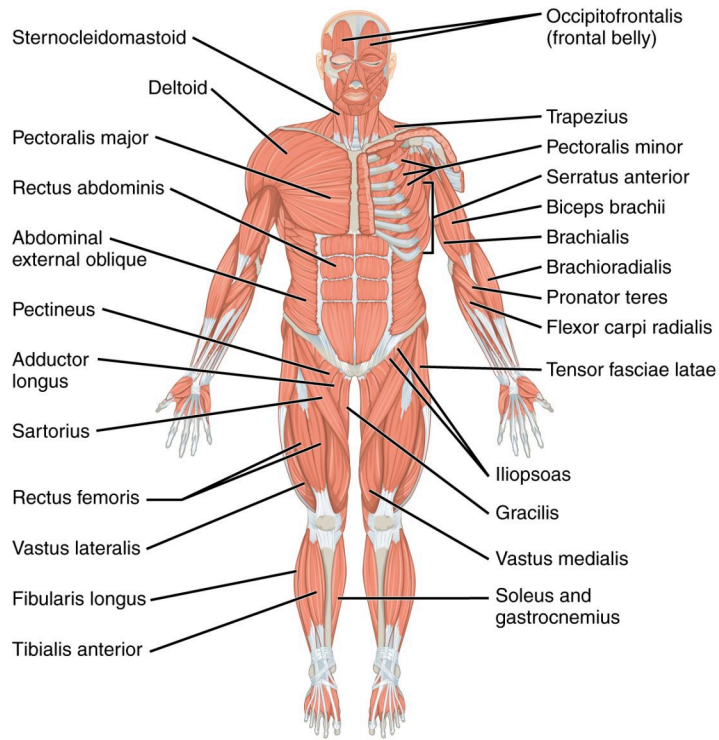
Major muscles of the body.
Right side: superficial; left side: deep (anterior view)
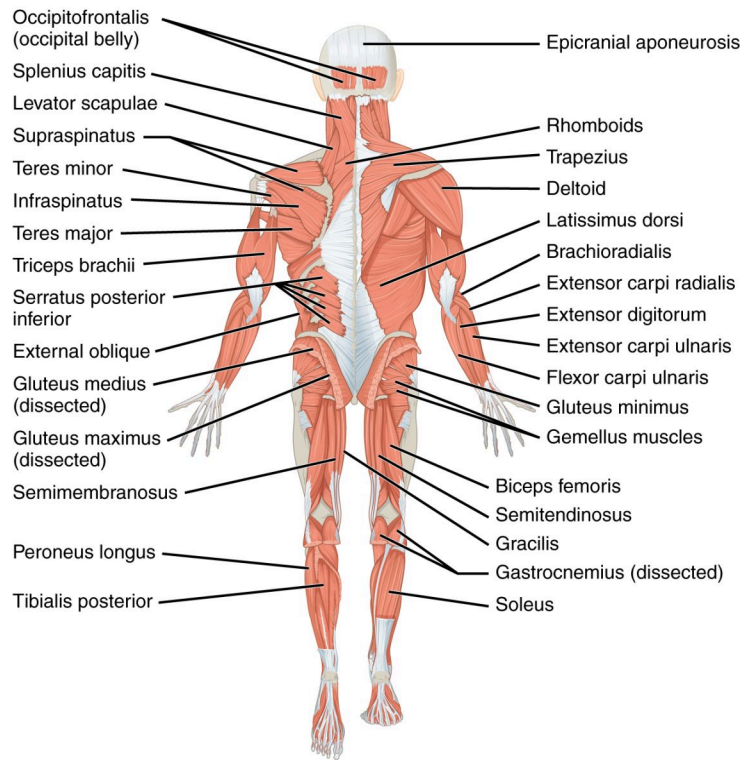
Major muscles of the body.
Right side: superficial; left side: deep (posterior view)

Figure 6.7 Overview of the Muscular System On the anterior and

posterior views of the muscular system above, superficial muscles (those at the surface) are shown on the right side of the body while deep muscles (those underneath the superficial muscles) are shown on the left half of the body. For the legs, superficial muscles are shown in the anterior view while the posterior view shows both superficial and deep muscles.

Table 6.1 Understanding a Muscle Name from the Latin

Example	Word	Latin Roots	Meaning	Translation
"abductor digiti minimi"	abductor	ab = away from; duct = to move	a muscle that moves away from	A muscle that moves the little finger or toe away
	digiti	digitus = digit	a finger or toe	
	minimi	minimus = mini, tiny	little	
"adductor digiti minimi"	adductor	ad = to, toward; duct = to move	a muscle that moves towards	A muscle that moves the little finger or toe toward
	digiti	digitus = digit	a finger or toe	
	minimi	minimus = mini, tiny	little	

Anatomists name the skeletal muscles according to a number of criteria, each of which describes the muscle in some way. These include naming the muscle after its shape, its size compared to other muscles in the area, its location in the body or the location of its attachments to the skeleton, how many origins it has, or its action.

The skeletal muscle's anatomical location or its relationship to a particular bone often determines its name. For example, the frontalis muscle is located on top of the frontal bone of the skull. Similarly, the shapes of some muscles are very distinctive and the names, such as orbicularis, reflect the shape. For the buttocks, the size of the muscles influences the names: gluteus **maximus** (largest), gluteus **medius** (medium), and the gluteus **minimus** (smallest). Names were given to indicate length—**brevis** (short), **longus** (long)—and to identify position relative to the midline: **lateralis** (to the outside away from the midline), and **medialis** (toward the midline). The direction of the muscle fibers and fascicles are used to describe muscles relative to the midline, such as the **rectus** (straight) abdominis, or the **oblique** (at an angle) muscles of the abdomen.

Some muscle names indicate the number of muscles in a group. One example of this is the quadriceps, a group of four muscles located on the anterior (front) thigh. Other muscle names can provide information as to how many origins a particular muscle has, such as the biceps brachii. The prefix bi indicates that the muscle has two origins and tri indicates three origins.

The location of a muscle's attachment can also appear in its name. When the name of a muscle is based on the attachments, the origin is always named first. For instance, the sternocleidomastoid muscle of the neck has a dual origin on the sternum (sterno) and clavicle (cleido), and it inserts on the mastoid process of the temporal bone. The last feature by which to name a muscle is its action. When muscles are named for the movement they produce, one can find action words in their name. Some examples are **flexor** (decreases the angle at the joint), **extensor** (increases the angle at the joint), **abductor** (moves the bone away from the midline), or **adductor** (moves the bone toward the midline).

Skeletal Muscles by Region

The skeletal muscles are divided into **axial** (muscles of the trunk and head) and **appendicular** (muscles of the arms and legs) categories. This system reflects the bones of the skeleton system, which are also arranged in this manner. The axial and appendicular muscles are grouped based on location, function, or both. Some of the axial muscles may seem to blur the boundaries because they cross over to the appendicular skeleton.

In lab this week, we will look at the appendicular muscles in the hindlimb first because these are easiest to start with on our dissection. Next week we will continue exploring the skeletal muscles by region and look at the appendicular muscles in the forelimb and the axial muscles.

Appendicular Muscles of the Pelvic Girdle and Lower Limbs

The appendicular muscles of the lower body position and stabilize the **pelvic girdle**, which serves as a foundation for the lower limbs. Comparatively, there is much more movement at the pectoral girdle than at the pelvic girdle. There is very little movement of the pelvic girdle because of its connection with the sacrum at the base of the axial skeleton. The pelvic girdle is less range of motion because it was designed to stabilize and support the body.

Muscles of the Thigh

What would happen if the pelvic girdle, which attaches the lower limbs to the torso, were capable of the same range of motion as the shoulder girdle? For one thing, walking would expend more energy if the heads of the femurs were not secured in the acetabula of the pelvis. The body's center of gravity is in the area of the pelvis. If the center of gravity were not to remain fixed, standing up would be difficult as well. Therefore, what the leg muscles lack in range of motion and versatility, they make up for in size and power, facilitating the body's stabilization, posture, and movement.

Gluteal Region Muscles That Move the Femur

Most muscles that insert on the femur (the thigh bone) and move it, originate on the pelvic girdle. The **psoas major** and **iliacus** make up the **iliopsoas group**. Some of the largest and most powerful muscles in the body are the gluteal muscles or **gluteal group**. The **gluteus maximus** is the largest; deep to the gluteus maximus is the **gluteus medius**, and deep to the **gluteus medius** is the **gluteus minimus**, the smallest of the trio (**Figure 6.8** and **Table 6.2**).

Quadratus lumborum
Iliacus
Crest of ilium
Tensor fascia latae
Rectus femoris
Vastus lateralis

Psoas major
Pectineus
Sacrum
Adductor longus
Gracilis
Adductor magnus
Sartorius
Vastus medialis
Quadriceps tendon (or patellar tendon)
Patellar ligament
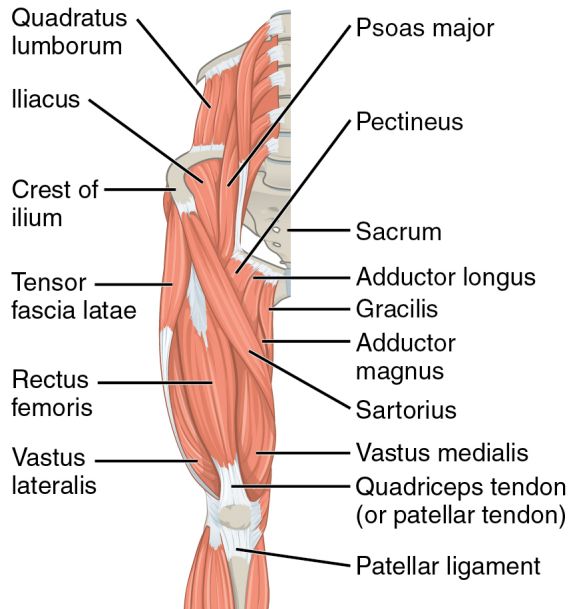
Superficial pelvic and thigh muscles of right leg (anterior view)
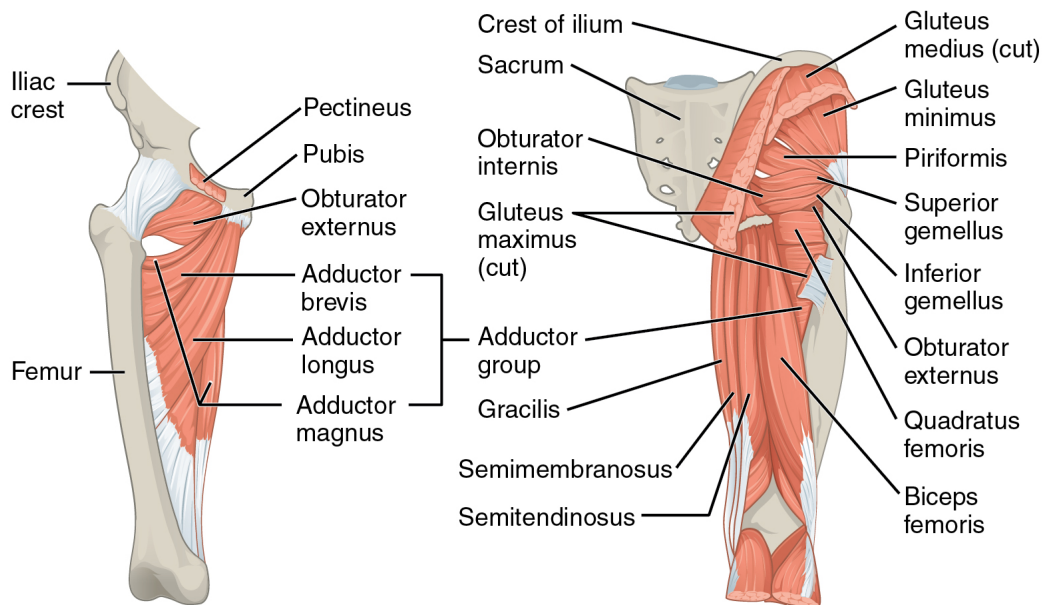
Iliac crest
Femur

Pectineus
Pubis
Obturator externus
Adductor brevis
Adductor longus
Adductor magnus

Deep pelvic and thigh muscles of right leg (anterior view)

Crest of ilium
Sacrum
Obturator internis
Gluteus maximus (cut)
Adductor group
Gracilis
Semimembranosus
Semitendinosus

Gluteus medius (cut)
Gluteus minimus
Piriformis
Superior gemellus
Inferior gemellus
Obturator externus
Quadratus femoris
Biceps femoris

Pelvic and thigh muscles of right leg (posterior view)

Figure 6.8 Hip and Thigh Muscles. The large and powerful muscles of the hip that move the femur generally originate on the pelvic girdle and insert into the femur. The muscles that move the lower leg typically originate on the femur and insert into the bones of the knee joint. The anterior muscles of the femur extend the lower leg but also aid in flexing the thigh. The posterior muscles of the femur flex the lower leg but also aid in extending the thigh. A combination of gluteal and thigh muscles also adduct, abduct, and rotate the thigh and lower leg.

Table 6.2. Gluteal Region Muscles That Move the Femur

Group	Target	Movement	Target motion direction	Prime mover	Origin	Insertion
Iliopsoas group	femur	raises the knee at the hip, as if performing a knee attack; it also assists the lateral rotators in twisting the thigh (and lower leg) outward, and assists with bending over and maintaining posture	thigh: flexion and lateral rotation; torso: flexion	**psoas major**	lumbar vertebrae (L1 through L5) and thoracic vertebra (T12)	lesser trochanter of femur
	femur	raises the knee at the hip, as if performing a knee attack; it also assists the lateral rotators in twisting the thigh (and lower leg) outward, and assists with bending over and maintaining posture	thigh: flexion and lateral rotation; torso: flexion	**iliacus**	iliac fossa, iliac crest, and lateral sacrum	lesser trochanter of femur
Gluteal group	femur	lowers the knee and moves the thigh back, as when getting ready to kick a ball	extension	**gluteous maximus**	dorsal ilium, sacrum, and coccyx	gluteal tuberosity of femur; iliotibial tract
	femur	opens the thigh, as when doing a split	abduction	**gluteus medius**	lateral surface of the ilium	greater trochanter of femur
	femur	brings the thighs back together	abduction	**gluteus minimus**	external surface of the ilium	greater trochanter of femur
	femur	assists with raising the knee at the hip and opening the thighs; it also maintains posture by stabilizing the iliotibial track, which connects to the knee	flexion; abduction	**tensor fascia lata**	anterior aspect of the iliac crest and the anterior superior iliac spine	iliotibial tract
Lateral rotators	femur	twists the thigh (and lower leg) outward; it also maintains posture by stabilizing the hip joint	lateral rotation	**piriformis**	anterolateral surface of the sacrum	greater trochanter of femur
	femur	twists the thigh (and lower leg) outward; it also maintains posture by stabilizing the hip joint	lateral rotation	**obturator internus**	inner surface of the obturator membrane, the greater sciatic notch, and the margins of the obturator foramen	greater trochanter in front of piriformis
	femur	twists thigh (and lower leg) outward; maintains posture by stabilizing hip joint	lateral rotation	**obturator externus**	outer surfaces of obturator membrane, pubic, and ischium; margins of obturator foramen	trochanteric fossa of posterior femur

Group	Target	Movement	Target motion direction	Prime mover	Origin	Insertion
	femur	twists the thigh (and lower leg) outward; it also maintains posture by stabilizing the hip joint	lateral rotation	**superior gemellus**	ischial spine	greater trochanter of femur
	femur	twists the thigh (and lower leg) outward; it also maintains posture by stabilizing the hip joint	lateral rotation	**inferior gemellus**	ischial tuberosity	greater trochanter of femur
	femur	twists the thigh (and lower leg) outward; it also maints posture by stabilizing the hip joint	lateral rotation	**quatratus femoris**	ischial tuberosity	trochanteric crest of femur
Adductors	femur	brings the thighs back together; it also assists with raising the knee	adduction; flexion	**adductor longus**	pubis near the pubic symphysis	linea aspera
	femur	brings the thighs back together; it also assists with raising the knee	adduction; flexion	**adductor brevis**	body of the pubis and in the inferior ramus of the pubis	linea aspera above adductor longus
	femur	brings the thighs back together; it also assists with raising the knee and moving the thigh back	adduction; flexion; extension	**adductor magnus**	ischial rami, the pubic rami, and the ischial tuberosity	linea aspera; adductor tubercle of femur
	femur	opens the thigh; with raising the knee and turning the thigh (and lower leg) inward	adduction; flexion; medial rotation	**pectineus**	pectineal line of the pubis	lesser trochanter to linea aspera of posterior aspect of femur

The **tensor fascia latae** is a thick, squarish muscle in the superior aspect of the lateral thigh. It acts as a synergist of the gluteus medius and iliopsoas in flexing and abducting the thigh. It also helps stabilize the lateral aspect of the knee by pulling on the **iliotibial tract** (band), making it taut. Deep to the gluteus maximus, the **piriformis, obturator internus, obturator externus, superior gemellus, inferior gemellus**, and **quadratus femoris** laterally rotate the femur at the hip.

The **adductor longus**, **adductor brevis**, and **adductor magnus** can both medially and laterally rotate the thigh depending on the placement of the foot. The adductor longus flexes the thigh, whereas the adductor magnus extends it. The pectineus adducts and flexes the femur at the hip as well. The **pectineus** is located in the **femoral triangle**, which is formed at the junction between the hip and the leg and also includes the femoral nerve, the femoral artery, the femoral vein, and the deep inguinal lymph nodes.

Thigh Muscles That Move the Femur, Tibia, and Fibula

Deep fascia in the thigh separates it into medial, anterior, and posterior compartments (see **Figure 6.8** and **Table 6.3**). The muscles in the **medial compartment of the thigh** are responsible for adducting the femur at the hip. Along with the adductor longus, adductor brevis, adductor magnus, and pectineus, the strap-like **gracilis** adducts the thigh in addition to flexing the leg at the knee.

Table 6.3: Thigh Muscles That Move the Femur, Tibia, and Fibula

Group	Movement	Target	Target motion direction	Prime mover	Origin	Insertion
Medial compartment of thigh	moves the back of the lower legs up toward the buttocks, as when kneeling; it also assists in opening the thighs	femur; tibia/fibula	tibia/fibula: flexion; thigh: adduction	**gracilis**	inferior ramus, the body of the pubis, and the ischial ramus	medial surface of tibia
Anterior compartment of the thigh: Quadriceps femoris group	moves the lower leg out in front of the body, as when kicking; it also assists in raising the knee	femur; tibia/fibula	tibia/fibula: extension; thigh: flexion	**rectus femoris**	anterior inferior iliac spine and in the superior margin of the acetabulum	patella; tibial tuberosity
	moves the lower leg out in front of the body, as when kicking	tibia/fibula	extension	**vastus lateralis**	greater trochanter, the intertrochanteric line, and the linea aspera	patella; tibial tuberosity
	moves the lower leg out in front of the body, as when kicking	tibia/fibula	extension	**vastus medialis**	linea aspera and the intertrochanteric line	patella; tibial tuberosity
	moves the lower leg out in front of the body, as when kicking	tibia/fibula	extension	**vastus intermedius**	proximal femur shaft	patella; tibial tuberosity
	moves the back of the lower legs up and back toward the buttocks, as when kneeling; it also assists in moving the thigh diagonally upward and outward as when mounting a bike	femur; tibia/fibula	tibia: flexion; thigh: flexion, abduction, lateral rotation	**sartorius**	anterior superior iliac spine	medial aspect of proximal tibia
Posterior compartment of the thigh: Hamstring group	moves the back of the lower leg up and back toward the buttocks, as when kneeling; it also moves the thigh down and back and twists the thigh (and lower leg) outward	femur; tibia/fibula	tibia/fibula: flexion; thigh: extension, lateral rotation	**biceps femoris**	ischial tuberosity, linea aspera, and distal femur	head of fibula; lateral condyle of tibia
	moves the back of the lower legs up toward the buttocks, as when kneeling; it also moves the thigh down and back and twists the thigh (and lower leg) inward	femur; tibia/fibula	tibia/fibula: flexion; thigh: extension, medial rotation	**semitendinosus**	ischial tuberosity	upper tibial shaft

Group	Movement	Target	Target motion direction	Prime mover	Origin	Insertion
	moves the back of the lower legs up and back toward the buttocks, as when kneeling; it also moves the thigh down and back and twists the thigh (and lower leg) inward	femur; tibia/ fibula	tibia/fibula: flexion; thigh: extension, medial rotation	**semimembranosus**	ischial tuberosity	medial condyle of tibia; medial condyle of femur

The muscles of the **anterior compartment of the thigh** flex the thigh and extend the leg. This compartment contains the **quadriceps femoris group**, which actually comprises four muscles that extend and stabilize the knee. The **rectus femoris** is on the anterior aspect of the thigh, the vastus lateralis is on the lateral aspect of the thigh, the vastus medialis is on the medial aspect of the thigh, and the **vastus intermedius** is between the **vastus lateralis** and **vastus medialis** and deep to the rectus femoris. The tendon common to all four is the **quadriceps tendon** (patellar tendon), which inserts into the patella and continues below it as the **patellar ligament**. The patellar ligament attaches to the tibial tuberosity. In addition to the quadriceps femoris, the **sartorius** is a band-like muscle that extends from the anterior superior iliac spine to the medial side of the proximal tibia. This versatile muscle flexes the leg at the knee and flexes, abducts, and laterally rotates the leg at the hip. This muscle allows us to sit cross-legged.

The **posterior compartment of the thigh** includes muscles that flex the leg and extend the thigh. The three long muscles on the back of the knee are the **hamstring group**, which flexes the knee. These are the **biceps femoris**, **semitendinosus**, and **semimembranosus**. The tendons of these muscles form the **popliteal fossa**, the diamond-shaped space at the back of the knee.

Muscles That Move the Feet and Toes

Similar to the thigh muscles, the muscles of the leg are divided by deep fascia into compartments, although the leg has three: anterior, lateral, and posterior (**Figure 6.9** and **Table 6.4**).

Tibialis anterior
Fibularis longus
Extensor digitorum longus
Fibularis brevis
Extensor hallucis longus
Fibularis tertius
Superior extensor retinaculum
Inferior extensor retinaculum

Superficial muscles of the right lower leg (anterior view)

Gastrocnemius (lateral head)
Gastrocnemius (medial head)
Plantaris
Soleus
Calcaneal (Achilles) tendon
Calcaneus (heel)

Superficial muscles of the right lower leg (posterior view)

Popliteus
Soleus (cut)
Fibularis longus
Tibialis posterior
Flexor digitorum longus
Flexor hallucis longus
Fibularis brevis

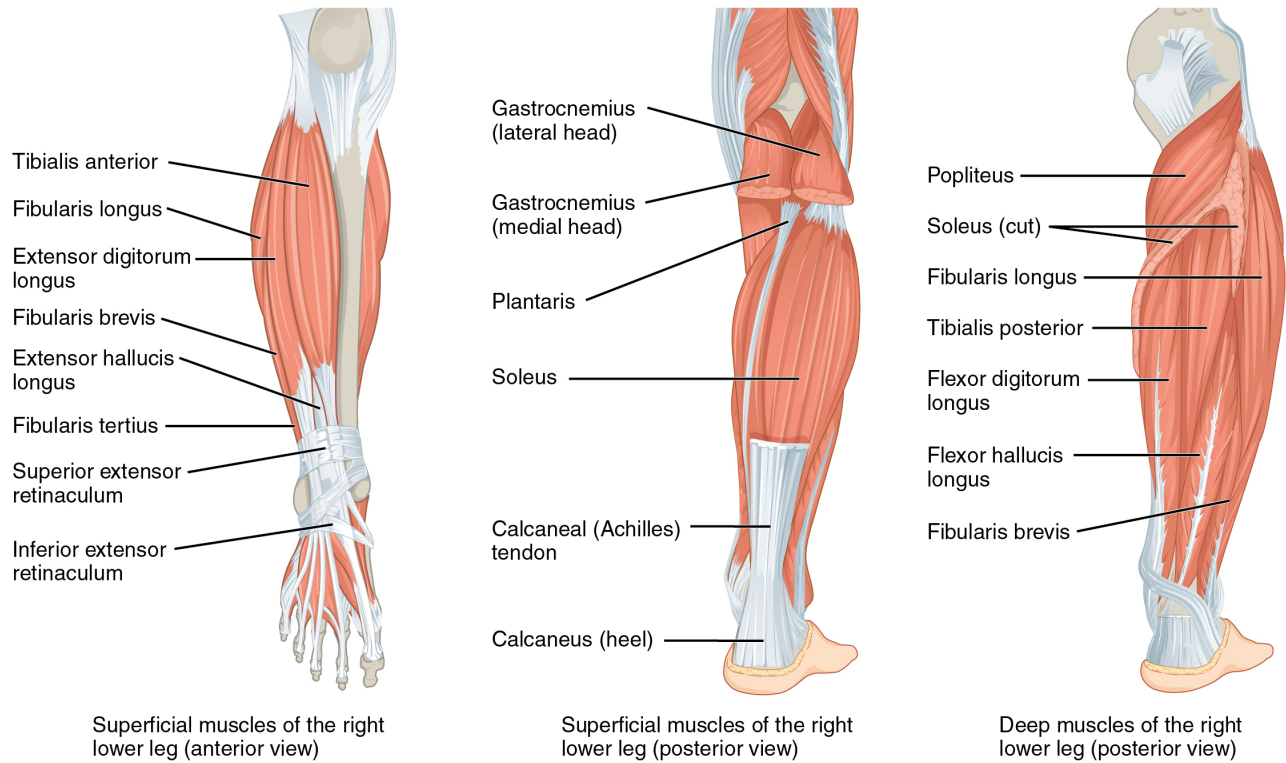Deep muscles of the right lower leg (posterior view)

Figure 6.9 Muscles of the Lower Leg. The muscles of the anterior compartment of the lower leg are generally responsible for dorsiflexion, and the muscles of the posterior compartment of the lower leg are generally responsible for plantar flexion. The lateral and medial muscles in both compartments invert, evert, and rotate the foot.

Table 6.4. Muscles That Move the Feet and Toes

| Group	Movement	Target	Target movement direction	Prime mover	Origin	Insertion
Anterior compartment of leg	Raises the sole of the foot off the ground, as when preparing to foot-tap; bends the inside of the foot upwards, as when catching your balance while falling laterally toward the opposite side as the balancing foot	foot	dorsiflexion; inversion	**tibialis anterior**	lateral condyle and upper tibial shaft; interosseous membrane	interior surface of medial cuneiform; first metatarsal bone
	raises the sole of the foot off the ground, as when preparing to foot-tap; extends the big toe	foot; big toe	foot: dorsiflexion; big toe: extension	**extensor hallucis longus**	anteromedial fibula shaft and interosseous membrane	distal phalanx of big toe
	raises the sole of the foot off the ground, as when preparing to foot-tap; extends the toes	foot; toes 2–5	foot: dorsiflexion; toes: extension	**extensor digitorum longus**	lateral condyle of the tibia, the proximal portion of the fibula, and the interosseous membrane	middle and distal phalanges of toes 2–5
Lateral compartment of leg	lowers the sole of the foot to the ground, as when foot-tapping or jumping; it also bends the inside of the foot downwards, as when catching your balance while falling laterally toward the same side as the balancing foot	foot	plantar flexion and eversion	**fibularis longus**	upper portion of the lateral fibula	first metatarsal; medial cuneiform
	lowers the side of the foot to the ground, as when foot-tapping or jumping; it also bends the inside of the foot downward, as when catching your balance while falling laterally toward the same side as the balancing foot	foot	plantar flexion and eversion	**fibularis (peroneus) brevis**	distal fibula shaft	proximal end of fifth metatarsal
Posterior compartment of leg: Superficial muscles	lowers the sole of the foot to the ground, as when foot-tapping or jumping; it also assists in moving the back of the lower legs up and back toward the buttocks	foot; tibia/ fibula	foot: plantar flexion; tibia/fibula: flexion	**gastrocnemius**	medial and lateral condyles of the femur	posterior calcaneus

Group	Movement	Target	Target movement direction	Prime mover	Origin	Insertion
	lowers the sole of the foot the ground, as when foot-tapping or jumping; it also maintains posture while walking	foot	plantar flexion	**soleus**	superior tibia, fibula, and interosseous membrane	posterior calcaneus
	lowers the sole of the foot to the ground, as when foot-tapping or jumping; it also assists in moving the back of the lower legs up and back toward the buttocks	foot; tibia/fibula	foot: plantar flexion; tibia/fibula: flexion	**plantaris**	posterior femur above the lateral condyle	calcaneus or calcaneus tendon
	lowers the sole of the foot to the ground, as when foot-tapping or jumping	foot	plantar flexion	**tibialis posterior**	superior tibia and fibula and in the interosseous membrane	several tarsals and metatarsals 2–4
Posterior compartment of leg: Deep muscles	moves the back of the lower legs up and back toward the buttocks; it also assists in rotation of the leg at the knee and thigh	tibia/fibula	tibia/fibula: flexion; thigh and lower leg: medial and lateral rotation	**popliteus**	lateral condyle of the femur and the lateral meniscus	proximal tibia
	lowers the sole of the foot to the ground, as when foot-tapping or jumping; it also bends the inside of the foot upward and flexes the toes	foot; toes 2–5	foot: plantar flexion and inversion; toes: flexion	**flexor digitorum longus**	posterior tibia	distal phalanges of toes 2–5
	flexes the big toe	big toe; foot	big toe: flexion; foot: plantar flexion	**flexor hallicis longus**	midshaft of fibula; interosseous membrane	distal phalanx of big toe

The muscles in the **anterior compartment of the leg**: the **tibialis anterior**, a long and thick muscle on the lateral surface of the tibia, the **extensor hallucis longus**, deep under it, and the **extensor digitorum longus**, lateral to it, all contribute to raising the front of the foot when they contract. The **fibularis tertius**, a small muscle that originates on the anterior surface of the fibula, is associated with the extensor digitorum longus and sometimes fused to it, but is not present in all people. Thick bands of connective tissue called the **superior extensor retinaculum** (transverse ligament of the ankle) and the **inferior extensor retinaculum**, hold the tendons of these muscles in place during dorsiflexion.

The **lateral compartment of the leg** includes two muscles: the **fibularis longus** (peroneus longus) and the **fibularis brevis** (peroneus brevis). The superficial muscles in the **posterior compartment of the leg** all insert onto the **calcaneal tendon** (Achilles tendon), a strong tendon that inserts into the calcaneal bone of the ankle. The muscles in this compartment are large and strong and keep humans upright. The most superficial and visible muscle of

the calf is the **gastrocnemius**. Deep to the gastrocnemius is the wide, flat **soleus**. The **plantaris** runs obliquely between the two; some people may have two of these muscles, whereas no plantaris is observed in about seven percent of other cadaver dissections. The plantaris tendon is a desirable substitute for the fascia lata in hernia repair, tendon transplants, and repair of ligaments. There are four deep muscles in the posterior compartment of the leg as well: the**popliteus, flexor digitorum longus, flexor hallucis longus,** and **tibialis posterior.**

The foot also has intrinsic muscles, which originate and insert within it (similar to the intrinsic muscles of the hand). These muscles primarily provide support for the foot and its arch, and contribute to movements of the toes (**Figure 6.10** and **Table 6.5**). The principal support for the longitudinal arch of the foot is a deep fascia called **plantar aponeurosis**, which runs from the calcaneus bone to the toes (inflammation of this tissue is the cause of "plantar fasciitis," which can affect runners. The intrinsic muscles of the foot consist of two groups. The **dorsal group** includes only one muscle, the **extensor digitorum brevis**. The second group is the **plantar group**, which consists of four layers, starting with the most superficial.
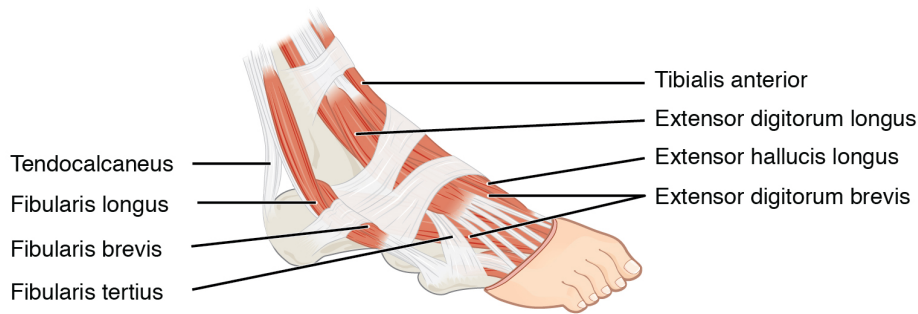
(a) Dorsal superficial muscles of
the right foot (lateral view)
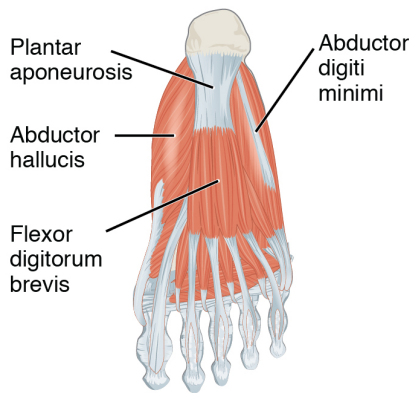
(b) Superficial muscles of the
left sole (plantar view)
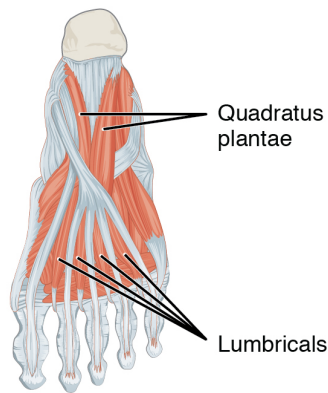
(c) Intermediate muscles of
the left sole (plantar view)
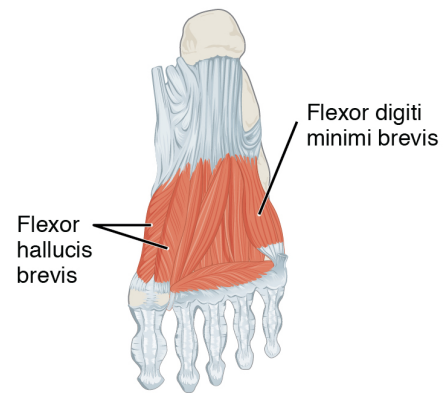
(d) Deep muscles of the
left sole (plantar view)

Figure 6.10 Intrinsic Muscles of the Foot. The muscles along the dorsal side of the foot (a) generally extend the toes while the muscles of the plantar side of the foot (b, c, d) generally flex the toes. The plantar muscles exist in three layers, providing the foot the strength to counterbalance the weight of the body. In this diagram, these three layers are shown from a plantar view beginning with the bottom-most layer just under the plantar skin of the foot (b) and ending with the top-most layer (d) located just inferior to the foot and toe bones.

Table 6.5. Intrinsic Muscles in the Foot

Group	Movement	Target	Target motion direction	Primve mover	Origin	Insertion
Dorsal group	extends toes 2 through 5	toes 2−5	extension	**extensor digitorum brevis**	calcaneus; extensor retinaculum	base of proximal phalanx of big toe; extensor expansions on toes 2−5
Plantar group (layer 1)	abducts and flexes the big toe	big toe	adduction; flexion	**abductor hallucis**	calcaneal tuberosity; flexor retinaculum	proximal phalanx of big toe
	flexes toes 2 through 4	middle toes	flexion	**flexor digitorum brevis**	calcaneal tuberosity	middle phalanx of toes 2−4
	abducts and flexes the small toe	toe 5	abduction; flexion	**abductor digiti minimi**	calcaneal tuberosity	proximal phalanx of little toe
Plantar group (layer 2)	assists in flexing toes 2-5	toes 2−5	flexion	**quadratus plantae**	medial and lateral sides of calcaneus	tendon of flexor digitorum longus
	extends toes 2-5 at the interphalangeal joints; flexes the small toes at the metatarsophalnageal joints	toes 2−5	extension; flexion	**lumbricals**	tendons of flexor digitorum longus	medial side of proximal phalanx of toes 2-5
Plantar group (layer 3)	flexes the big toe	big toe	flexion	**flexor hallucis brevis**	lateral cuneiform; cuboid bones	base of proximal phalanx of big toe
	adducts and flexes the big toe	big toe	adduction; flexion	**adductor hallucis**	bases of metatarsals 2 through 4; fibularis longus tendon sheath; ligament across the metatarsophalangeal joints	base of proximal phalanx of big toe
	flexes the small toe	little toe	flexion	**flexor digiti minimi brevis**	base of metatarsal 5; tendon sheath of the fibularis longus	base of proximal phalanx of little toe
Plantar group (layer 4)	abducts and flexes the middle toes at the metatarsophalangeal joints; it also extends the middle toes at the interphalangeal joints	middle toes	abduction; flexion; extension	**dorsal interossei**	sides of the metatarsals	both sides of toe 2; for each tother to, extensor expansion over first phalanx on side opposite toe 2

Group	Movement	Target	Target motion direction	Primve mover	Origin	Insertion
	abducts toes 3 through 5; it also flexes the proximal phalanges and extends the distal phalanges	small toes	abduction; flexion; extension	**plantar interossei**	side of each metatarsal that faces metatarsal 2 (absent from metatarsal 2)	extensor expansion on first phalanx of each toe (except toe 2) on side facing toe 2

Lab 7: Muscular System II - Forelimb and Axial Muscles

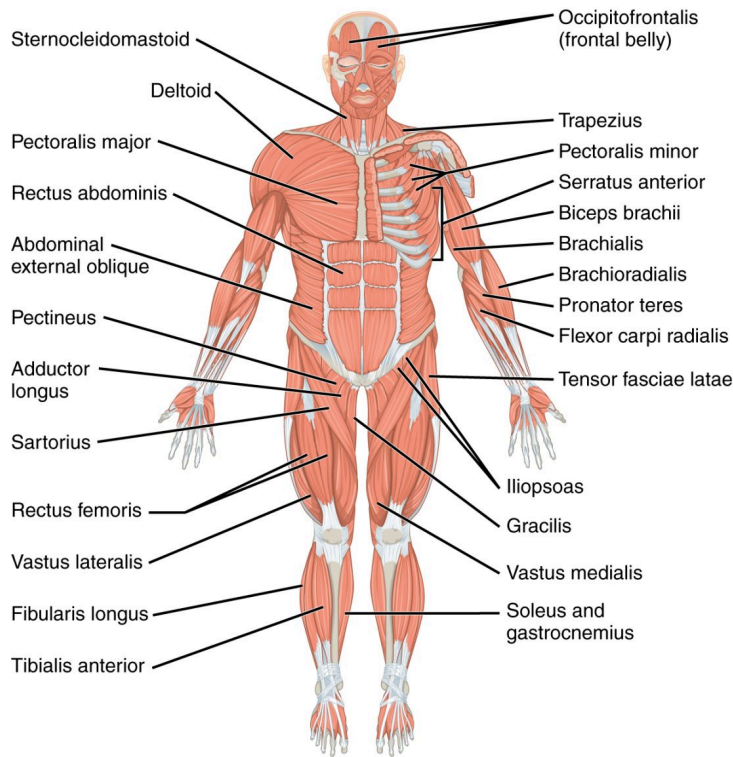Muscles of the forelimb, trunk, and head; Muscle groups

Learning Objectives

When you are prepared for the Test on Week 6-7 Learning Objectives in Week 8*, you will be able to:
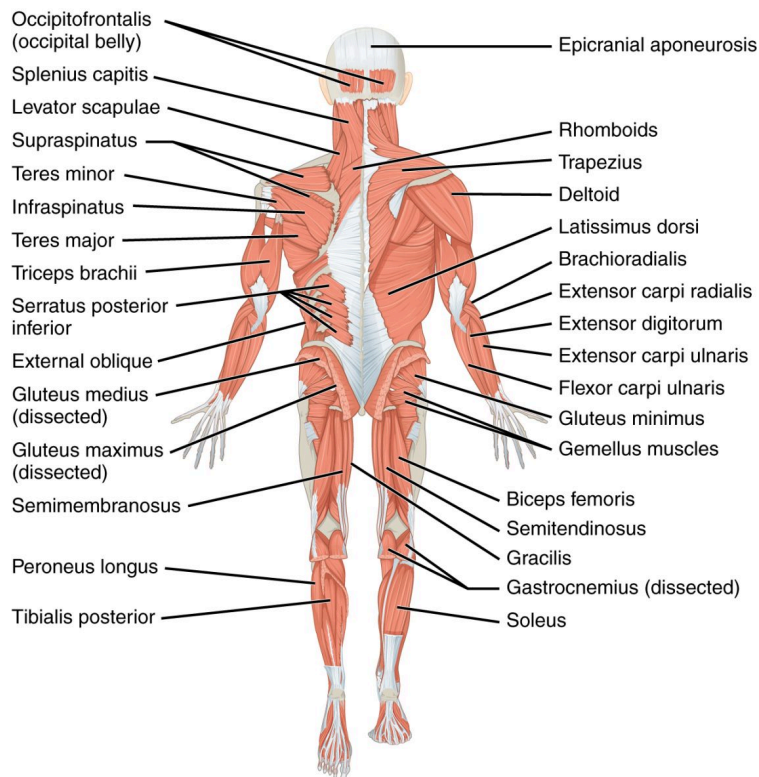
1. Identify components of a muscle cell and the neuromuscular junction.
2. Identify connective tissues of muscles.
3. Identify significant muscles on both human models and cats (listed in the lab activity).
4. For the hamstrings, quadriceps and rotator cuff muscle groups: identify the muscles within them, the bony features that act as their attachment sites, and their general functions.

*Muscle dissections will span weeks 6-7. There will be no test in Week 7. In week 8, there will be a test covering all of the above learning objectives.

In last week's lab, we looked at muscles of the hindlimb. In lab this week, we will look at the skeletal muscles in the forelimb, as well as in the axial region. By the end of these two weeks, you should have a broad understanding of the muscular system and be able to identify the major muscles in the body (**Figure 7.1**).

Sternocleidomastoid

Occipitofrontalis
(frontal belly)

Deltoid

Trapezius

Pectoralis major

Pectoralis minor

Rectus abdominis

Serratus anterior

Biceps brachii

Abdominal
external oblique

Brachialis

Brachioradialis

Pectineus

Pronator teres

Flexor carpi radialis

Adductor
longus

Tensor fasciae latae

Sartorius

Rectus femoris

Iliopsoas

Vastus lateralis

Gracilis

Fibularis longus

Vastus medialis

Tibialis anterior

Soleus and
gastrocnemius

Major muscles of the body.
Right side: superficial; left side: deep (anterior view)

Occipitofrontalis
(occipital belly)

Epicranial aponeurosis

Splenius capitis

Levator scapulae

Rhomboids

Supraspinatus

Trapezius

Teres minor

Deltoid

Infraspinatus

Latissimus dorsi

Teres major

Brachioradialis

Triceps brachii

Extensor carpi radialis

Serratus posterior
inferior

Extensor digitorum

Extensor carpi ulnaris

External oblique

Flexor carpi ulnaris

Gluteus medius
(dissected)

Gluteus minimus

Gemellus muscles

Gluteus maximus
(dissected)

Biceps femoris

Semimembranosus

Semitendinosus

Gracilis

Peroneus longus

Gastrocnemius (dissected)

Tibialis posterior

Soleus

Major muscles of the body.
Right side: superficial; left side: deep (posterior view)

Figure 7.1 Overview of the Muscular System. On the anterior and posterior views of the muscular system above, superficial muscles (those at the surface) are shown on the right side of the body while deep muscles (those underneath the superficial muscles) are shown on the left half of the body. For the legs, superficial muscles are shown in the anterior view while the posterior view shows both superficial and deep muscles.

Muscles of the Forelimb

Muscles of the shoulder and upper limb can be divided into four groups: muscles that stabilize and position the shoulder girdle, muscles that move the arm, muscles that move the forearm, and muscles that move the wrists, hands, and fingers. The shoulder girdle consists of the lateral ends of the clavicle and scapula, along with the proximal end of the humerus, and the muscles covering these three bones to stabilize the shoulder joint. The girdle creates a base from which the head of the humerus, in its ball-and-socket joint with the glenoid fossa of the scapula, can move the arm in multiple directions.

Muscles That Position the Pectoral Girdle

Muscles that position the pectoral girdle are located either on the anterior thorax or on the posterior thorax (**Figure 7.2** and **Table 7.1**). The anterior muscles include the **subclavius**, **pectoralis minor**, and **serratus anterior**. The posterior muscles include the **trapezius**, **rhomboid major**, and **rhomboid minor**. When the rhomboids are contracted, your scapula moves medially, which can pull the shoulder and upper limb posteriorly.
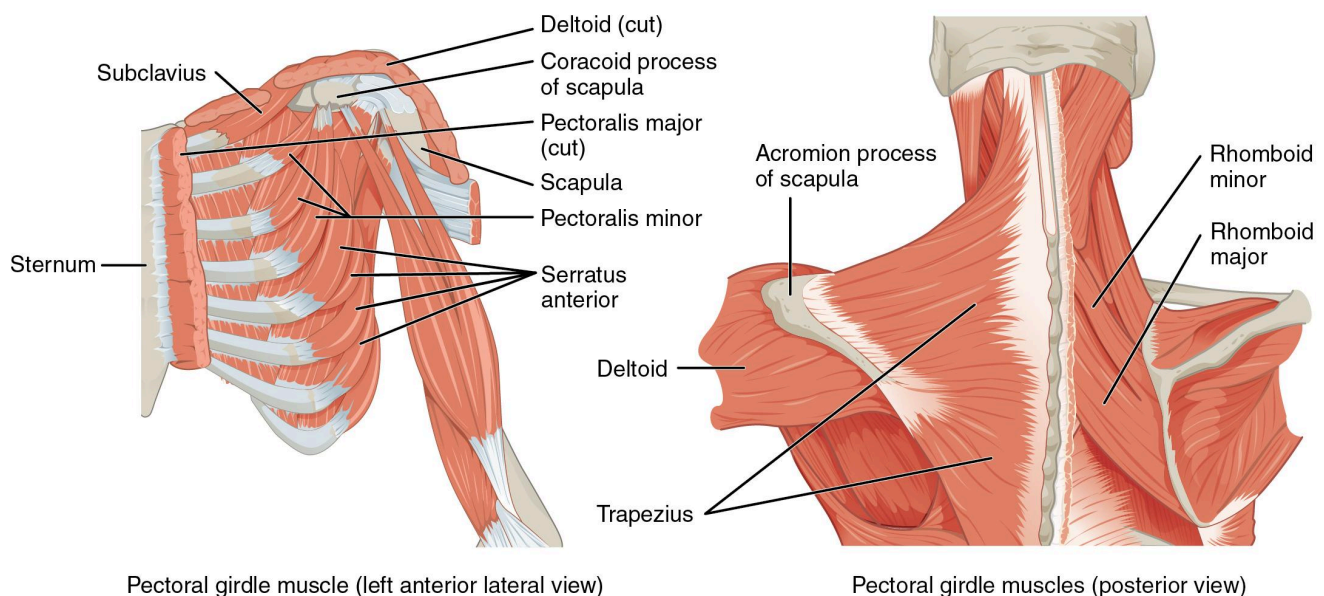

Pectoral girdle muscle (left anterior lateral view)   Pectoral girdle muscles (posterior view)

Figure 7.2 Muscles That Position the Pectoral Girdle. The muscles that stabilize the pectoral girdle make it a steady base on which other muscles can move the arm. Note that the pectoralis major and deltoid, which move the humerus, are cut here to show the deeper positioning muscles.

Table 7.1 – Muscles that Position the Pectoral Girdle

Position in the thorax	Movement	Target	Target motion direction	Prime mover	Origin	Insertion
Anterior thorax	Stabilizes clavicle during movement by depressing it	Clavicle	Depression	**Subclavius**	First rib	Inferior surface of clavicle
Anterior thorax	Rotates shoulder anteriorly (throwing motion); assists with inhalation	Scapula; ribs	Scapula: depresses; ribs: elevates	**Pectoralis minor**	Anterior surfaces of certain ribs (2–4 or 3–5)	Coracoid process of scapula
Anterior thorax	Moves arm from side of body to front of body; assists with inhalation	Scapula; ribs	Scapula: protracts; ribs: elevates	**Serratus anterior**	Muscle slips from certain ribs (1–8 or 1–9)	Anterior surface of vertebral border of scapula
Posterior thorax	Elevates shoulders (shrugging); pulls shoulder blades together; tilts head backwards	Scapula; cervical spine	Scapula: rotests inferiorly, retracts, elevates, and depresses; spine: extends	**Trapezius**	Skull; vertebral column	Acromion and spine of scapula; clavicle
Posterior thorax	Stabilizes scapula during pectoral girdle movement	Scapula	Retracts; rotates inferiorly	**Rhomboid major**	Thoracic vertebrae (T2–T5)	Medial border of scapula
Posterior thorax	Stabilizes scapula during pectoral girdle movement	Scapula	Retracts; rotates inferiorly	**Rhomboid minor**	Cervical and thoracic vertebrae (C7 and T1)	Medial border of scapula

Muscles That Move the Humerus

Similar to the muscles that position the pectoral girdle, muscles that cross the shoulder joint and move the humerus bone of the arm include both axial and scapular muscles (**Figure 7.3** and **Table 7.2**). The two axial muscles are the pectoralis major and the latissimus dorsi. The **pectoralis major** is thick and fan-shaped, covering much of the superior portion of the anterior thorax. The broad, triangular **latissimus dorsi** is located on the inferior part of the back, where it inserts into a thick connective tissue sheath called an aponeurosis.
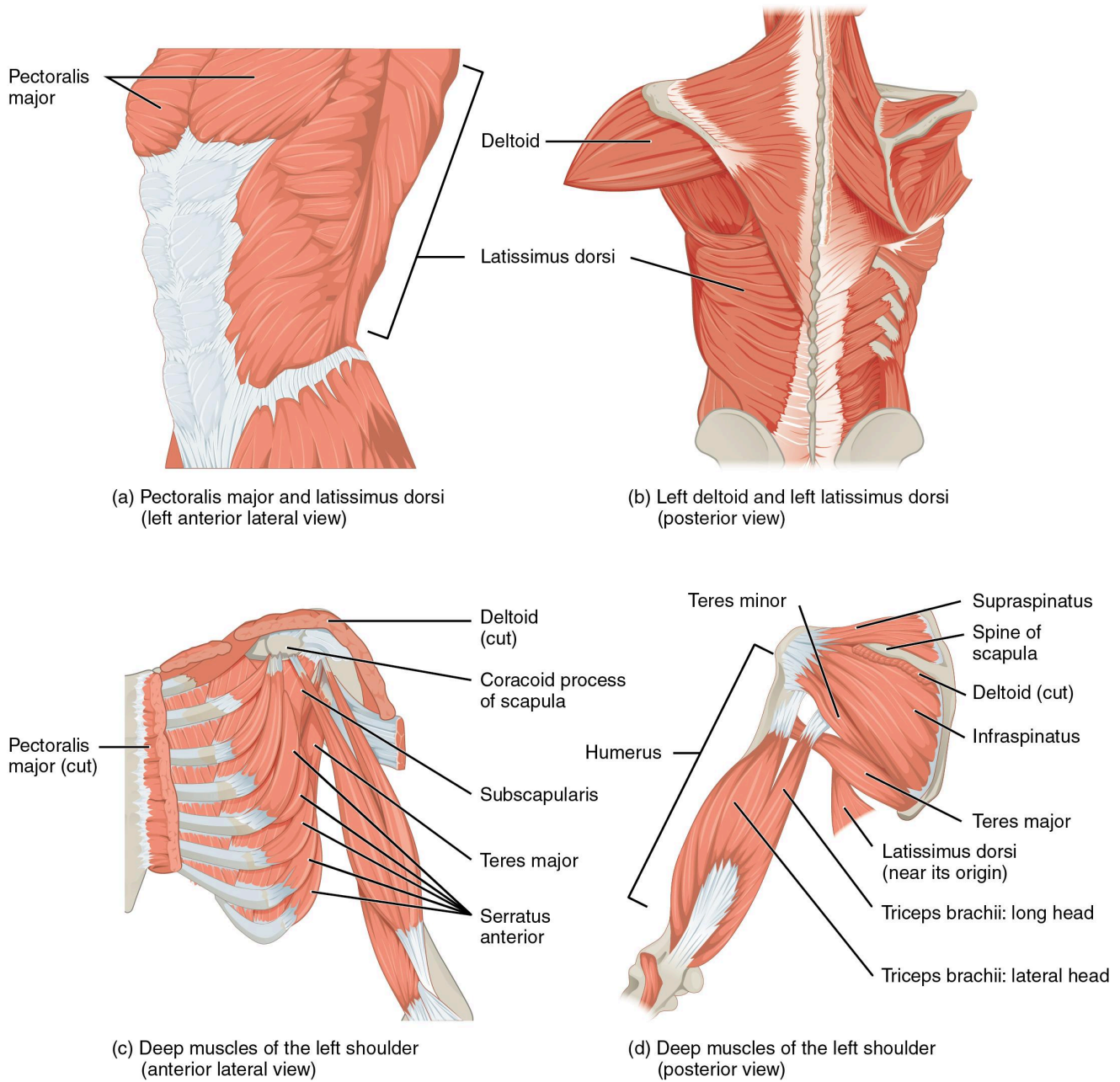
(a) Pectoralis major and latissimus dorsi
(left anterior lateral view)

(b) Left deltoid and left latissimus dorsi
(posterior view)

(c) Deep muscles of the left shoulder
(anterior lateral view)

(d) Deep muscles of the left shoulder
(posterior view)

Figure 7.3 Muscles That Move the Humerus. (a, c) The muscles that move the humerus anteriorly are generally located on the anterior side of the body and originate from the sternum (e.g., pectoralis major) or the anterior side of the scapula (e.g., subscapularis). (b) The muscles that move the humerus superiorly generally originate from the superior surfaces of the scapula and/or the clavicle (e.g., deltoids). The muscles that move the humerus inferiorly generally originate from middle or lower back (e.g., latissiumus dorsi). (d) The muscles that move the humerus posteriorly are generally located on the posterior side of the body and insert into the scapula (e.g., infraspinatus).

Table 7.2 – Muscles that Move the Humerus

Group	Movement	Target	Target motion direction	Prime mover	Origin	Insertion
Axial Muscles	Brings elbows together; moves elbow up (as during an uppercut punch)	Humerus	Flexion; adduction; medial rotation	**Pectoralis major**	Clavicle; sternum; cartilage of certain ribs (1-6 or 1-7); aponeurosis of external oblique muscle	Greater tubercle of humerus
	Moves elbow back (as in elbowing someone standing behind you); spreads elbows apart	Humerus; scapula	Humerus; extension, adduction, and medial rotation; scapula: depression	**Latissimus dorsi**	Thoracic vertebrae (T7-T12); lumbar vertebrae; lower ribs (9-12); iliac crest	Intertubercular sulcus of humerus
Rotator Cuff (scapular muscles)	Assists pectoralis major in bringing elbows together ans stabilizes shoulder joint during movement of the pectoral girdle	Humerus	Medial rotation	**Subscapularis**	Subscapular fossa of scapula	Lesser tubercle of humerus
	Rotates elbow outwards, as during a tennis swing	Humerus	Abduction	**Supraspinatus**	Supraspinous foss of scapula	Greater tubercle of humerus
	Rotates elbow outwards, as during a tennis swing	Humerus	Extension; adduction	**Infraspinatus**	Infraspinous fossa of scapula	Greater tubercle of humerus
	Assists infraspinatus in rotating elbow outwards	Humerus	Extension; adduction	**Teres minor**	Lateral border of dorsal scapular surface	Greater tubercle of humerus
Other scapular muscles	Assists infraspinatus in rotating elbow outwards	Humerus	Extension; adduction	**Teres major**	Posterior surface of scapula	Intertubercular sulcus of humerus
	Lifts arms at shoulder	Humerus	Abduction; flexion; extension; medial and lateral rotation	**Deltoid**	Trapezius; clavicle; acromion; spine of scapula	Deltoid tuberosity of humerus
	Moves elbow up and across body, as when putting hand on chest	Humerus	Flexion; adduction	**Coracobrachialis**	Coracoid process of scapula	Medial surface of humerus shaft

The rest of the shoulder muscles originate on the scapula. The anatomical and ligamental structure of the shoulder joint and the arrangements of the muscles covering it, allows the arm to carry out different types of movements. The **deltoid**, the thick muscle that creates the rounded lines of the shoulder is the major abductor of the arm, but it also facilitates flexing and medial rotation, as well as extension and lateral rotation. The

subscapularis originates on the anterior scapula and medially rotates the arm. Named for their locations, the **supraspinatus** (superior to the spine of the scapula) and the **infraspinatus** (inferior to the spine of the scapula) abduct the arm, and laterally rotate the arm, respectively. The thick and flat **teres major** is inferior to the teres minor and extends the arm, and assists in adduction and medial rotation of it. The long **teres minor** laterally rotates and extends the arm. Finally, the **coracobrachialis** flexes and adducts the arm.

The tendons of the deep subscapularis, supraspinatus, infraspinatus, and teres minor connect the scapula to the humerus, forming the **rotator cuff** (musculotendinous cuff), the circle of tendons around the shoulder joint. When baseball pitchers undergo shoulder surgery it is usually on the rotator cuff, which becomes pinched and inflamed, and may tear away from the bone due to the repetitive motion of bring the arm overhead to throw a fast pitch.

Muscles That Move the Forearm

The forearm, made of the radius and ulna bones, has four main types of action at the hinge of the elbow joint: flexion, extension, pronation, and supination. The elbow flexors include the **biceps brachii**, **brachialis**, and **brachioradialis**. The elbow extensor is the **triceps brachii**. The forearm pronators are the **pronator teres** and the **pronator quadratus**, and the **supinator** is the only one that supinates the forearm (turns the palm of the hand anteriorly).

The biceps brachii, brachialis, and brachioradialis flex the elbow. The two-headed **biceps brachii** crosses the shoulder and elbow joints to flex the elbow, also taking part in supinating the forearm at the radioulnar joints and flexing the arm at the shoulder joint. Deep to the biceps brachii, the **brachialis** provides additional power in flexing the elbow. Finally, the **brachioradialis** can flex the elbow quickly or help lift a load slowly. These muscles and their associated blood vessels and nerves form the anterior compartment of the arm (anterior flexor compartment of the arm) (**Figure 7.4** and **Table 7.3**).
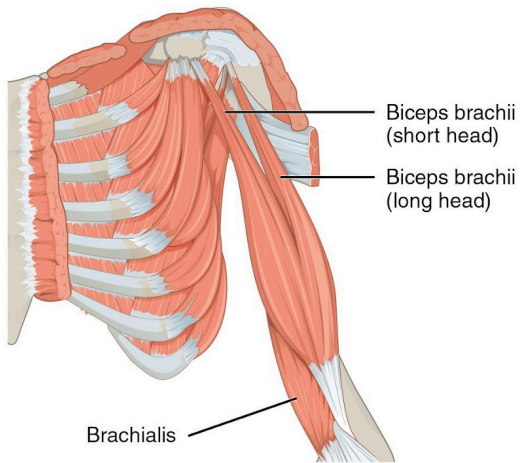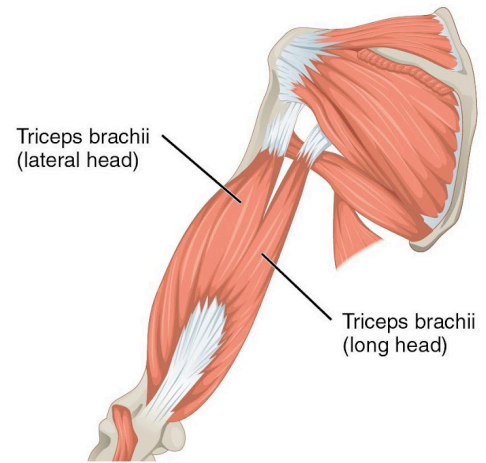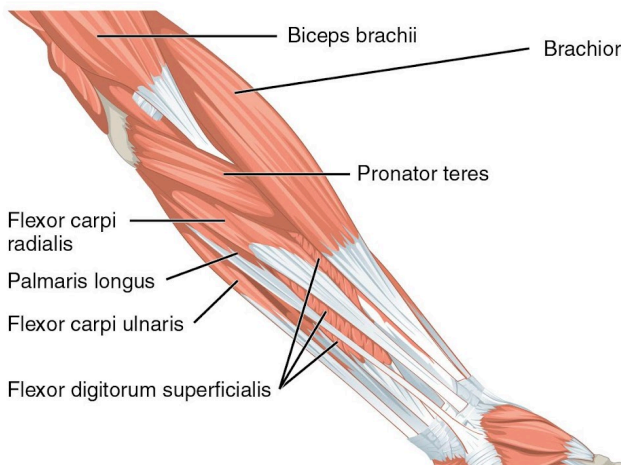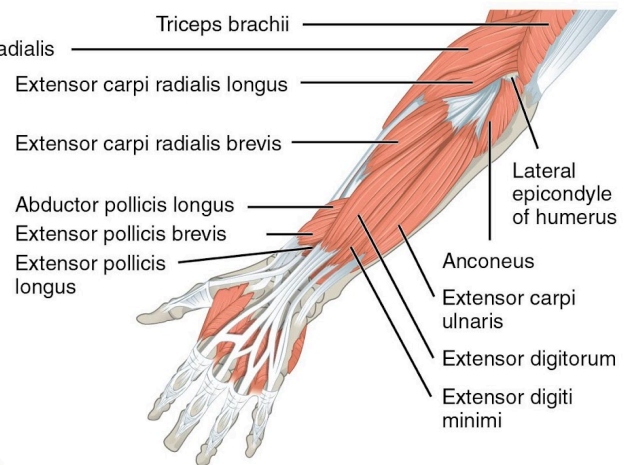
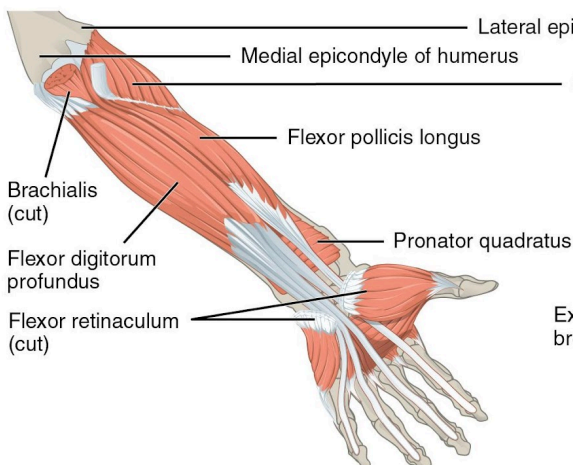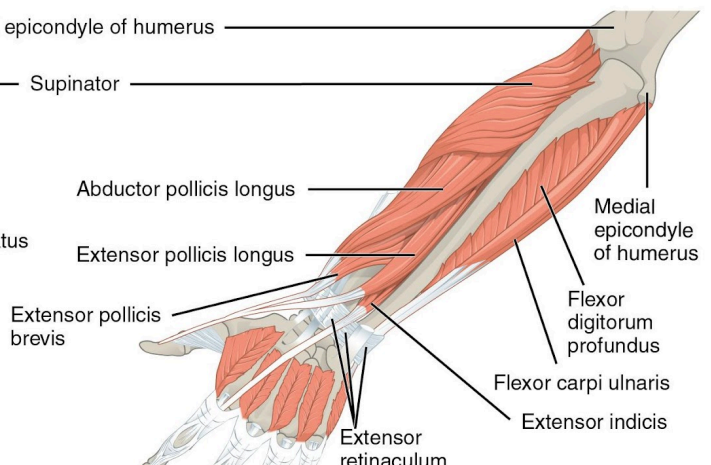**Figure 7.4 Muscles That Move the Forearm** The muscles originating in the upper arm flex, extend, pronate, and supinate the forearm. The muscles originating in the forearm move the wrists, hands, and fingers.

Table 7.3 Muscles that Move the Elbow and Forearm

Movement	Target	Target Motion Direction	Prime Mover	Origin	Insertion
Anterior Muscles (Flexion)					
Performs a bicep curl; also allows palm of hand to point toward body while flexing	Forearm	Flexion; supination	**Biceps brachii**	Coracoid process; tubercle above glenoid cavity	Radial tuberosity
Performs a bicep curl	Forearm	Flexion	**Brachialis**	Front of distal humerus	Coronoid process of ulna
Assists and stabilizes elbow during bicep curl motion	Forearm	Flexion	**Brachioradialis**	Lateral supracondylar ridge at distal end of humerus	Base of styloid process of radius
Posterior Muscles (Extension)					
Assists in extending forearm; also allows forearm to extend away from the body	Forearm	Extension; abduction	**Anconeus**	Lateral epicondyle of humerus	Lateral aspect of olecranon process of ulna
Extends forearm, as during a punch	Forearm	Extension	**Triceps brachii**	Infraglenoid tubercle of scapula ; posterior shaft of humerus ; posterior humeral shaft distal to the radial groove	Olecranon process of ulna
Anterior Muscles (Pronation)					
Assists in turning hand palm down	Forearm	Pronation	**Pronator quadratus**	Distal portion of anterior ulnar shaft	Distal surface of anterior radius
Turns hand palm down	Forearm	Pronation	**Pronator teres**	Medial epicondyle of humerus ; coronoid process of ulna	Lateral radius
Posterior Muscles (Supination)					
Turns hand palm up	Forearm	Supination	**Supinator**	Lateral epicondyle of humerus; proximal ulna	Proximal end of radius

Muscles That Move the Wrist, Hand, and Fingers

Wrist, hand, and finger movements are facilitated by two groups of muscles. The forearm is the origin of the extrinsic muscles of the hand. The palm is the origin of the intrinsic muscles of the hand.

The muscles in the **anterior compartment of the forearm** (anterior flexor compartment of the forearm) originate on the humerus and insert into different parts of the hand. These make up the bulk of the forearm. From lateral to medial, the **superficial anterior compartment of the forearm** includes the **flexor carpi radialis**, **palmaris longus**, **flexor carpi ulnaris**, and **flexor digitorum superficialis**. The flexor digitorum superficialis flexes the hand as well as the digits at the knuckles, which allows for rapid finger movements, as in typing or playing a musical instrument (see **Table 7.4**). However, poor ergonomics can irritate the tendons of these muscles as they slide back and forth with the carpal tunnel of the anterior wrist and pinch the median nerve, which also travels through the tunnel, causing Carpal Tunnel Syndrome. The **deep anterior compartment** produces wrist and digit flexion, bending the fingers to make a fist. These are the **flexor pollicis longus** and the **flexor digitorum profundus**.

The muscles in the **superficial posterior compartment of the forearm** (superficial posterior extensor compartment of the forearm) originate on the humerus. These are the **extensor radialis longus**, **extensor carpi radialis brevis**, **extensor digitorum**, **extensor digiti minimi**, and the **extensor carpi ulnaris**.

The muscles of the **deep posterior compartment of the forearm** (deep posterior extensor compartment of the forearm) originate on the radius and ulna. These include the **abductor pollicis longus**, **extensor pollicis brevis**, **extensor pollicis longus**, and **extensor indicis**.

The tendons of the forearm muscles attach to the wrist and extend into the hand. Fibrous bands called **retinacula** sheath the tendons at the wrist. The **flexor retinaculum** extends over the palmar surface of the hand while the **extensor retinaculum** extends over the dorsal surface of the hand.

Table 7.4 – Muscles that Move the Wrist, Hand, and Forearm

Movement	Target	Target motion direction	Prime mover	Origin	Insertion
Superficial anterior compartment of forearm					
Wrist flexion and abduction	Wrist; hand	Flexion; abduction	**Flexor carpi radialis**	Medial epicondyle of humerus	Base of 2nd and 3rd metacarpals
Wrist flexion and adduction	Wrist	Flexion	**Flexor carpi ulnaris**	Medial epicondyle of humerus	Pisiform, hamate, base of 5th metacarpal
Wrist flexion; finger flexion digits 2-5	Wrist; hand	Flexion; adduction	**Flexor digitorum superficialis**	Medial epicondyle of humerus; anterior shaft of radius	Middle phalanges of digits 2-5
Wrist flexion	Wrist; fingers 2-5	Flexion	**Palmaris longus**	Medial epicondyle of humerus	Palmar aponeurosis
Deep anterior compartment of forearm					
Wrist flexion; finger flexion digits 2-5	Thumb	Flexion	**Flexor digitorum profundus**	Coronoid process; anteromedial surface of ulna	Distal phalanges of digits 2-5
Thumb flexion	Wrist; fingers	Flexion	**Flexor pollicis longus**	Anterior surface of radius	Distal phalanx of thumb
Superficial posterior compartment of forearm					
Wrist extension and abduction	Wrist	Extension; abduction	**Extensor carpi radialis longus**	Lateral supracondylar ridge of humerus	Base of 2nd metacarpal
Wrist extension and abduction	Wrist	Extension; abduction	**Extensor carpi radialis brevis**	Lateral epicondyle of humerus	Base of 3rd metacarpal
Wrist extension and adduction	Wrist; fingers	Extension; abduction	**Extensor carpi ulnaris**	Lateral epicondyle of humerus	Base of 5th metacarpal
Wrist extension; finger extension	Little fingers	Extension	**Extensor digitorum**	Lateral epicondyle of humerus	Extensor expansions; distal phalanges of digits 2-5
Finger extension of digit 5	Wrist	Extension; adduction	**Extensor digiti minimi**	Lateral epicondyle of humerus	Extensor expansions; distal phalanx of digit 5
Deep posterior compartment of forearm					
Thumb abduction and extensionWrist abduction	Wrist; thumb	Thumb: abduction, extension; wrist: abduction	**Abductor pollicis longus**	Posterior surface of radius and ulna	Base of first metacarpal; trapezium
Thumb extension	Thumb	Extension	**Extensor pollicis longus**	Posterior shaft of radius and ulna	Base of distal phalanx of thumb

Movement	Target	Target motion direction	Prime mover	Origin	Insertion
Thumb extension	Thumb	Extension	**Extensor pollicis brevis**	Posterior shaft of radius and ulna	Base of proximal phalanx of thumb
Finger extension of digit 2	Wrist; index finger	Extension	**Extensor indicis**	Posterior surface of radius and ulna	Tendon of extensor digitorum of index finger

Intrinsic Muscles of the Hand

The **intrinsic muscles of the hand** both originate and insert within it (**Figure 7.5**). These muscles allow your fingers to also make precise movements for actions, such as typing or writing. These muscles are divided into three groups. The **thenar** muscles are on the radial aspect of the palm. The **hypothenar** muscles are on the medial aspect of the palm, and the **intermediate** muscles are midpalmar.

The thenar muscles include the **abductor pollicis brevis**, **opponens pollicis**, **flexor pollicis brevis**, and the **adductor pollicis**. These muscles form the **thenar eminence**, the rounded contour of the base of the thumb, and all act on the thumb. The movements of the thumb play an integral role in most precise movements of the hand.

The hypothenar muscles include the **abductor digiti minimi**, **flexor digiti minimi brevis**, and the **opponens digiti minimi**. These muscles form the **hypothenar eminence**, the rounded contour of the little finger, and as such, they all act on the little finger. Finally, the intermediate muscles act on all the fingers and include the **lumbrical**, the **palmar interossei**, and the **dorsal interossei**.
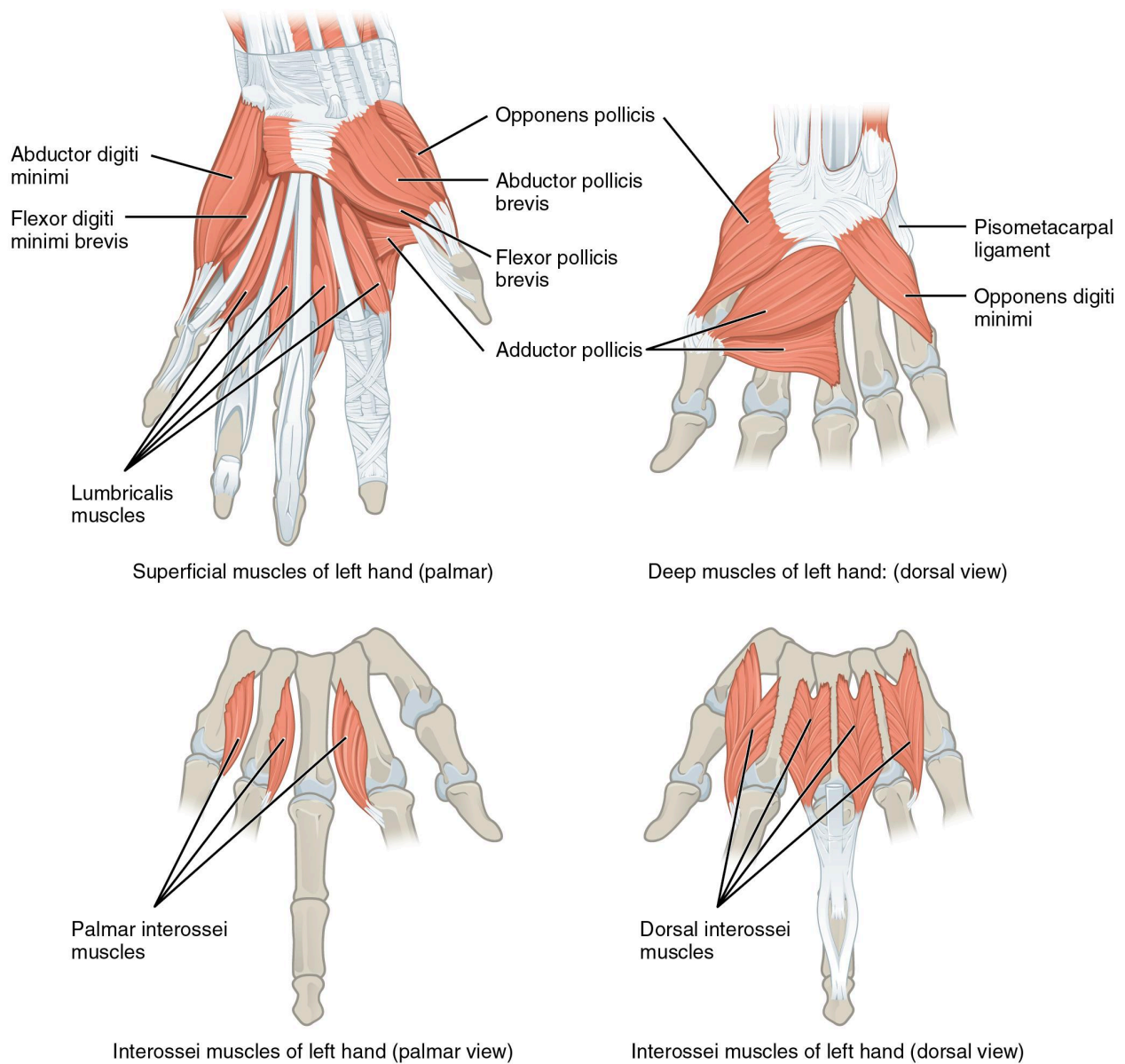
Superficial muscles of left hand (palmar)

Deep muscles of left hand: (dorsal view)

Interossei muscles of left hand (palmar view)

Interossei muscles of left hand (dorsal view)

Figure 7.5 Intrinsic Muscles of the Hand The intrinsic muscles of the hand both originate and insert within the hand. These muscles provide the fine motor control of the fingers by flexing, extending, abducting, and adducting the more distal finger and thumb segments.

Axial Muscles

The skeletal muscles are divided into **axial** (muscles of the trunk and head) and **appendicular** (muscles of the arms and legs) categories. The axial muscles are grouped based on location, function, or both. Some of the axial muscles may seem to blur the boundaries because they cross over to the appendicular skeleton. The first

grouping of the axial muscles you will review includes the muscles of the head and neck, then you will review the muscles of the vertebral column, and finally you will review the oblique and rectus muscles.

Muscles That Create Facial Expression

The origins of the muscles of facial expression are on the surface of the skull (remember, the origin of a muscle does not move). The insertions of these muscles have fibers intertwined with connective tissue and the dermis of the skin. Because the muscles insert in the skin rather than on bone, when they contract, the skin moves to create facial expression (**Figure 7.6** and **Table 7.5**).
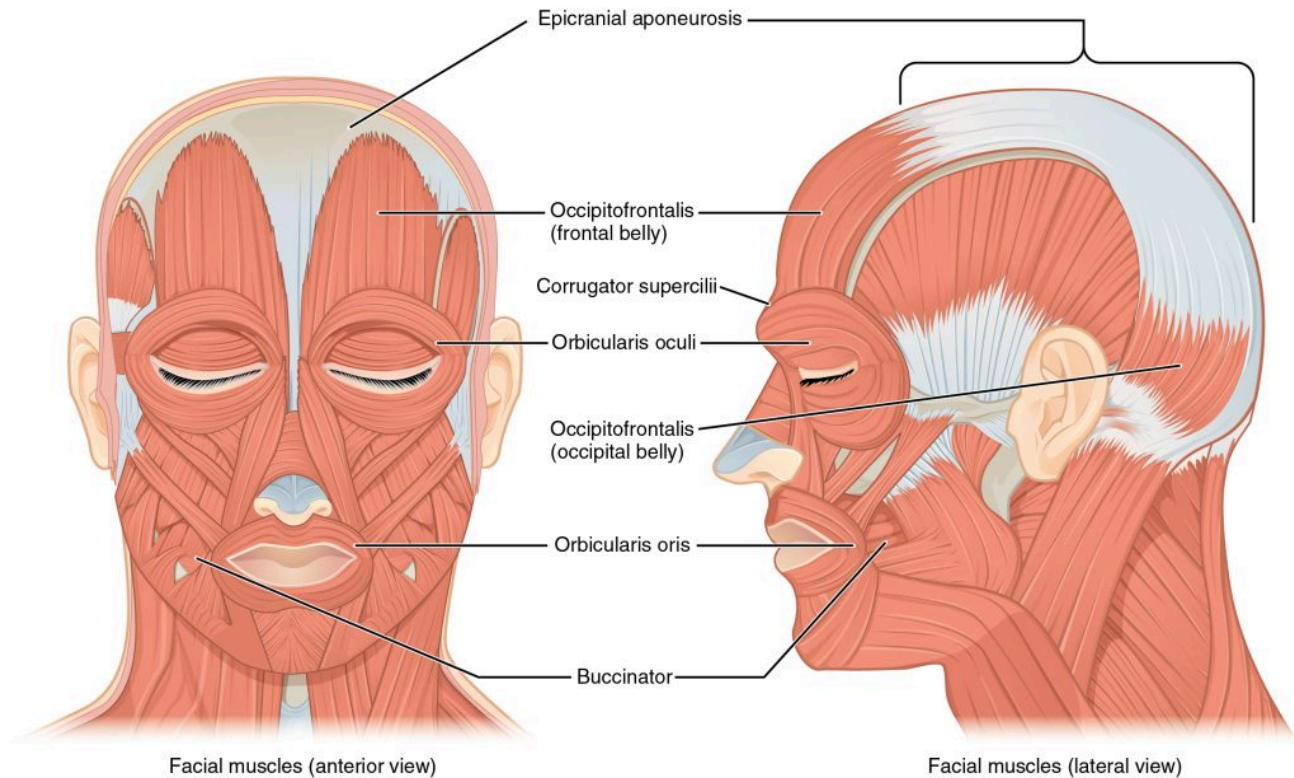
Figure 7.6 Muscles of Facial Expression Many of the muscles of facial expression insert into the skin surrounding the eyelids, nose and mouth, producing facial expressions by moving the skin rather than bones.

The **orbicularis oris** is a circular muscle that moves the lips, and the **orbicularis oculi** is a circular muscle that closes the eye. The **occipitofrontalis** muscle moves up the scalp and eyebrows. The muscle has a frontal belly and an occipital (near the occipital bone on the posterior part of the skull) belly. In other words, there is a muscle on the forehead (**frontalis**) and one on the back of the head (**occipitalis**), but there is no muscle across the top of the head. Instead, the two bellies are connected by a broad tendon called the **epicranial aponeurosis**, or galea aponeurosis (galea = "helmet"). The physicians originally studying human anatomy thought the skull looked like a helmet.

A large portion of the face is composed of the **buccinator** muscle, which compresses the cheek. This muscle allows you to whistle, blow, and suck; and it contributes to the action of chewing. There are several small facial muscles, one of which is the **corrugator supercilii**, which is the prime mover of the eyebrows. Place your finger on

your eyebrows at the point of the bridge of the nose. Raise your eyebrows as if you were surprised and lower your eyebrows as if you were frowning. With these movements, you can feel the action of the corrugator supercilii.

Table 7.5 – Muscle in Facial Expression

Movement	Target	Target Motion Direction	Primer Mover	Origin	Insertion
Brow					
Raising eyebrows (e.g. showing surprise)	Skin of scalp	Anterior	Occipitofrontalis (front belly)	Epicraneal aponeurosis	Underneath skin of forehead
Tensing and retracting scalp	Skin of scalp	Posterior	Occipitofrontalis (occipital belly)	Occipital bone; mastoid process (temporal bone)	Epicranial aponeurosis
Lowering eyebrows (e.g. scowling, frowning)	Skin underneath eyebrows	Inferior	Corrugator supercilii	Frontal bone	Skin underneath eyebrow
Nose					
Flaring nostrils	Nasal cartilage (pushes nostrils open when cartilage is compressed)	Inferior compression; posterior compression	Nasalis	Maxilla	Nasal bone
Mouth					
Raising upper lip	Upper lip	Elevation	Levator labii superioris	Maxilla	Underneath skin at corners of the mouth; prbicularis oris
Lowering lower lip	Lower lip	Depression	Depressor labii inferioris	Mandible	Underneath skin of lower lip
Opening mouth and sliding lower jaw left and right	Lower jaw	Depression, lateral	Depressor angulus oris	Mandible	Underneath skin at corners of mouth
Smiling	Corners of mouth	Lateral elevation	Zygomaticus major	Zygomatic bone	Underneath skin at corners of mouth (dimple area); orbicularis oris
Shaping of lips (during speech)	Lips	Multiple	Orbicularis oris	Tissue surrounding lips	Underneath skin at corners of mouth
Lateral movement of cheeks (e.g. sucking on a straw; also used to compress air in mouth while blowing)	Cheeks	Lateral	Buccinator	Maxilla, mandible; sphenoid bone (via pterygomandibular raphe)	Orbicularis oris

Movement	Target	Target Motion Direction	Primer Mover	Origin	Insertion
Pursing of lips by straightening them laterally	Corners of mouth	Lateral	Risorius	Fascia of parotid salivary gland	Underneath skin at corners of the mouth
Protrusion of lower lip (e.g. pouting expression)	Lower lip and skin of chin	Protraction	Mentalis	Mandible	Underneath skin of chin

Muscles That Move the Lower Jaw

In anatomical terminology, chewing is called **mastication**. Muscles involved in chewing must be able to exert enough pressure to bite through and then chew food before it is swallowed (**Figure 7.7**). The **masseter** muscle is the main muscle used for chewing because it elevates the mandible (lower jaw) to close the mouth, and it is assisted by the **temporalis** muscle, which retracts the mandible. You can feel the temporalis move by putting your fingers to your temple as you chew. Although the masseter and temporalis are responsible for elevating and closing the jaw to break food into digestible pieces, the **medial pterygoid** and **lateral pterygoid** muscles provide assistance in chewing and moving food within the mouth.
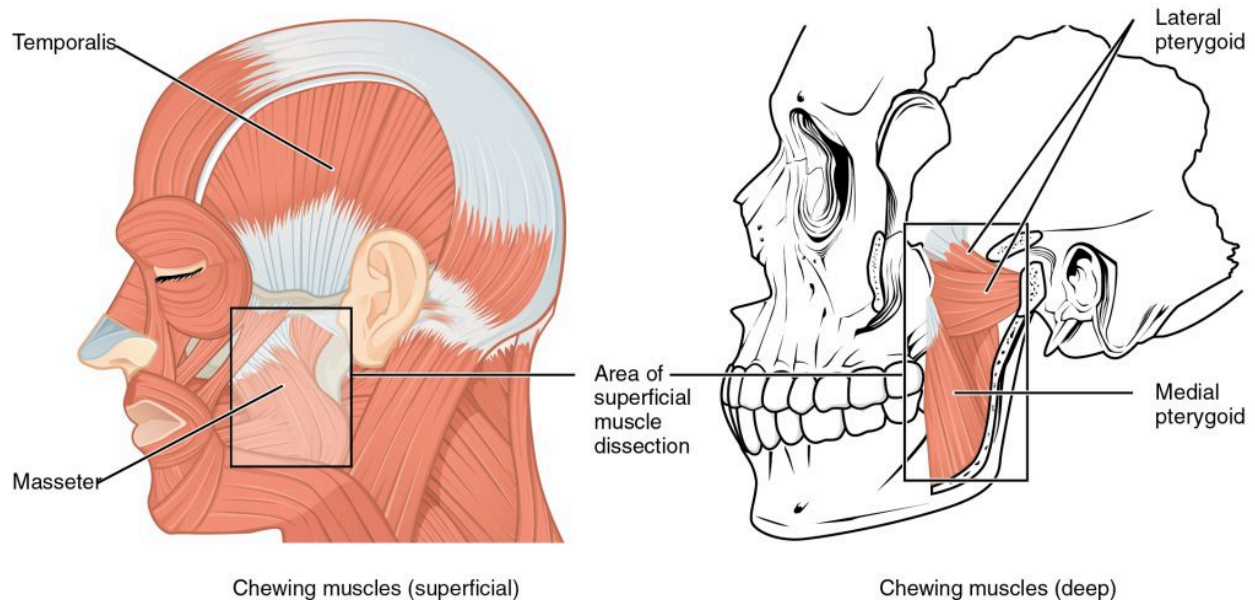
Figure 7.7 Muscles That Move the Lower Jaw The muscles that move the lower jaw are typically located within the cheek and originate from processes in the skull. This provides the jaw muscles with the large amount of leverage needed for chewing.

Muscles of the Anterior Neck

The muscles of the anterior neck assist in deglutition (swallowing) and speech by controlling the positions of the larynx (voice box), and the hyoid bone, a horseshoe-shaped bone that functions as a solid foundation on which

the tongue can move. The muscles of the neck are categorized according to their position relative to the hyoid bone (**Figure 7.8**). **Suprahyoid muscles** are superior to it, and the **infrahyoid muscles** are located inferiorly.
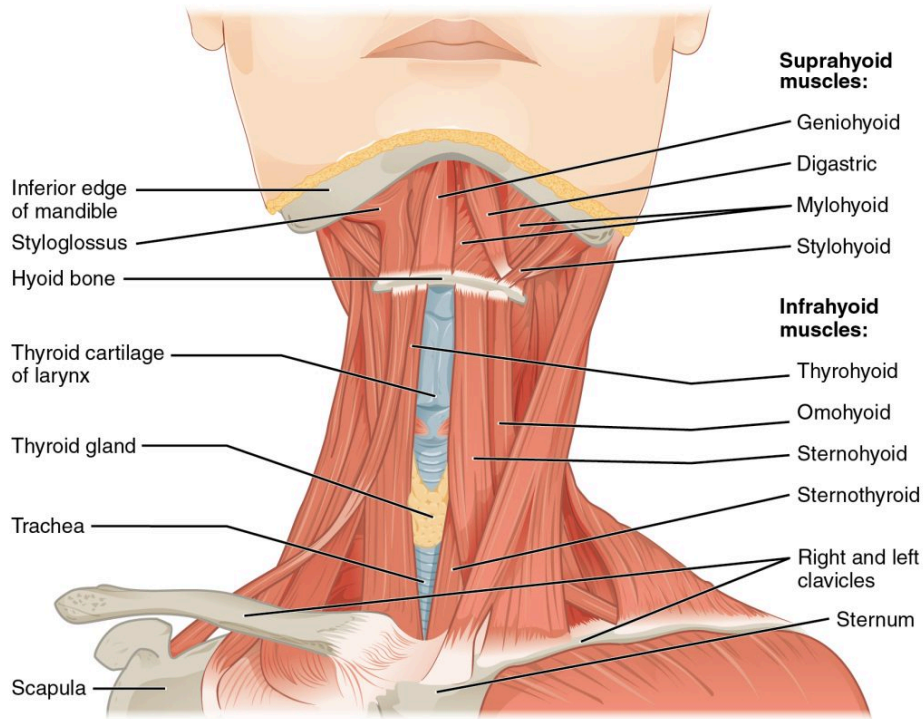

Figure 7.8 Muscles of the Anterior Neck The anterior muscles of the neck facilitate swallowing and speech. The suprahyoid muscles originate from above the hyoid bone in the chin region. The infrahyoid muscles originate below the hyoid bone in the lower neck.

The suprahyoid muscles raise the hyoid bone, the floor of the mouth, and the larynx during deglutition. These include the **digastric** muscle, which has anterior and posterior bellies that work to elevate the hyoid bone and larynx when one swallows; it also depresses the mandible. The **stylohyoid** muscle moves the hyoid bone posteriorly, elevating the larynx, and the **mylohyoid** muscle lifts it and helps press the tongue to the top of the mouth. The **geniohyoid** depresses the mandible in addition to raising and pulling the hyoid bone anteriorly.

The strap-like infrahyoid muscles generally depress the hyoid bone and control the position of the larynx. The **omohyoid** muscle, which has superior and inferior bellies, depresses the hyoid bone in conjunction with the **sternohyoid** and **thyrohyoid** muscles. The thyrohyoid muscle also elevates the larynx's thyroid cartilage, whereas the **sternothyroid** depresses it to create different tones of voice.

Muscles That Move the Head and Back

The head, attached to the top of the vertebral column, is balanced, moved, and rotated by the neck muscles. When these muscles act unilaterally, the head rotates. When they contract bilaterally, the head flexes or extends. The major muscle that laterally flexes and rotates the head is the **sternocleidomastoid**. In addition, both muscles working together are the flexors of the head. Place your fingers on both sides of the neck and turn your head to

the left and to the right. You will feel the movement originate there. This muscle divides the neck into anterior and posterior triangles when viewed from the side (**Figure 7.9**).

The posterior muscles of the neck are primarily concerned with head movements, like extension. The back muscles stabilize and move the vertebral column, and are grouped according to the lengths and direction of the fascicles.

The **splenius** muscles originate at the midline and run laterally and superiorly to their insertions. From the sides and the back of the neck, the **splenius capitis** inserts onto the head region, and the **splenius cervicis** extends onto the cervical region. These muscles can extend the head, laterally flex it, and rotate it.

Muscles of the neck (left lateral view)

Superficial (left side) and deep
(right side) muscles of the neck and
upper back (posterior view)

Deep muscles of the back
(posterior view)

**Deep spinal muscles
(multifidus removed)**
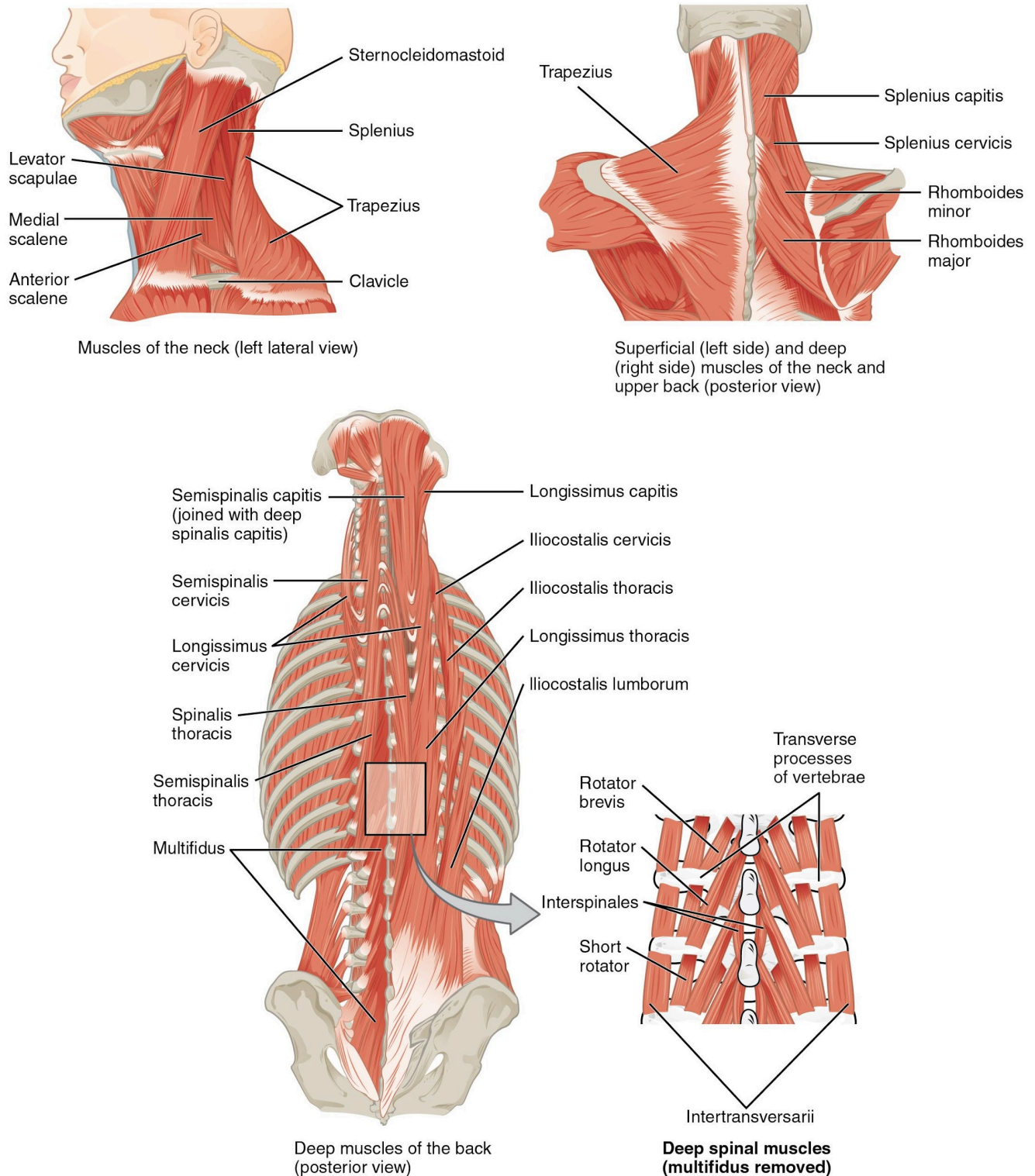
Figure 7.9 Muscles of the Neck and Back The large, complex muscles of the neck and back move the head,
shoulders, and vertebral column.

The **erector spinae group** forms the majority of the muscle mass of the back and it is the primary extensor of the

vertebral column. It controls flexion, lateral flexion, and rotation of the vertebral column, and maintains the lumbar curve. The erector spinae comprises the iliocostalis (laterally placed) group, the longissimus (intermediately placed) group, and the spinalis (medially placed) group.

The **iliocostalis group** includes the **iliocostalis cervicis**, associated with the cervical region; the **iliocostalis thoracis**, associated with the thoracic region; and the **iliocostalis lumborum**, associated with the lumbar region. The three muscles of the **longissimus group** are the **longissimus capitis**, associated with the head region; the **longissimus cervicis**, associated with the cervical region; and the **longissimus thoracis**, associated with the thoracic region. The third group, the **spinalis group**, comprises the **spinalis capitis** (head region), the **spinalis cervicis** (cervical region), and the **spinalis thoracis** (thoracic region).

The **transversospinales** muscles run from the transverse processes to the spinous processes of the vertebrae. Similar to the erector spinae muscles, the semispinalis muscles in this group are named for the areas of the body with which they are associated. The semispinalis muscles include the **semispinalis capitis**, the **semispinalis cervicis**, and the **semispinalis thoracis**. The **multifidus** muscle of the lumbar region helps extend and laterally flex the vertebral column.

Important in the stabilization of the vertebral column is the **segmental muscle group**, which includes the interspinales and intertransversarii muscles. These muscles bring together the spinous and transverse processes of each consecutive vertebra. Finally, the **scalene muscles** work together to flex, laterally flex, and rotate the head. They also contribute to deep inhalation. The scalene muscles include the **anterior scalene** muscle (anterior to the middle scalene), the **middle scalene** muscle (the longest, intermediate between the anterior and posterior scalenes), and the **posterior scalene** muscle (the smallest, posterior to the middle scalene).

Muscles of the Abdomen

It is a complex job to balance the body on two feet and walk upright. The muscles of the vertebral column, thorax, and abdominal wall extend, flex, and stabilize different parts of the body's trunk. The deep muscles of the core of the body help maintain posture as well as carry out other functions. The brain sends out electrical impulses to these various muscle groups to control posture by alternate contraction and relaxation. This is necessary so that no single muscle group becomes fatigued too quickly. If any one group fails to function, body posture will be compromised.

There are four pairs of abdominal muscles that cover the anterior and lateral abdominal region and meet at the anterior midline. These muscles of the anterolateral abdominal wall can be divided into four groups: the external obliques, the internal obliques, the transversus abdominis, and the rectus abdominis (**Figure 7.10**).
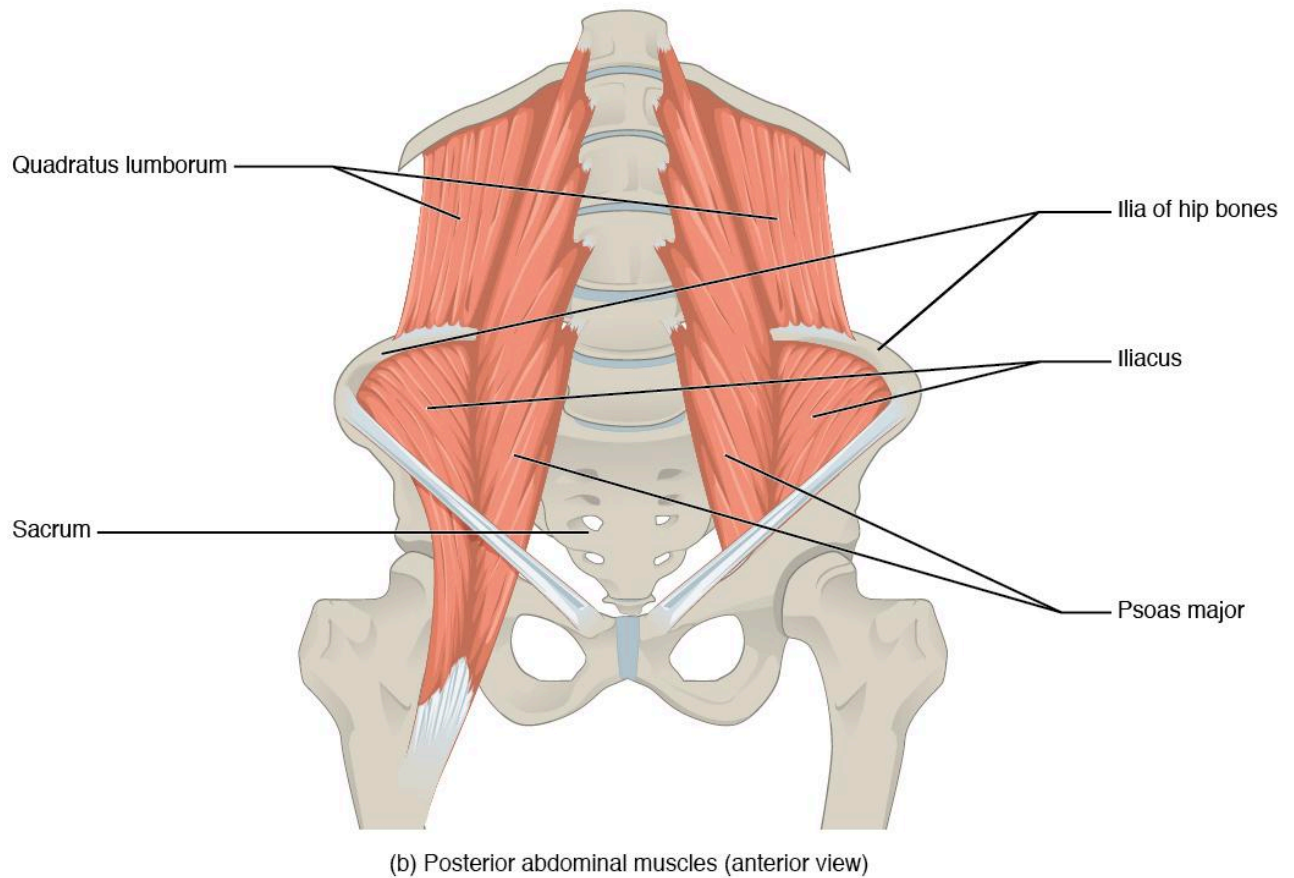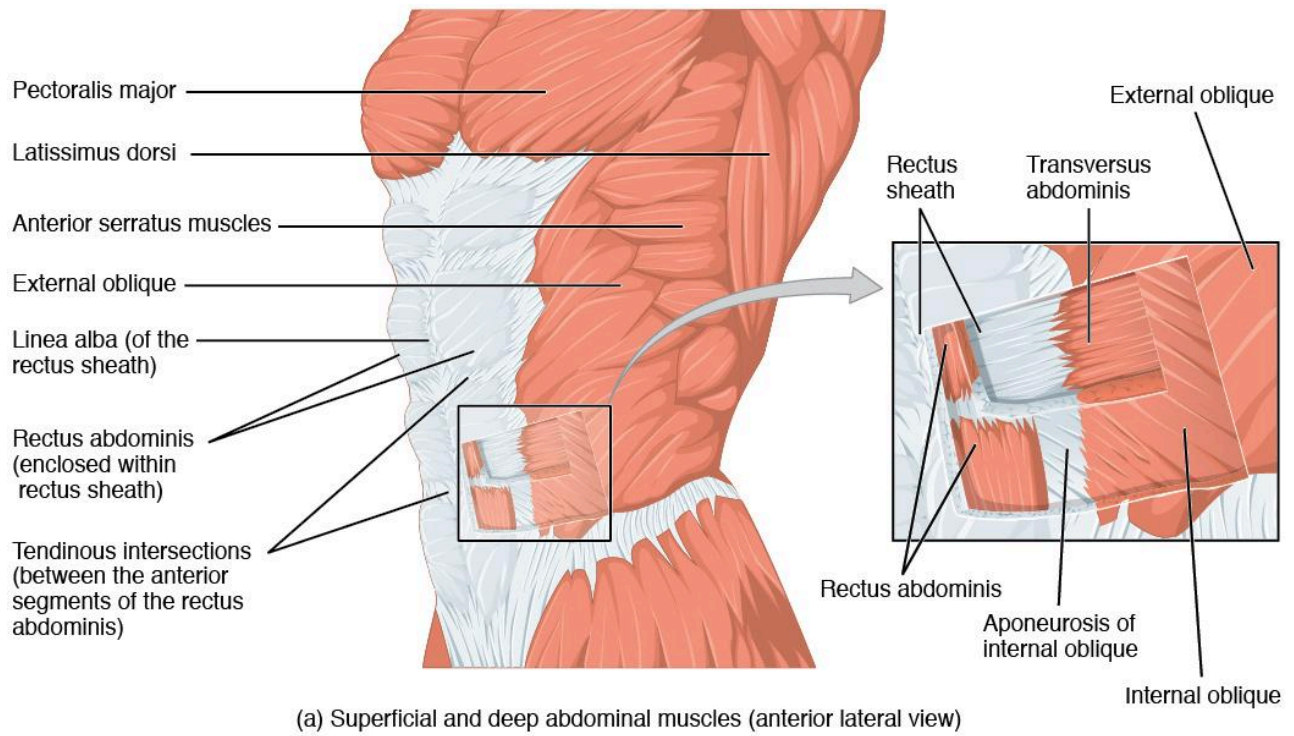
Pectoralis major

Latissimus dorsi

Anterior serratus muscles

External oblique

Linea alba (of the rectus sheath)

Rectus abdominis (enclosed within rectus sheath)

Tendinous intersections (between the anterior segments of the rectus abdominis)

External oblique

Rectus sheath

Transversus abdominis

Rectus abdominis

Aponeurosis of internal oblique

Internal oblique

(a) Superficial and deep abdominal muscles (anterior lateral view)

Quadratus lumborum

Ilia of hip bones

Iliacus

Sacrum

Psoas major

(b) Posterior abdominal muscles (anterior view)

Figure 7.10 Muscles of the Abdomen (a) The anterior abdominal muscles include the medially located rectus

abdominis, which is covered by a sheet of connective tissue called the rectus sheath. On the flanks of the body, medial to the rectus abdominis, the abdominal wall is composed of three layers. The external oblique muscles form the superficial layer, while the internal oblique muscles form the middle layer, and the transversus abdominis forms the deepest layer. (b) The muscles of the lower back move the lumbar spine but also assist in femur movements.

There are three flat skeletal muscles in the antero-lateral wall of the abdomen. The **external oblique**, closest to the surface, extend inferiorly and medially, in the direction of sliding one's four fingers into pants pockets. Perpendicular to it is the intermediate **internal oblique**, extending superiorly and medially, the direction the thumbs usually go when the other fingers are in the pants pocket. The deep muscle, the **transversus abdominis**, is arranged transversely around the abdomen, similar to the front of a belt on a pair of pants. This arrangement of three bands of muscles in different orientations allows various movements and rotations of the trunk. The three layers of muscle also help to protect the internal abdominal organs in an area where there is no bone.

The **linea alba** is a white, fibrous band that is made of the bilateral **rectus sheaths** that join at the anterior midline of the body. These enclose the **rectus abdominis** muscles (a pair of long, linear muscles, commonly called the "sit-up" muscles) that originate at the pubic crest and symphysis, and extend the length of the body's trunk. Each muscle is segmented by three transverse bands of collagen fibers called the **tendinous intersections**. This results in the look of "six-pack abs," as each segment hypertrophies on individuals at the gym who do many sit-ups.

The posterior abdominal wall is formed by the lumbar vertebrae, parts of the ilia of the hip bones, psoas major and iliacus muscles, and **quadratus lumborum** muscle. This part of the core plays a key role in stabilizing the rest of the body and maintaining posture.

Muscles of the Thorax

The muscles of the chest serve to facilitate breathing by changing the size of the thoracic cavity. When you inhale, your chest rises because the cavity expands. Alternately, when you exhale, your chest falls because the thoracic cavity decreases in size.

The Diaphragm

The change in volume of the thoracic cavity during breathing is due to the alternate contraction and relaxation of the **diaphragm** (**Figure 7.11**). It separates the thoracic and abdominal cavities, and is dome-shaped at rest. The superior surface of the diaphragm is convex, creating the elevated floor of the thoracic cavity. The inferior surface is concave, creating the curved roof of the abdominal cavity.
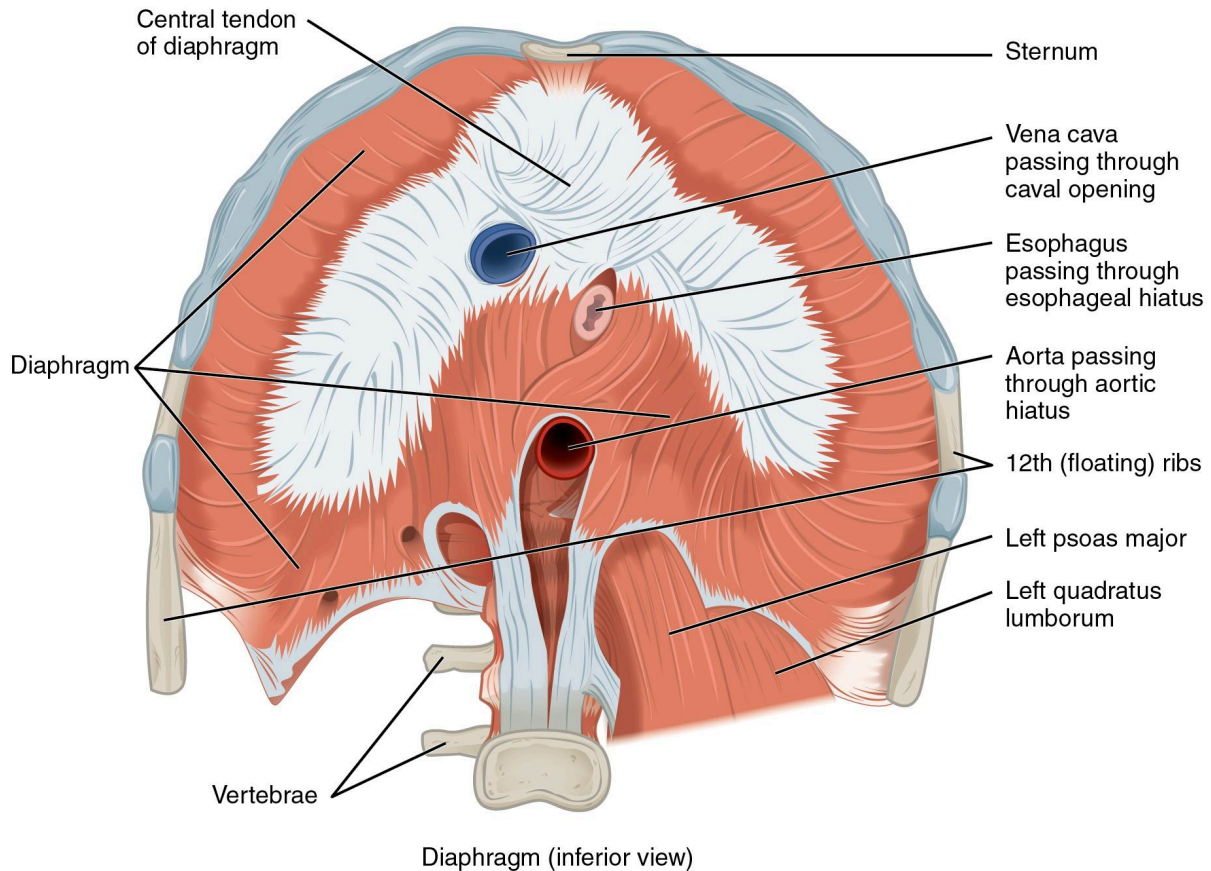
Central tendon of diaphragm

Sternum

Vena cava passing through caval opening

Esophagus passing through esophageal hiatus

Diaphragm

Aorta passing through aortic hiatus

12th (floating) ribs

Left psoas major

Left quadratus lumborum

Vertebrae

Diaphragm (inferior view)

Figure 7.11 Muscles of the Diaphragm The diaphragm separates the thoracic and abdominal cavities.

Defecating, urination, and even childbirth involve cooperation between the diaphragm and abdominal muscles (this cooperation is referred to as the "Valsalva maneuver"). You hold your breath by a steady contraction of the diaphragm; this stabilizes the volume and pressure of the peritoneal cavity. When the abdominal muscles contract, the pressure cannot push the diaphragm up, so it increases pressure on the intestinal tract (defecation), urinary tract (urination), or reproductive tract (childbirth).

The inferior surface of the pericardial sac and the inferior surfaces of the pleural membranes (parietal pleura) fuse onto the central tendon of the diaphragm. To the sides of the tendon are the skeletal muscle portions of the diaphragm, which insert into the tendon while having a number of origins including the xiphoid process of the sternum anteriorly, the inferior six ribs and their cartilages laterally, and the lumbar vertebrae and 12th ribs posteriorly.

The diaphragm also includes three openings for the passage of structures between the thorax and the abdomen. The inferior vena cava passes through the **caval opening**, and the esophagus and attached nerves pass through the esophageal hiatus. The aorta, thoracic duct, and azygous vein pass through the aortic hiatus of the posterior diaphragm.

The Intercostal Muscles

There are three sets of muscles, called **intercostal muscles**, which span each of the intercostal spaces. The principal role of the intercostal muscles is to assist in breathing by changing the dimensions of the rib cage (**Figure 7.12**).

The 11 pairs of superficial **external intercostal** muscles aid in inspiration of air during breathing because when they contract, they raise the rib cage, which expands it. The 11 pairs of **internal intercostal** muscles, just under the externals, are used for expiration because they draw the ribs together to constrict the rib cage. The **innermost intercostal** muscles are the deepest, and they act as synergists for the action of the internal intercostals.
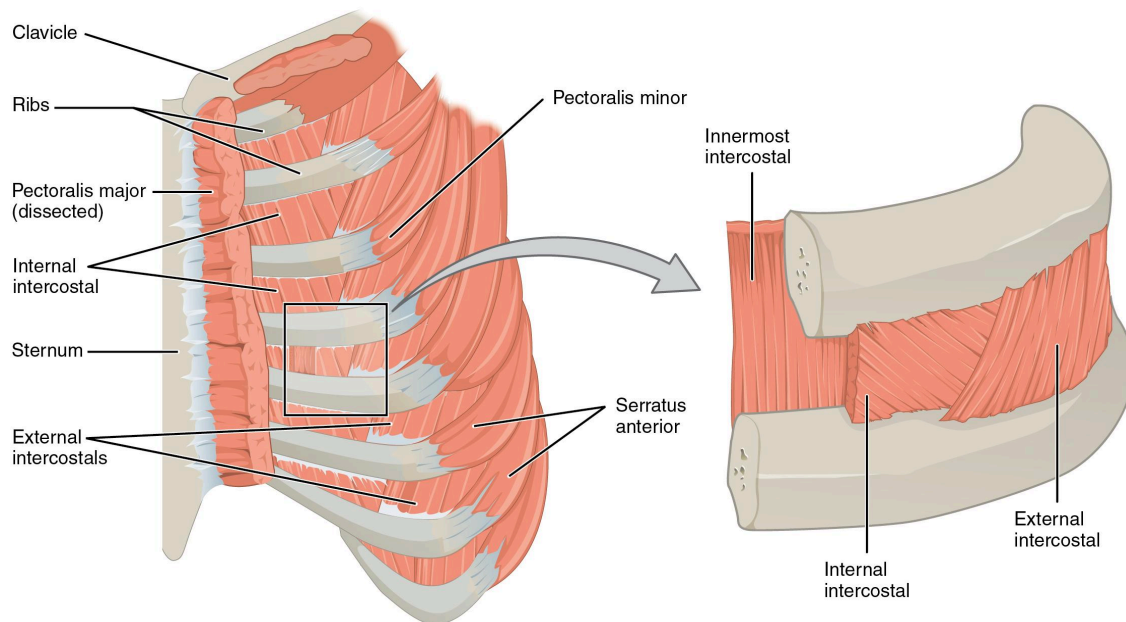
Figure 7.12 Intercostal Muscles The external intercostals are located laterally on the sides of the body. The internal intercostals are located medially near the sternum. The innermost intercostals are located deep to both the internal and external intercostals.

Lab 8: Nervous system I - Nervous Tissue, Brain, Spinal Cord, and Cranial Nerves

Nervous tissue, structures of the central and peripheral nervous systems

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Learning Objectives

When you are prepared for the **Test on Week 8 Learning Objectives** in Week 9, you will be able to:

- Identify structures of the neuron and describe their functions.
- Identify regions of the brain and describe their functions.
- Identify cerebral lobes and functional areas of the brain.
- Identify meninges of the central nervous system and their functions.
- Describe where cerebrospinal fluid is created, circulates, and is recycled.
- Identify cranial nerves, describing their basic function and whether each is sensory, motor, or both.
- Identify structures of the spinal cord region and their functions.

The nervous system is a complex organ system that sends signals throughout the body to control both voluntary and involuntary functions. The nervous system can detect many different forms of stimuli, integrate those stimuli, and respond to them by sending signals out to the muscle cells or glands. This week we will look at the cells and tissue of the nervous system capable of sending signals and the organs where those signals can be processed and integrated. Next week we will look at the structures capable of detecting stimuli, when we look at the special senses.

Divisions of the Nervous System

The nervous system can be divided into two major regions: the central and peripheral nervous systems. The **central nervous system (CNS)** is the brain and spinal cord, and the **peripheral nervous system (PNS)** is everything else (**Figures 8.1 and 8.2**). The brain is contained within the cranial cavity of the skull, and the spinal cord is contained within the vertebral cavity of the vertebral column. It is a bit of an oversimplification to say that the CNS is what is inside these two cavities and the peripheral nervous system is outside of them, but that is one way to start to think about it. In actuality, there are some elements of the peripheral nervous system that are within the cranial or vertebral cavities. The peripheral nervous system is so named because it is on the

periphery—meaning beyond the brain and spinal cord. Depending on different aspects of the nervous system, the dividing line between central and peripheral is not necessarily universal.
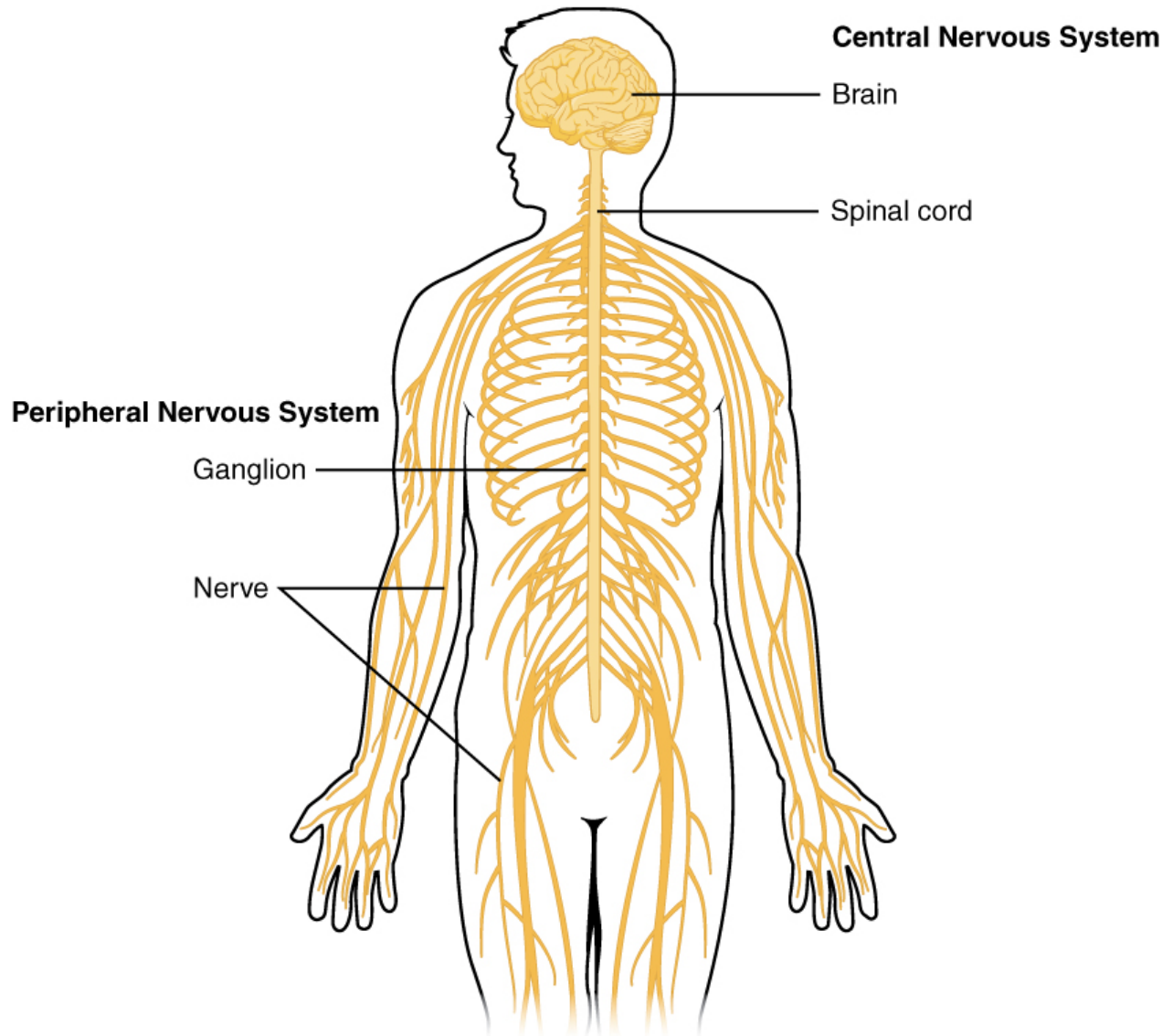
Figure 8.1 Central and Peripheral Nervous System. The structures of the PNS are referred to as ganglia and nerves, which can be seen as distinct structures. The equivalent structures in the CNS are not obvious from this overall perspective and are best examined in prepared tissue under the microscope.
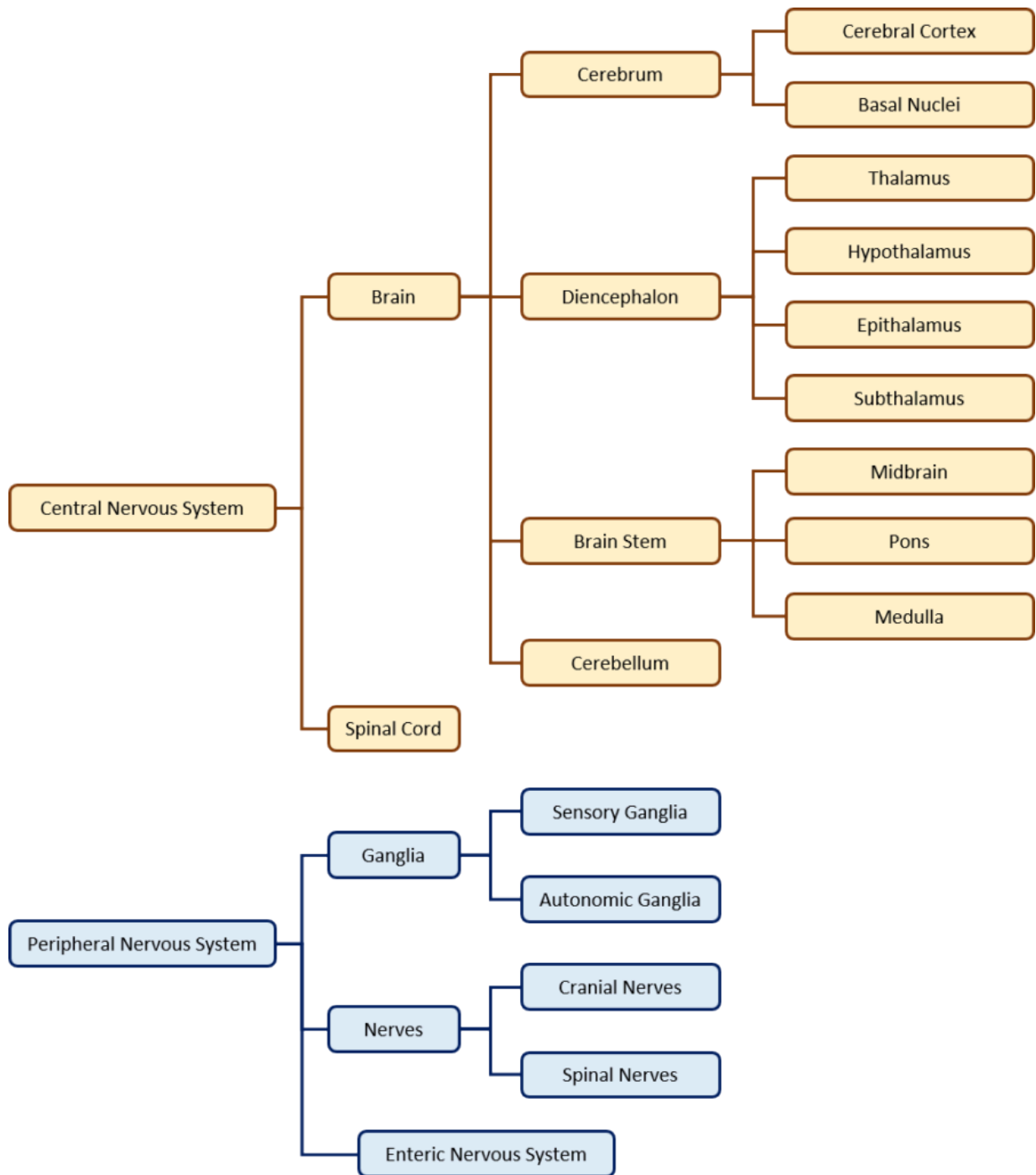
Figure 8.2 The Anatomical Organization of the Nervous System. The nervous system has two major regions, the central nervous system and peripheral nervous system, which are both made up of many smaller structures. Image Source: Douglas College Human Anatomy & Physiology I (2nd ed.), Unit 9. Licensed CC BY 4.0.

The nervous system can also be organized into functional divisions, based on sensing, integrating, and responding to stimuli (**Figure 8.3**). The response division is sometimes called the motor division, because it often involves signaling muscle tissue.
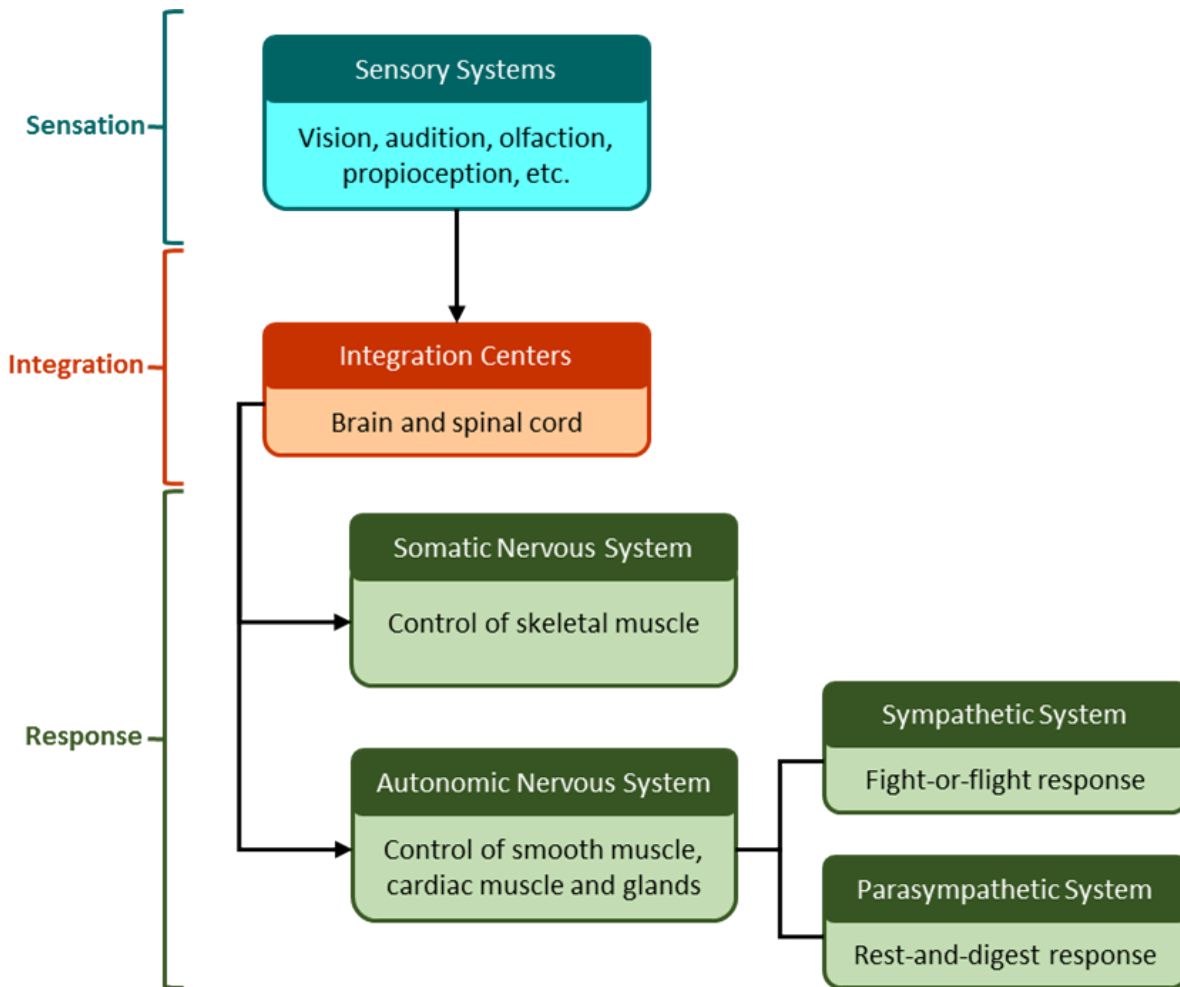
Figure 8.3 The Functional Organization of the Nervous System. The diagram represents the divisions of the nervous system involved in each of the basic functions: sensation (receiving and processing information from the external and internal environment), integration (comparing the sensory input with stored information and with other sensory inputs in order for the body to react appropriately) and response (most commonly, a motor command generated by the somatic nervous system or the autonomic nervous system). Image Source: Douglas College Human Anatomy & Physiology I (2nd ed.), Unit 9. Licensed CC BY 4.0.

Divisions of the nervous system can also be functionally classified as somatic and autonomic. The **somatic nervous system (SNS)** is responsible for conscious perception and voluntary motor responses. Voluntary motor response means the contraction of skeletal muscle, but those contractions are not always voluntary in the sense that you have to want to perform them. Some somatic motor responses are reflexes, and often happen without a conscious decision to perform them. If your friend jumps out from behind a corner and yells "Boo!" you will be startled and you might scream or leap back. You didn't decide to do that, and you may not have wanted to give your friend a reason to laugh at your expense, but it is a reflex involving skeletal muscle contractions. Other motor responses become automatic (in other words, unconscious) as a person learns motor skills (referred to as "habit learning" or "procedural memory").

The **autonomic nervous system (ANS)** is responsible for involuntary control of the body, usually for the sake of homeostasis (regulation of the internal environment). Sensory input for autonomic functions can be from sensory

structures tuned to external or internal environmental stimuli. The motor output extends to smooth and cardiac muscle as well as glandular tissue. The role of the autonomic system is to regulate the organ systems of the body, which usually means to control homeostasis. Sweat glands, for example, are controlled by the autonomic system. When you are hot, sweating helps cool your body down. That is a homeostatic mechanism. But when you are nervous, you might start sweating also. That is not homeostatic, it is the physiological response to an emotional state.

There is another division of the nervous system that describes functional responses. The **enteric nervous system (ENS)** is responsible for controlling the smooth muscle and glandular tissue in your digestive system. It is a large part of the PNS, and is not dependent on the CNS. It is sometimes valid, however, to consider the enteric system to be a part of the autonomic system because the neural structures that make up the enteric system are a component of the autonomic output that regulates digestion. There are some differences between the two, but for our purposes here there will be a good bit of overlap. See **Figure 8.4** for examples of where these divisions of the nervous system can be found.

Brain (CNS)
Perception and processing of sensory
    stimuli (somatic/autonomic)
Execution of voluntary motor
    responses (somatic)
Regulation of homeostatic
    mechanisms (autonomic)

Nerves (PNS)
Fibers of sensory and motor
neurons (somatic/autonomic)

Digestive tract (ENS)
The enteric nervous system
(ENS), located in the digestive
tract, is responsible for autonomous
functions and can operate independently
of the brain and spinal cord.

Spinal cord (CNS)
Initiation of reflexes from ventral
    horn (somatic) and lateral horn
    (autonomic) gray matter
Pathways for sensory and motor
    functions between periphery
    and brain (somatic/autonomic)

Ganglia (PNS)
Reception of sensory stimuli by
    dorsal root and cranial ganglia
    (somatic/autonomic)
Relay of visceral motor responses
    by autonomic ganglia (autonomic)

Figure 8.4 Somatic, Autonomic, and Enteric Structures of the Nervous System Somatic structures include the spinal nerves, both motor and sensory fibers, as well as the sensory ganglia (posterior root ganglia and cranial nerve ganglia). Autonomic structures are found in the nerves also, but include the sympathetic and parasympathetic ganglia. The enteric nervous system includes the nervous tissue within the organs of the digestive tract.

Nervous Tissue

Nervous tissue, present in both the CNS and PNS, contains two basic types of cells: neurons and glial cells. A **glial cell** is one of a variety of cells that provide a framework of tissue that supports the neurons and their activities. The **neuron** is the more functionally important of the two, in terms of the communicative function of the nervous system. Neurons are responsible for the electrical signals that communicate information about sensations, and that produce movements in response to those stimuli, along with inducing thought processes within the brain.

An important part of the function of neurons is in their structure, or shape. The three-dimensional shape of these cells makes the immense numbers of connections within the nervous system possible.

Neurons are cells and therefore have a **soma**, or cell body, which contains the nucleus and most of the major organelles. But what makes neurons special is that they have many extensions of their cell membranes, which are generally referred to as processes. Neurons are usually described as having one, and only one, axon—a fiber that emerges from the cell body and projects to target cells. That single axon can branch repeatedly to communicate with many target cells. It is the axon that propagates the nerve impulse, which is communicated to one or more cells. The other processes of the neuron are dendrites, which receive information from other neurons at specialized areas of contact called **synapses**. The dendrites are usually highly branched processes, providing locations for other neurons to communicate with the cell body. Information flows through a neuron from the dendrites, across the cell body, and down the axon. This gives the neuron a polarity—meaning that information flows in this one direction. **Figure 8.5** shows the relationship of these parts to one another.
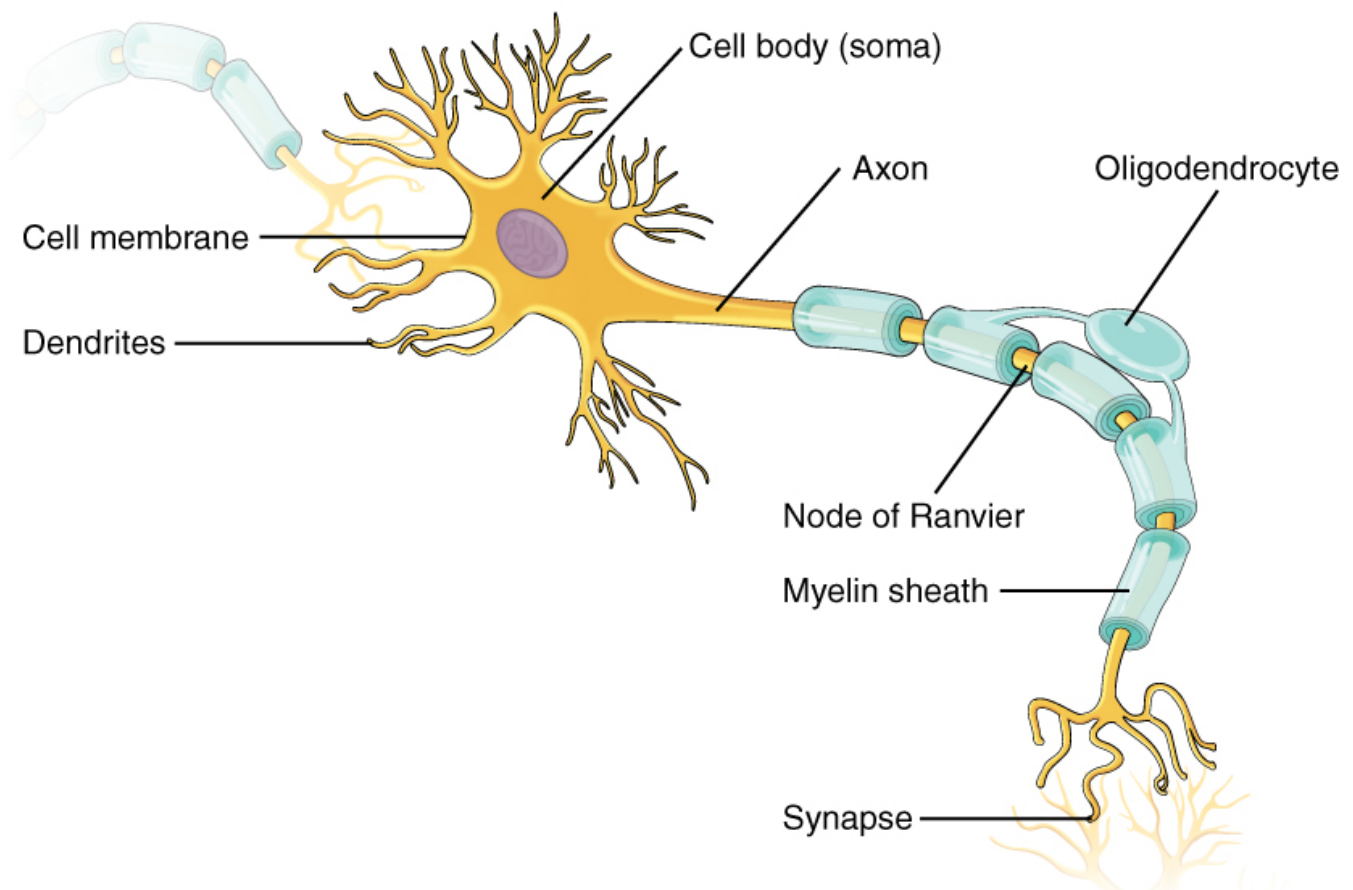
Figure 8.5 Parts of a Neuron The major parts of the neuron are labeled on a multipolar neuron from the CNS.

Where the axon emerges from the cell body, there is a special region referred to as the **axon hillock**. This is a tapering of the cell body toward the axon fiber. Many axons are wrapped by an insulating substance called **myelin**. Myelin acts as insulation much like the plastic or rubber that is used to insulate electrical wires. A key difference between myelin and the insulation on a wire is that there are gaps in the myelin covering of an axon. Each gap is called a **neurofibril node** (=node of Ranvier) and is important to the way that electrical signals travel down the axon. The length of the axon between each gap, which is wrapped in myelin, is referred to as an **axon segment**.

At the end of the axon is the **axon terminal**, where there are usually several branches extending toward the target cell, each of which ends in an enlargement called a **synaptic end bulb**. These bulbs are what make the connection with the target cell at the synapse.

The myelin sheath is made from glial cells, called **oligodendrocytes** in the central nervous system, or **neurolemmocytes** (=Schwann cells) in the peripheral nervous system. One oligodendrocyte will provide the myelin for multiple axon segments, either for the same axon or for separate axons. Schwann cells are different than oligodendrocytes, in that a Schwann cell wraps around a portion of only one axon segment and no others. The neurolemmocyte is wrapped around the axon several times with little to no cytoplasm between the glial cell layers. The nucleus and cytoplasm of the Schwann cell are on the edge of the myelin sheath (**Figure 8.6**).

(a)

(b)
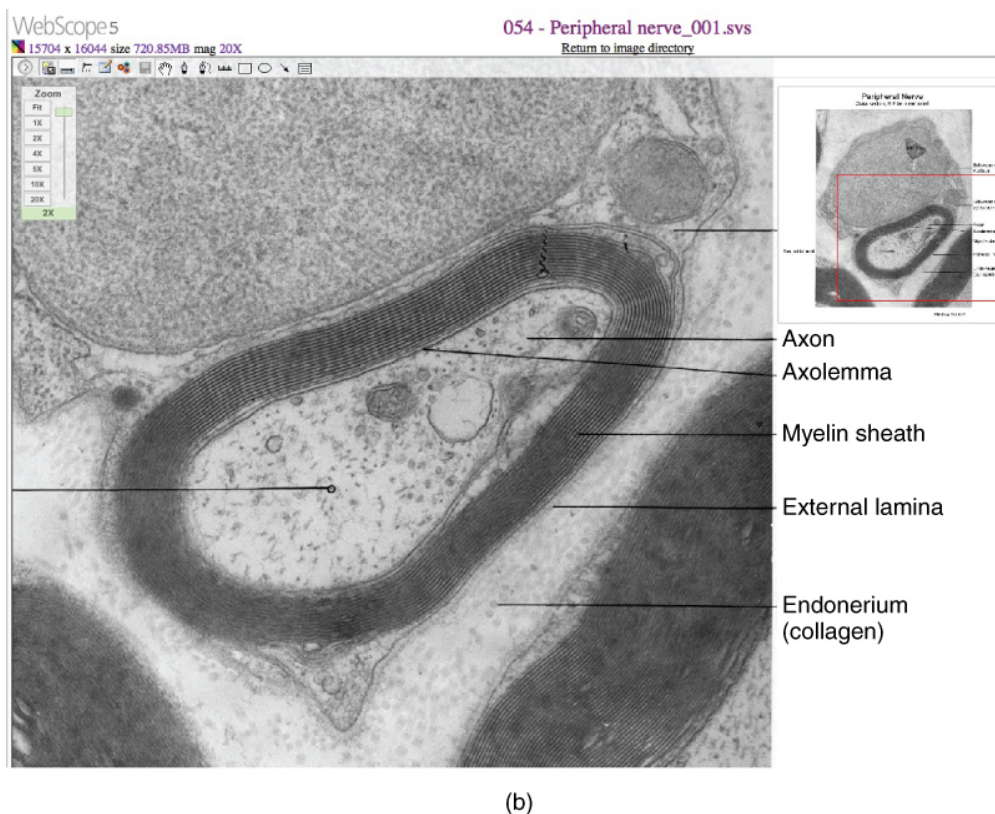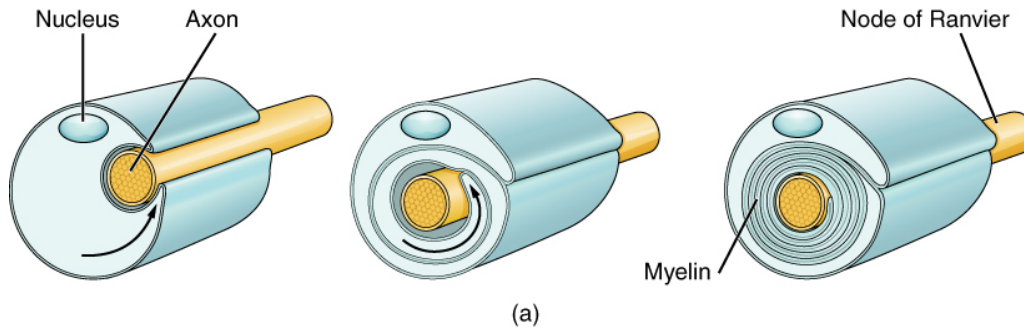
Figure 8.6 The Process of Myelination Myelinating glia wrap several layers of cell membrane around the cell membrane of an axon segment. A single Schwann cell insulates a segment of a peripheral nerve, whereas in the CNS, an oligodendrocyte may provide insulation for a few separate axon segments. EM × 1,460,000. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Signals travel down the axon of a neuron in the form of **action potentials,** which are localized changes in membrane potential, one triggering the next, until the signal reaches the axon terminal. Action potentials can propagate much more quickly down a myelinated axon than an unmyelinated axon because the action potential basically jumps from one node to the next. This is called **saltatory conduction** (saltare = "to leap").

White and Gray matter

Looking at nervous tissue, there are regions that predominantly contain cell bodies and regions that are largely composed of just myelinated axons. These two regions within nervous system structures are often referred to as **gray matter** (the regions with many cell bodies and dendrites) or **white matter** (the regions with many axons). **Figure 8.7** demonstrates the appearance of these regions in the brain and spinal cord. The colors ascribed to these regions are what would be seen in "fresh," or unstained, nervous tissue. Gray matter is not necessarily gray. It can be pinkish because of blood content, or even slightly tan, depending on how long the tissue has been preserved. But white matter is white because axons are insulated by the lipid-rich **myelin sheath**. Lipids can appear as white ("fatty") material, much like the fat on a raw piece of chicken or beef.
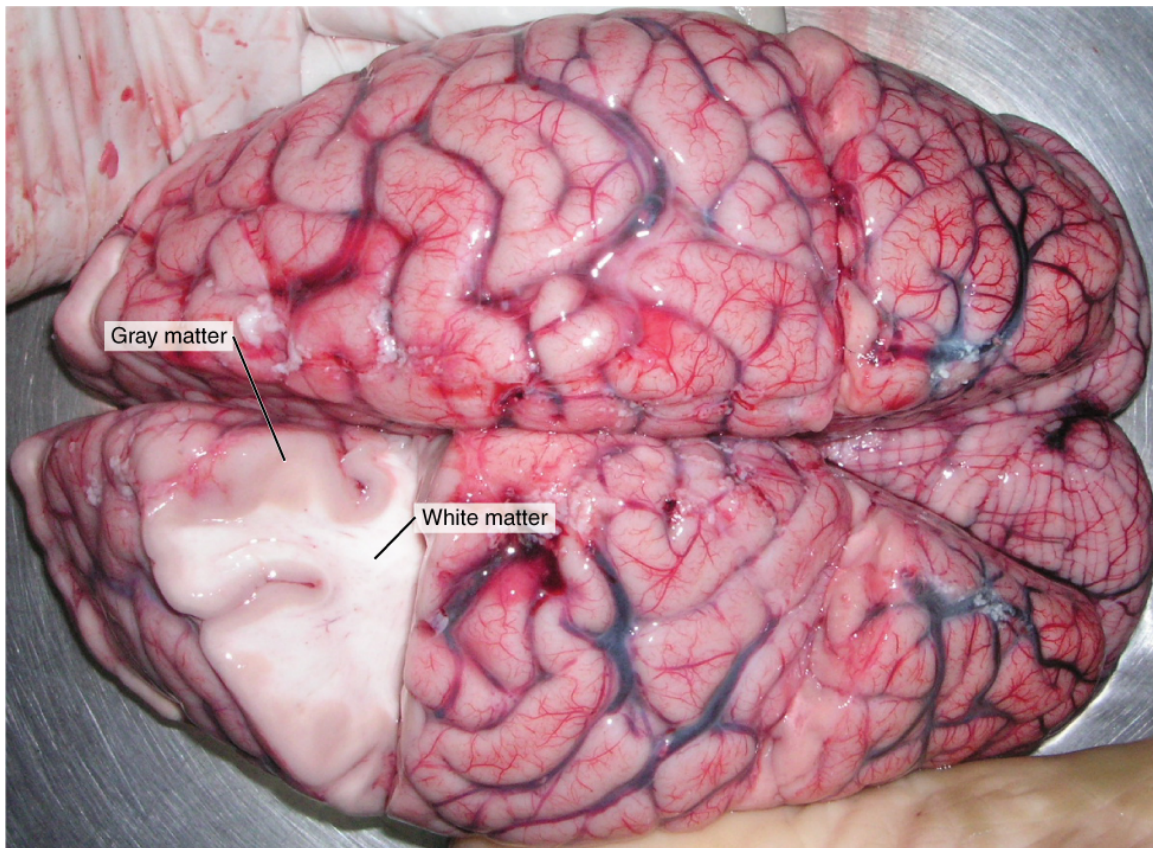
Figure 8.7 Gray Matter and White Matter A brain removed during an autopsy, with a partial section removed, shows white matter surrounded by gray matter. Gray matter makes up the outer cortex of the brain. (credit: modification of work by "Suseno"/Wikimedia Commons)

The distinction between gray matter and white matter is most often applied to central nervous tissue, which has large regions that can be seen with the unaided eye. When looking at peripheral structures, often a microscope is used and the tissue is stained with artificial colors. That is not to say that central nervous tissue cannot be stained

and viewed under a microscope, but unstained tissue is most likely from the CNS—for example, a frontal section of the brain or cross section of the spinal cord.

Regardless of the appearance of stained or unstained tissue, the cell bodies of neurons or axons can be located in discrete anatomical structures that need to be named. Those names are specific to whether the structure is central or peripheral. A localized collection of neuron cell bodies in the CNS is referred to as a **nucleus**. In the PNS, a cluster of neuron cell bodies is referred to as a **ganglion**.

Terminology applied to bundles of axons also differs depending on location. A bundle of axons, or fibers, found in the CNS is called a **tract** whereas the same thing in the PNS would be called a **nerve**. There is an important point to make about these terms, which is that they can both be used to refer to the same bundle of axons. When those axons are in the PNS, the term is nerve, but if they are CNS, the term is tract. The most obvious example of this is the axons that project from the retina into the brain. Those axons are called the optic nerve as they leave the eye, but when they are inside the cranium, they are referred to as the optic tract. There is a specific place where the name changes, which is the optic chiasm, but they are still the same axons (**Figure 8.8**). **Table 8.1** helps to clarify which of these terms apply to the central or peripheral nervous systems.
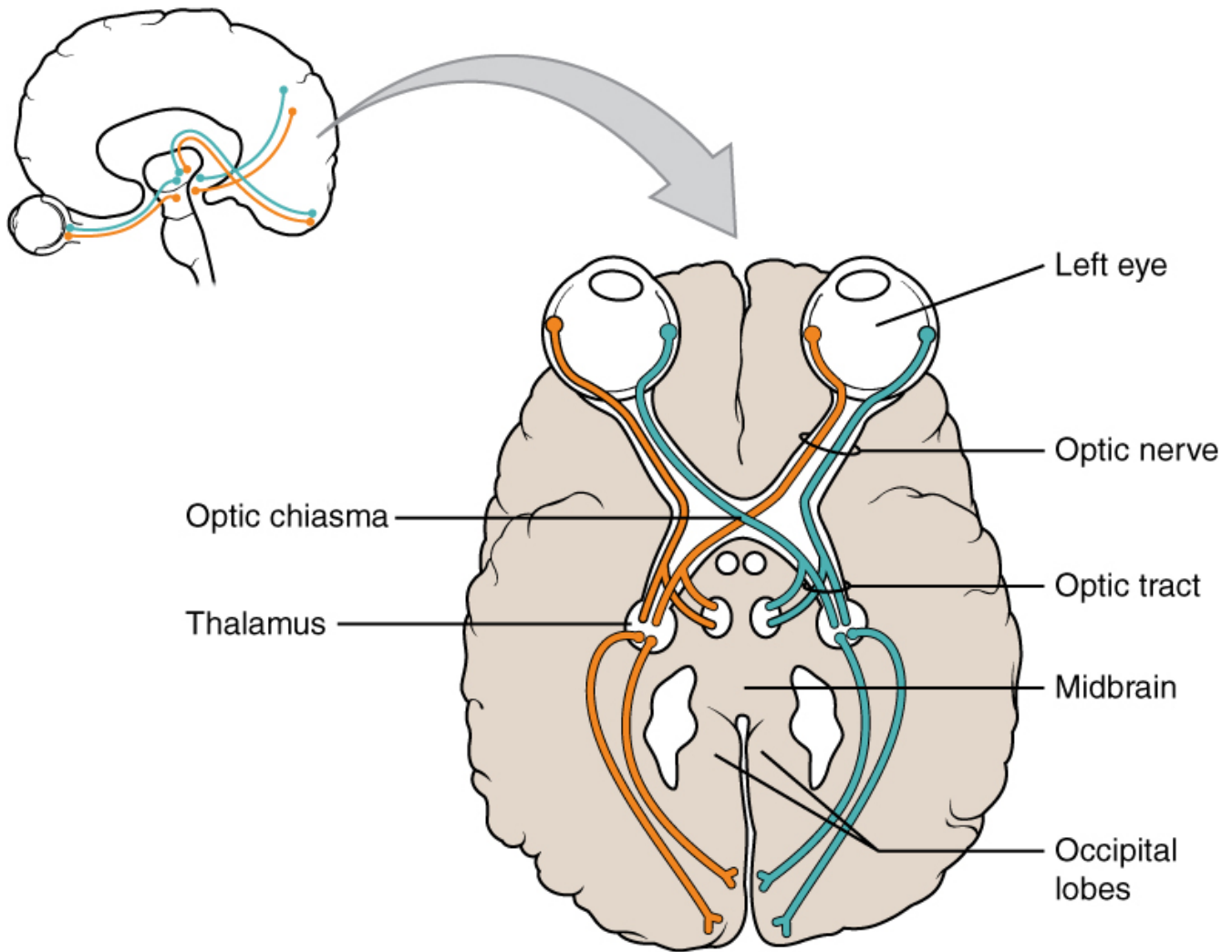
Figure 8.8 Optic Nerve Versus Optic Tract This drawing of the connections of the eye to the brain shows the optic nerve extending from the eye to the chiasm, where the structure continues as the optic tract. The same axons extend from the eye to the brain through these two bundles of fibers, but the chiasm represents the border between peripheral and central.

Table 8.1 Structures of the CNS and PNS

	CNS	PNS
Group of Neuron Cell Bodies (i.e., gray matter)	Nucleus	Ganglion
Bundle of Axons (i.e., white matter)	Tract	Nerve

The Central Nervous System

The brain and the spinal cord are the central nervous system, and they represent the main organs of the nervous

system. The spinal cord is a single structure, whereas the adult brain is described in terms of four major regions: the cerebrum, the diencephalon, the brain stem, and the cerebellum. A person's conscious experiences are based on neural activity in the brain. The regulation of homeostasis is governed by a specialized region in the brain. The coordination of reflexes depends on the integration of sensory and motor pathways in the spinal cord.

The Cerebrum

The iconic gray mantle of the human brain, which appears to make up most of the mass of the brain, is the **cerebrum** (**Figure 8.9**). The wrinkled portion is the **cerebral cortex**, and the rest of the structure is beneath that outer covering. There is a large separation between the two sides of the cerebrum called the **longitudinal fissure**. It separates the cerebrum into two distinct halves, a right and left **cerebral hemisphere**. Deep within the cerebrum, the white matter of the **corpus callosum** provides the major pathway for communication between the two hemispheres of the cerebral cortex.
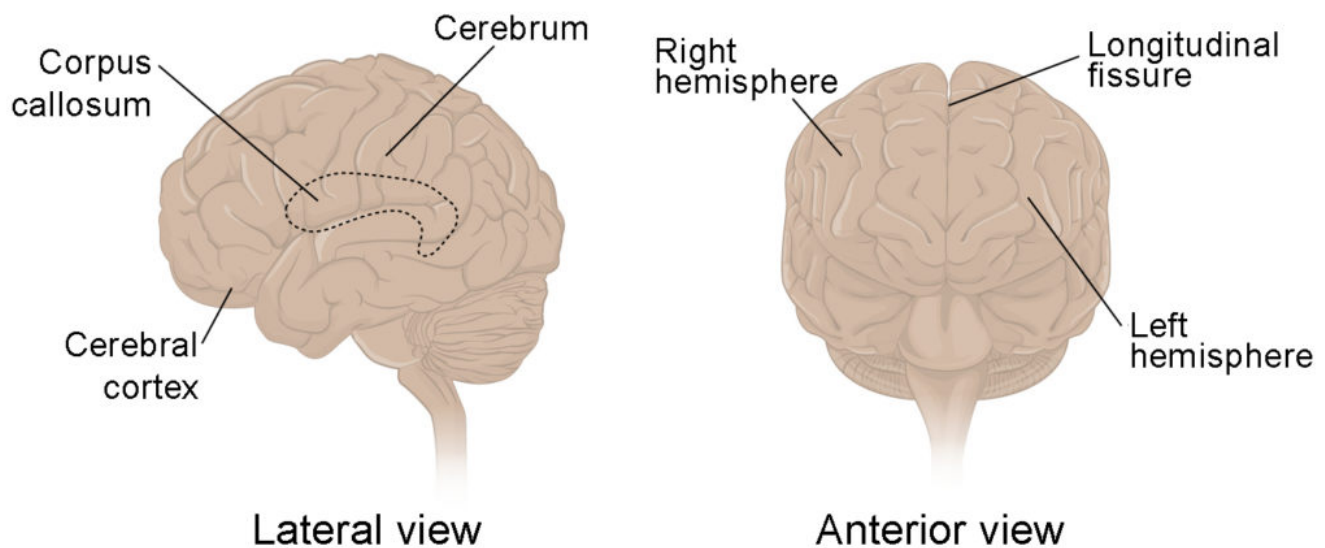
Figure 8.9 The Cerebrum The cerebrum is a large component of the CNS in humans, and the most obvious aspect of it is the folded surface called the cerebral cortex.

Many of the higher neurological functions, such as memory, emotion, and consciousness, are the result of cerebral function. The complexity of the cerebrum is different across vertebrate species. The cerebrum of the most primitive vertebrates is not much more than the connection for the sense of smell. In mammals, the cerebrum comprises the outer gray matter that is the cortex (from the Latin word meaning "bark of a tree") and several deep nuclei that belong to three important functional groups. The **basal nuclei** are responsible for cognitive processing, the most important function being that associated with planning movements. The **basal forebrain** contains nuclei that are important in learning and memory. The **limbic cortex** is the region of the cerebral cortex that is part of the **limbic system**, a collection of structures involved in emotion, memory, and behavior.

Cerebral Cortex

The cerebrum is covered by a continuous layer of gray matter that wraps around either side of the forebrain—the

cerebral cortex. This thin, extensive region of wrinkled gray matter is responsible for the higher functions of the nervous system. A **gyrus** (plural = *gyri*) is the ridge of one of those wrinkles, and a **sulcus** (plural = *sulci*) is the groove between two gyri. The pattern of these folds of tissue indicates specific regions of the cerebral cortex.

The head is limited by the size of the birth canal, and the brain must fit inside the cranial cavity of the skull. Extensive folding in the cerebral cortex enables more gray matter to fit into this limited space. If the gray matter of the cortex were peeled off of the cerebrum and laid out flat, its surface area would be roughly equal to one square meter.

The folding of the cortex maximizes the amount of gray matter in the cranial cavity. The surface of the brain can be mapped on the basis of the locations of large gyri and sulci. Using these landmarks, the cortex can be separated into four major regions, or lobes (**Figure 8.10**). The **lateral sulcus** that separates the **temporal lobe** from the other regions is one such landmark. Superior to the lateral sulcus are the **parietal lobe** and **frontal lobe**, which are separated from each other by the **central sulcus**. The posterior region of the cortex is the **occipital lobe**, which has no obvious anatomical border between it and the parietal or temporal lobes on the lateral surface of the brain. From the medial surface, an obvious landmark separating the parietal and occipital lobes is called the **parieto-occipital sulcus**. The fact that there is no obvious anatomical border between these lobes is consistent with the functions of these regions being interrelated.
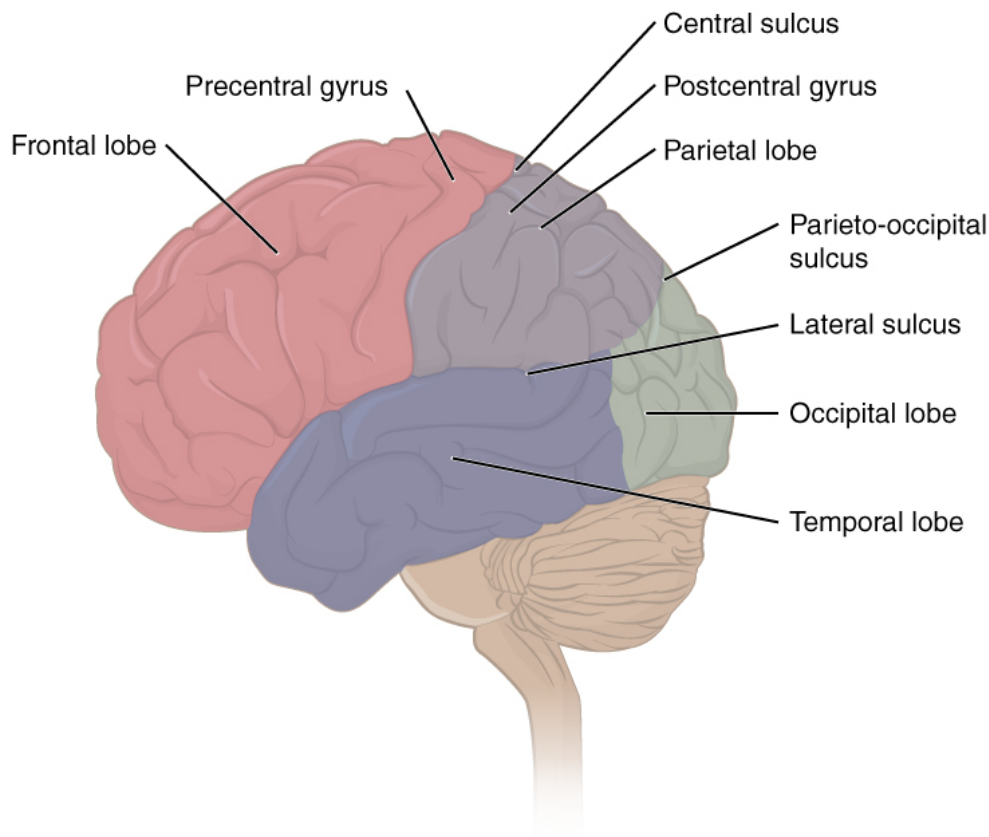
Figure 8.10 Lobes of the Cerebral Cortex The cerebral cortex is divided into four lobes. Extensive folding increases the surface area available for cerebral functions.

Different regions of the cerebral cortex can be associated with particular functions, a concept known as localization of function. In the early 1900s, a German neuroscientist named Korbinian Brodmann performed an

extensive study of the microscopic anatomy—the cytoarchitecture—of the cerebral cortex and divided the cortex into 52 separate regions on the basis of the histology of the cortex. His work resulted in a system of classification known as **Brodmann's areas**, which is still used today to describe the anatomical distinctions within the cortex (**Figure 8.11**). The results from Brodmann's work on the anatomy align very well with the functional differences within the cortex. Areas 17 and 18 in the occipital lobe are responsible for primary visual perception. That visual information is complex, so it is processed in the temporal and parietal lobes as well.

The temporal lobe is associated with primary auditory sensation, known as Brodmann's areas 41 and 42 in the superior temporal lobe. Because regions of the temporal lobe are part of the limbic system, memory is an important function associated with that lobe. Memory is essentially a sensory function; memories are recalled sensations such as the smell of Mom's baking or the sound of a barking dog. Even memories of movement are really the memory of sensory feedback from those movements, such as stretching muscles or the movement of the skin around a joint. Structures in the temporal lobe are responsible for establishing long-term memory, but the ultimate location of those memories is usually in the region in which the sensory perception was processed.

The main sensation associated with the parietal lobe is **somatosensation**, meaning the general sensations associated with the body. Posterior to the central sulcus is the **postcentral gyrus**, the **primary somatosensory cortex**, which is identified as Brodmann's areas 1, 2, and 3. All of the tactile senses are processed in this area, including touch, pressure, tickle, pain, itch, and vibration, as well as more general senses of the body such as proprioception and kinesthesia, which are the senses of body position and movement, respectively.

Anterior to the central sulcus is the frontal lobe, which is primarily associated with motor functions. The **precentral gyrus** is the **primary motor cortex**. Cells from this region of the cerebral cortex are the upper motor neurons that instruct cells in the spinal cord to move skeletal muscles. Anterior to this region are a few areas that are associated with planned movements. The **premotor area** is responsible for thinking of a movement to be made. The **frontal eye fields** are important in eliciting eye movements and in attending to visual stimuli. **Broca's area** is responsible for the production of language, or controlling movements responsible for speech; in the vast majority of people, it is located only on the left side. Anterior to these regions is the **prefrontal lobe**, which serves cognitive functions that can be the basis of personality, short-term memory, and consciousness.
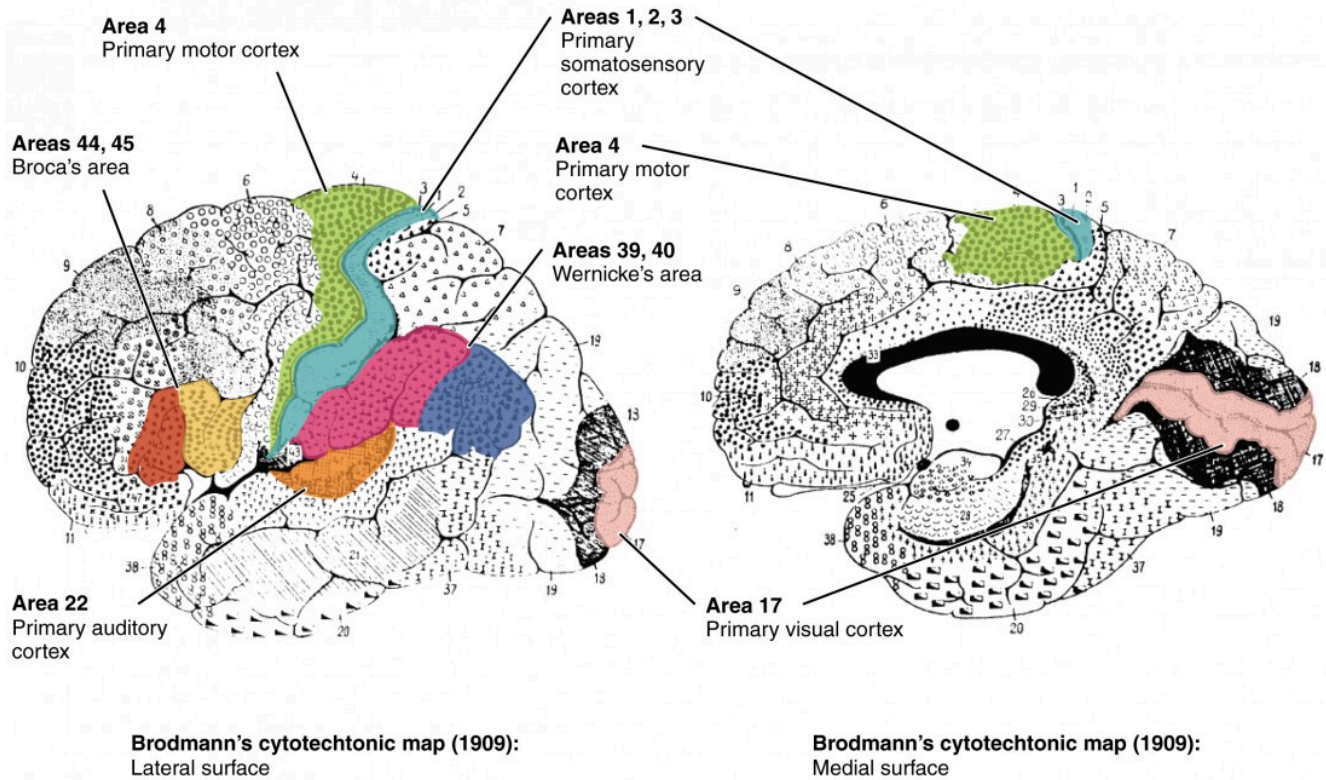
Figure 8.11 Brodmann's Areas of the Cerebral Cortex Brodmann mapping of functionally distinct regions of the cortex was based on its cytoarchitecture at a microscopic level.

The Diencephalon

The etymology of the word **diencephalon** translates to "through brain." It is the connection between the cerebrum and the rest of the nervous system, with one exception, **olfaction** (the sense of smell), which connects directly with the cerebrum. The rest of the brain, the spinal cord, and the PNS all send information to the cerebrum through the diencephalon. Output from the cerebrum passes through the diencephalon.

The diencephalon is deep beneath the cerebrum and constitutes the walls of the third ventricle. The diencephalon can be described as any region of the brain with "thalamus" in its name. The two major regions of the diencephalon are the **thalamus** itself and the **hypothalamus** (**Figure 8.12**). There are other structures, such as the **epithalamus**, which contains the pineal gland.
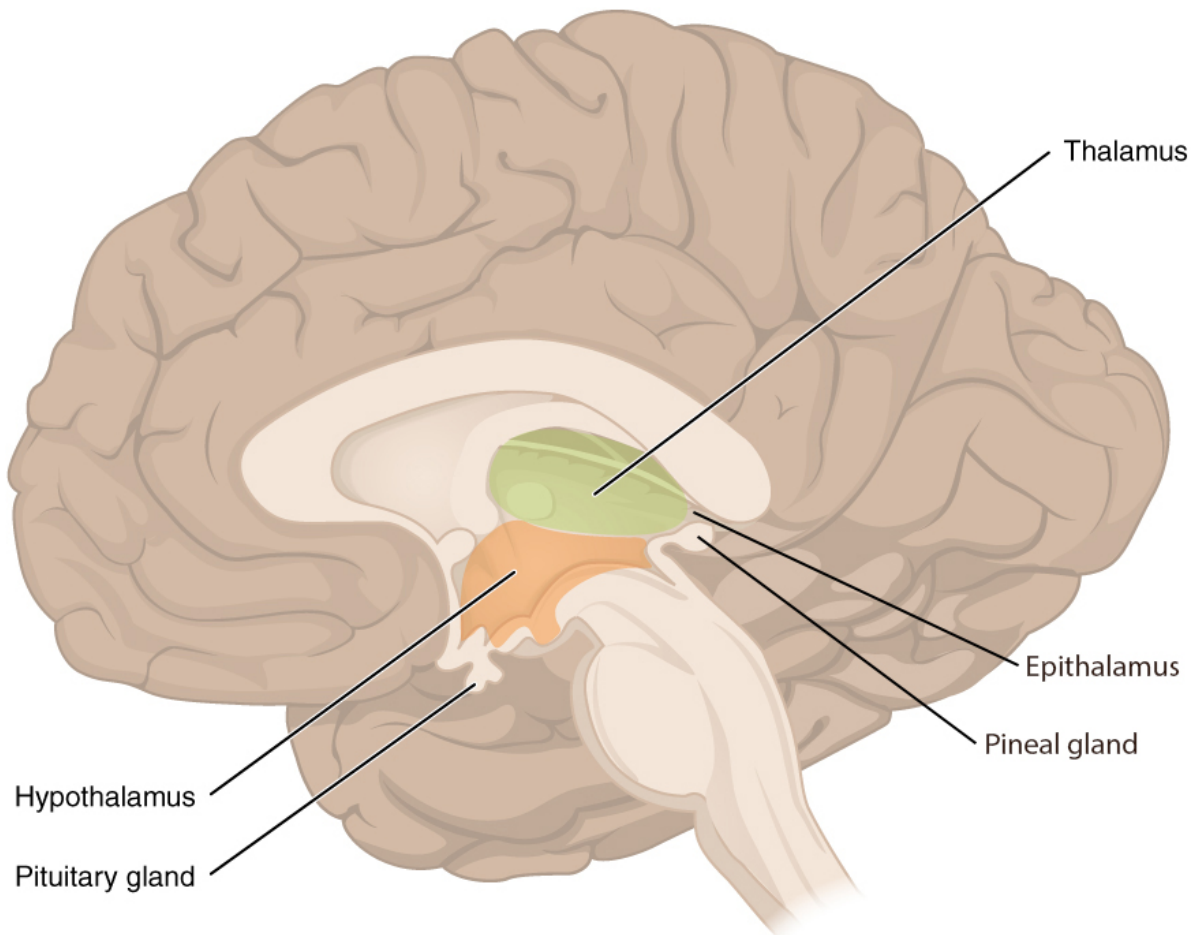
Figure 8.12. The Diencephalon. The diencephalon is composed primarily of the thalamus and hypothalamus, which together define the walls of the third ventricle. The thalami are two elongated, ovoid structures on either side of the midline that make contact in the middle. The hypothalamus is inferior and anterior to the thalamus, culminating in a sharp angle to which the pituitary gland is attached.

The **thalamus** is a collection of nuclei that relay information between the cerebral cortex and the periphery, spinal cord, or brain stem. All sensory information, except for the sense of smell, passes through the thalamus before processing by the cortex. Axons from the peripheral sensory organs, or intermediate nuclei, synapse in the thalamus, and thalamic neurons project directly to the cerebrum. The thalamus does not just pass the information on, it also processes that information. For example, the portion of the thalamus that receives visual information will influence what visual stimuli are important, or what receives attention. The cerebrum also sends information down to the thalamus, which usually communicates motor commands. This involves interactions with the cerebellum and other nuclei in the brain stem.

Inferior and slightly anterior to the thalamus is the **hypothalamus**, the other major region of the diencephalon. The hypothalamus is a collection of nuclei that are largely involved in regulating homeostasis. The hypothalamus is the executive region in charge of the autonomic nervous system and the endocrine system through its regulation of the anterior pituitary gland. Other parts of the hypothalamus are involved in memory and emotion as part of the limbic system.

Brain Stem

The **midbrain** and hindbrain (composed of the **pons** and the **medulla oblongata**) are collectively referred to as the brain stem (**Figure 8.13**). The structure emerges from the ventral surface of the forebrain as a tapering cone that connects the brain to the spinal cord. Attached to the brain stem, but considered a separate region of the adult brain, is the cerebellum. The midbrain coordinates sensory representations of the visual, auditory, and somatosensory perceptual spaces. The pons is the main connection with the cerebellum. The pons and the medulla regulate several crucial functions, including the cardiovascular and respiratory systems and rates.

The cranial nerves connect through the brain stem and provide the brain with the sensory input and motor output associated with the head and neck, including most of the special senses. The major ascending and descending pathways between the spinal cord and brain, specifically the cerebrum, pass through the brain stem.
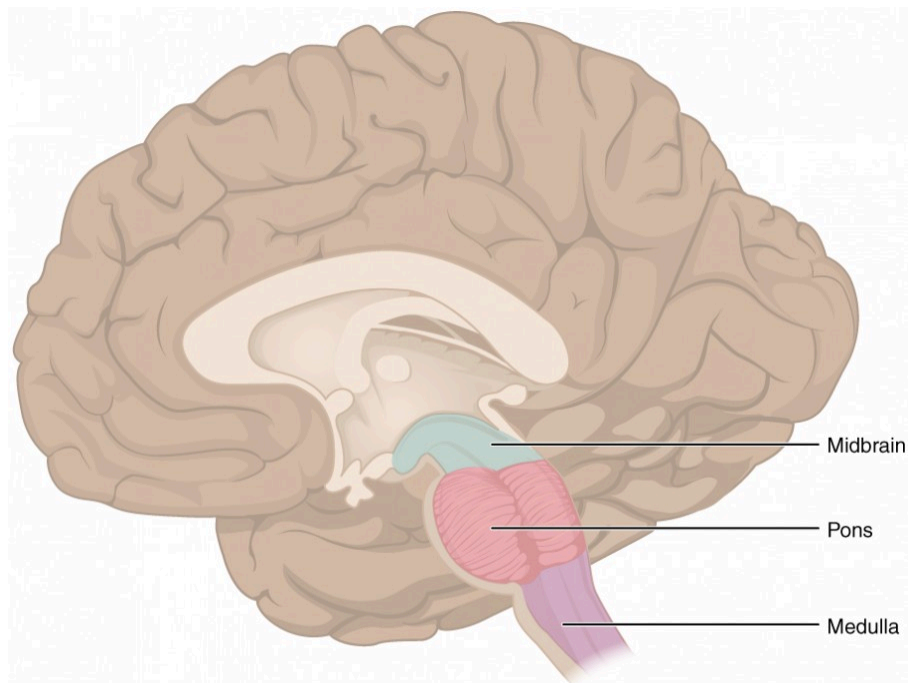
Figure 8.13 The Brain Stem The brain stem comprises three regions: the midbrain, the pons, and the medulla.

The Cerebellum

The **cerebellum**, as the name suggests, is the "little brain." It is covered in gyri and sulci like the cerebrum, and looks like a miniature version of that part of the brain (**Figure 8.14**). The cerebellum is largely responsible for comparing information from the cerebrum with sensory feedback from the periphery through the spinal cord. It accounts for approximately 10 percent of the mass of the brain.
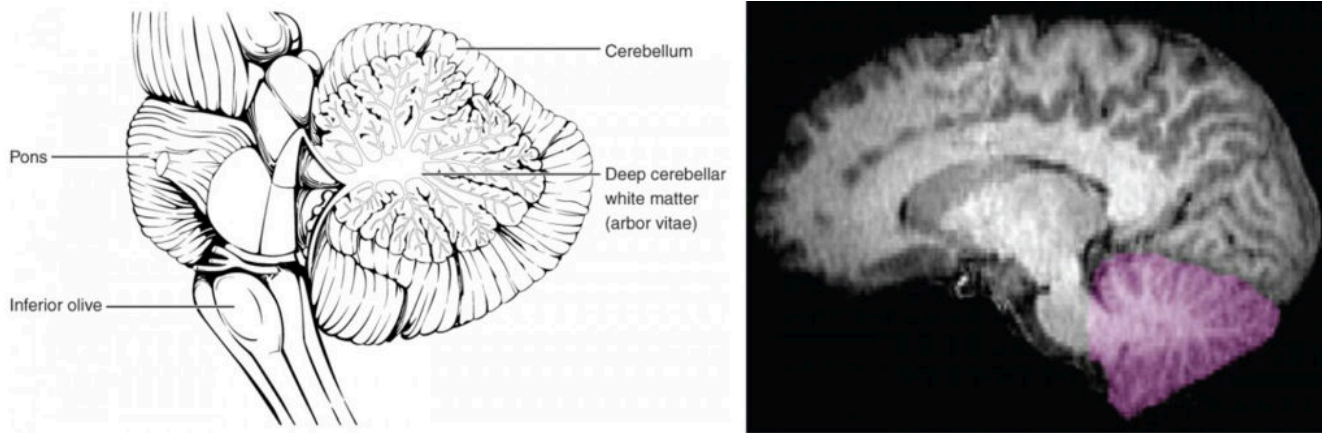
Figure 8.14 The Cerebellum The cerebellum is situated on the posterior surface of the brain stem. Descending input from the cerebellum enters through the large white matter structure of the pons. Ascending input from the periphery and spinal cord enters through the fibers of the inferior olive. Output goes to the midbrain, which sends a descending signal to the spinal cord.

When the cerebrum sends motor commands sent to the spinal cord, a copy is sent to the cerebellum, as well. A copy of sensory information from the periphery, which enters through spinal or cranial nerves, is also sent to the cerebellum. If the primary motor cortex of the frontal lobe sends a command down to the spinal cord to initiate walking, a copy of that instruction is sent to the cerebellum. Sensory feedback from the muscles and joints, proprioceptive information about the movements of walking, and sensations of balance are sent to the cerebellum and the cerebellum compares them. If walking is not coordinated, perhaps because the ground is uneven or a strong wind is blowing, then the cerebellum sends out a corrective command to compensate for the difference between the original cortical command and the sensory feedback. The output of the cerebellum is into the midbrain, which then sends a descending input to the spinal cord to correct the messages going to skeletal muscles.

The Spinal Cord

The description of the CNS is concentrated on the structures of the brain, but the spinal cord is another major organ of the system. The anterior midline is marked by the anterior median fissure, and the posterior midline is marked by the posterior median sulcus. Axons enter the posterior side through the **dorsal (posterior) nerve root**. The axons emerging from the anterior side do so through the **ventral (anterior) nerve root**. On the whole, the posterior regions are responsible for sensory functions and the anterior regions are associated with motor functions. Note that it is common to see the terms dorsal (dorsal = "back") and ventral (ventral = "belly") used interchangeably with posterior and anterior, particularly in reference to nerves and the structures of the spinal cord. You should learn to be comfortable with both.

The length of the spinal cord is divided into regions that correspond to the regions of the vertebral column. The name of a spinal cord region corresponds to the level at which spinal nerves pass through the intervertebral foramina. Immediately adjacent to the brain stem is the cervical region, followed by the thoracic, then the lumbar, and finally the sacral region. The spinal cord is not the full length of the vertebral column because the spinal cord does not grow significantly longer after the first or second year, but the skeleton continues to grow. The nerves that emerge from the spinal cord pass through the intervertebral foramina at the respective levels. As the vertebral column grows, these nerves grow with it and result in a long bundle of nerves that resembles a horse's tail and

is named the **cauda equina**. The sacral spinal cord is at the level of the upper lumbar vertebral bones. The spinal nerves extend from their various levels to the proper level of the vertebral column.

Gray Horns

In cross-section, the gray matter of the spinal cord has the appearance of an ink-blot test, with the spread of the gray matter on one side replicated on the other—a shape reminiscent of a bulbous capital "H." As shown in **Figure 8.15**, the gray matter is subdivided into regions that are referred to as horns. The **posterior horn** is responsible for sensory processing. The **anterior horn** sends out motor signals to the skeletal muscles. The **lateral horn**, which is only found in the thoracic, upper lumbar, and sacral regions, is the central component of the sympathetic division of the autonomic nervous system.
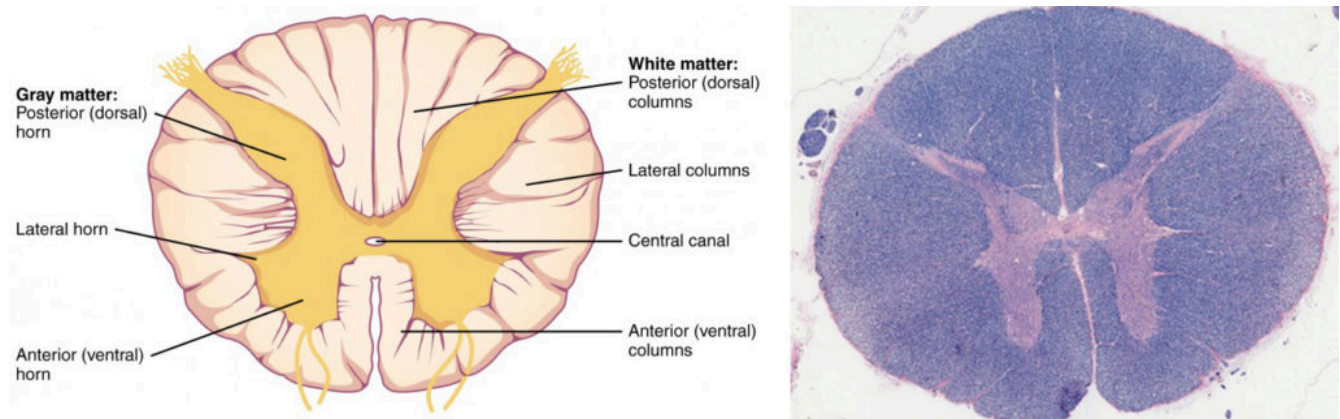
Figure 8.15. Cross-section of Spinal Cord. The cross-section of a thoracic spinal cord segment shows the posterior, anterior, and lateral horns of gray matter, as well as the posterior, anterior, and lateral columns of white matter. LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

White Columns

Just as the gray matter is separated into horns, the white matter of the spinal cord is separated into columns. **Ascending tracts** of nervous system fibers in these columns carry sensory information up to the brain, whereas **descending tracts** carry motor commands from the brain. Looking at the spinal cord longitudinally, the columns extend along its length as continuous bands of white matter. Between the two posterior horns of gray matter are the **posterior columns**. Between the two anterior horns, and bounded by the axons of motor neurons emerging from that gray matter area, are the **anterior columns**. The white matter on either side of the spinal cord, between the posterior horn and the axons of the anterior horn neurons, are the **lateral columns**. The posterior columns are composed of axons of ascending tracts. The anterior and lateral columns are composed of many different groups of axons of both ascending and descending tracts—the latter carrying motor commands down from the brain to the spinal cord to control output to the periphery.

Protective Coverings of the Brain and Spinal Cord

The outer surface of the CNS is covered by a series of membranes composed of connective tissue called the **meninges**, which protect the brain. The **dura mater** is a thick fibrous layer and a strong protective sheath

over the entire brain and spinal cord. It is anchored to the inner surface of the cranium and vertebral cavity. The **arachnoid mater** is a membrane of thin fibrous tissue that forms a loose sac around the CNS. Beneath the arachnoid is a thin, filamentous mesh called the **arachnoid trabeculae**, which looks like a spider web, giving this layer its name. Directly adjacent to the surface of the CNS is the **pia mater**, a thin fibrous membrane that follows the convolutions of gyri and sulci in the cerebral cortex and fits into other grooves and indentations (**Figure 8.16**).
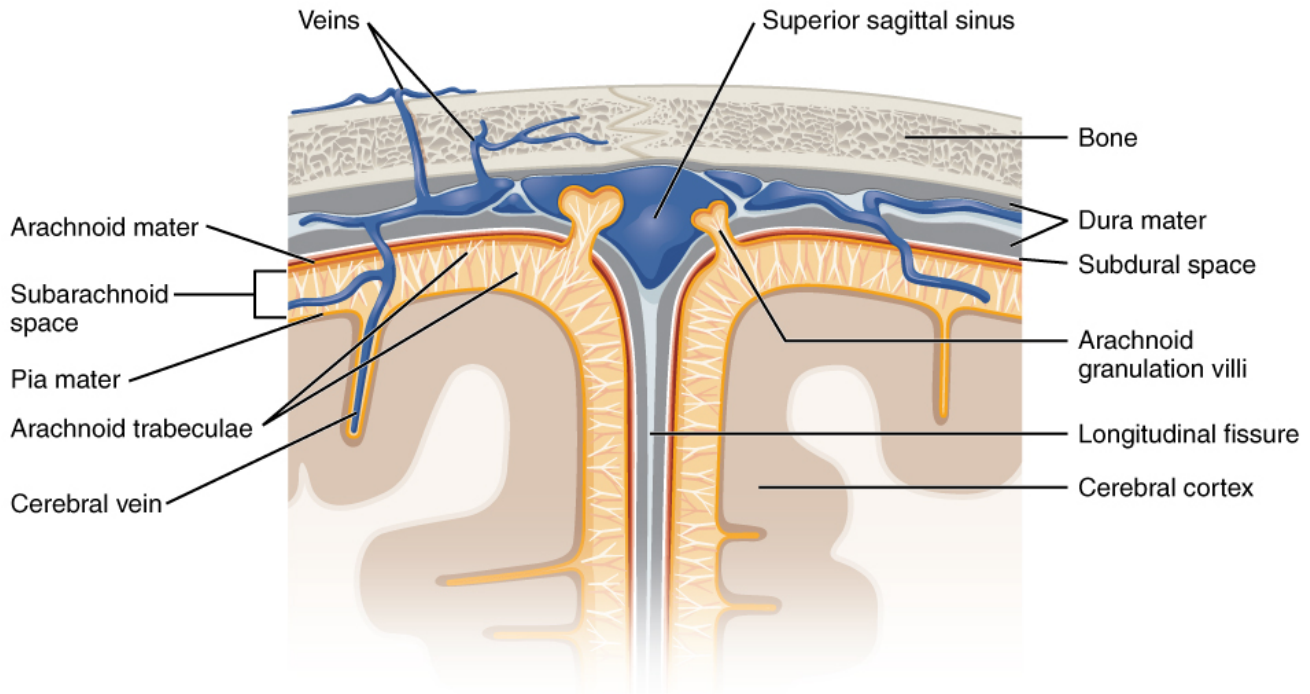
Figure 8.16. Meningeal Layers of Superior Sagittal Sinus. The layers of the meninges in the longitudinal fissure of the superior sagittal sinus are shown, with the dura mater adjacent to the inner surface of the cranium, the pia mater adjacent to the surface of the brain, and the arachnoid and subarachnoid space between them. An arachnoid villus is shown emerging into the dural sinus to allow CSF to filter back into the blood for drainage.

Dura Mater

Like a thick cap covering the brain, the **dura mater** is a tough outer covering. The name comes from the Latin for "tough mother" to represent its physically protective role. It encloses the entire CNS and the major blood vessels that enter the cranium and vertebral cavity. It is directly attached to the inner surface of the bones of the cranium and to the very end of the vertebral cavity. There are infoldings of the dura that fit into large crevasses of the brain. Two infoldings go through the midline separations of the cerebrum and cerebellum; one forms a shelf-like tent between the occipital lobes of the cerebrum and the cerebellum, and the other surrounds the pituitary gland. The dura also surrounds and supports the venous sinuses.

After passing through the CNS, blood returns to the circulation through a series of **dural sinuses** and veins (**Figure 8.17**). The **superior sagittal sinus** runs in the groove of the longitudinal fissure, where it absorbs CSF from the meninges. The superior sagittal sinus drains to the confluence of sinuses, along with the occipital sinuses and straight sinus, to then drain into the transverse sinuses. The transverse sinuses connect to the sigmoid sinuses, which then connect to the jugular veins. From there, the blood continues toward the heart to be pumped to the lungs for reoxygenation.
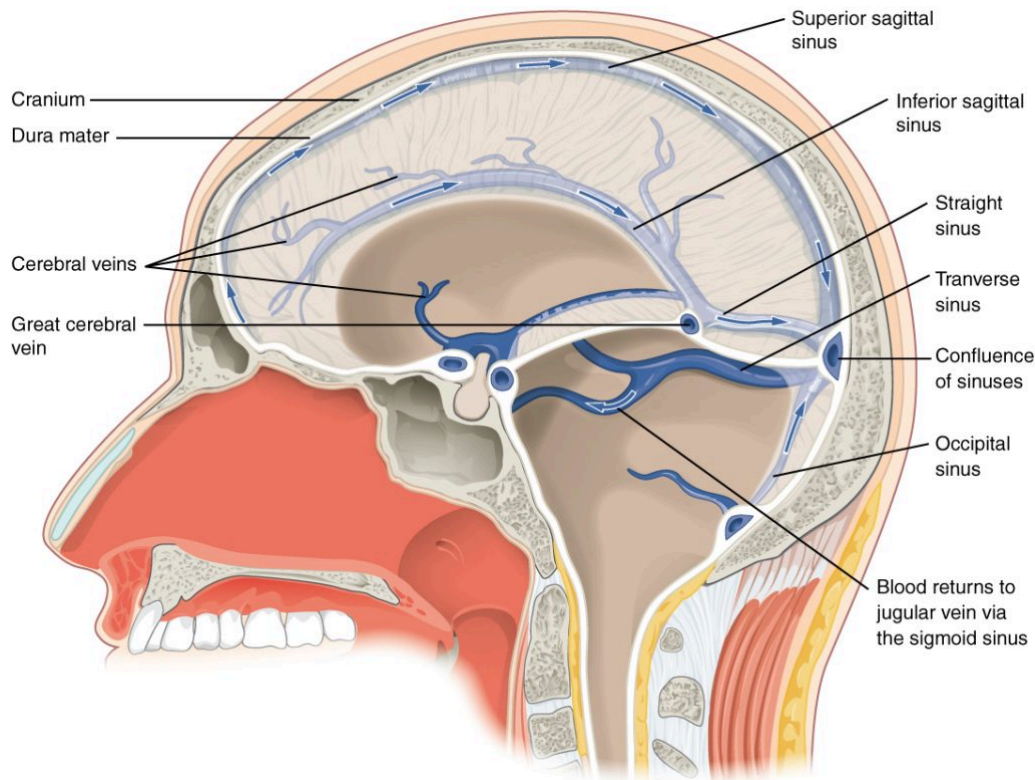
Figure 8.17 Dural Sinuses and Veins Blood drains from the brain through a series of sinuses that connect to the jugular veins.

Arachnoid Mater

The middle layer of the meninges is the arachnoid, named for the spider-web–like trabeculae between it and the pia mater. The arachnoid defines a sac-like enclosure around the CNS. The trabeculae are found in the **subarachnoid space**, which is filled with circulating CSF. The arachnoid emerges into the dural sinuses as the **arachnoid granulations**, where the CSF is filtered back into the blood for drainage from the nervous system (**Figure 8.16**).

The subarachnoid space is filled with circulating CSF, which also provides a liquid cushion to the brain and spinal cord. Similar to clinical blood work, a sample of CSF can be withdrawn to find chemical evidence of neuropathology or metabolic traces of the biochemical functions of nervous tissue.

Pia Mater

The outer surface of the CNS is covered in the thin fibrous membrane of the pia mater. It is thought to have a continuous layer of cells providing a fluid-impermeable membrane. The name pia mater comes from the Latin for "tender mother," suggesting the thin membrane is a gentle covering for the brain. The pia extends into every convolution of the CNS, lining the inside of the sulci in the cerebral and cerebellar cortices. Blood vessels that are nourishing the central nervous tissue are between the pia mater and the nervous tissue.

The Ventricular System

Cerebrospinal fluid (CSF) circulates throughout and around the CNS. In other tissues, water and small molecules are filtered through capillaries as the major contributor to the interstitial fluid. In the brain, CSF is produced in special structures to perfuse through the nervous tissue of the CNS and is continuous with the interstitial fluid. Specifically, CSF circulates to remove metabolic wastes from the interstitial fluids of nervous tissues and return them to the blood stream. The **ventricles** are the open spaces within the brain where CSF circulates. In some of these spaces, CSF is produced by filtering of the blood that is performed by a specialized membrane known as a **choroid plexus**. The CSF circulates through all of the ventricles to eventually emerge into the subarachnoid space where it will be reabsorbed into the blood.

There are four ventricles within the brain. The first two are named the **lateral ventricles** and are deep within the cerebrum. These ventricles are connected to the third ventricle by two openings called the interventricular foramina. The **third ventricle** is the space between the left and right sides of the diencephalon, which opens into the cerebral aqueduct that passes through the midbrain. The aqueduct opens into the **fourth ventricle**, which is the space between the cerebellum and the pons and upper medulla (**Figure 8.18**).
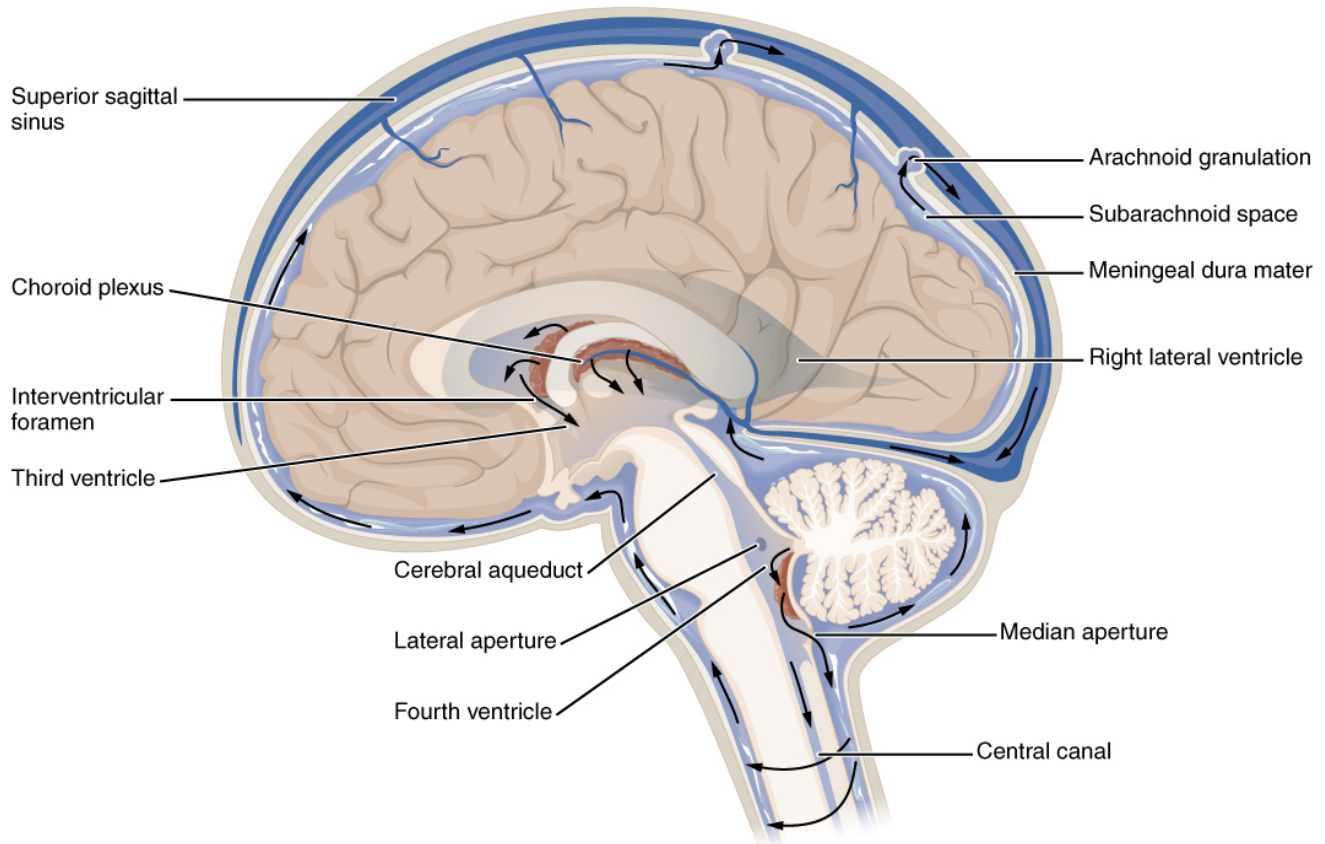
Figure 8.18. Cerebrospinal Fluid Circulation. The choroid plexus in the four ventricles produce CSF, which is circulated through the ventricular system and then enters the subarachnoid space through the median and lateral apertures. The CSF is then reabsorbed into the blood at the arachnoid granulations, where the arachnoid membrane emerges into the dural sinuses.

The ventricular system opens up to the subarachnoid space from the fourth ventricle. The single median aperture

and the pair of lateral apertures connect to the subarachnoid space so that CSF can flow through the ventricles and around the outside of the CNS. Cerebrospinal fluid is produced within the ventricles by a type of specialized membrane called a **choroid plexus**. Ependymal cells (one of the types of glial cells described in the introduction to the nervous system) surround blood capillaries and filter the blood to make CSF. The fluid is a clear solution with a limited amount of the constituents of blood. It is essentially water, small molecules, and electrolytes. Oxygen and carbon dioxide are dissolved into the CSF, as they are in blood, and can diffuse between the fluid and the nervous tissue.

A very small amount of CSF is filtered at any one of the plexuses, for a total of about 500 milliliters daily, but it is continuously made and pulses through the ventricular system, keeping the fluid moving. Within the subarachnoid space, the CSF flows around all of the CNS, providing two important functions. As with elsewhere in its circulation, the CSF picks up metabolic wastes from the nervous tissue and moves it out of the CNS. It also acts as a liquid cushion for the brain and spinal cord. By surrounding the entire system in the subarachnoid space, it provides a thin buffer around the organs within the strong, protective dura mater. The arachnoid granulations are outpocketings of the arachnoid membrane into the dural sinuses so that CSF can be reabsorbed into the blood, along with the metabolic wastes. From the dural sinuses, blood drains out of the head and neck through the jugular veins, along with the rest of the circulation for blood, to be reoxygenated by the lungs and wastes to be filtered out by the kidneys.

The Peripheral Nervous System

The PNS is not as contained as the CNS because it is defined as everything that is not the CNS. Some peripheral structures are incorporated into the other organs of the body. In describing the anatomy of the PNS, it is necessary to describe the common structures, the nerves and the ganglia, as they are found in various parts of the body. Many of the neural structures that are incorporated into other organs are features of the digestive system; these structures are known as the enteric nervous system and are a special subset of the PNS.

Ganglia

A ganglion is a group of neuron cell bodies in the periphery. Ganglia can be categorized, for the most part, as either sensory ganglia or autonomic ganglia, referring to their primary functions. The most common type of sensory ganglion is a **dorsal (posterior) root ganglion**. These ganglia are the cell bodies of neurons with axons that are sensory endings in the periphery, such as in the skin, and that extend into the CNS through the dorsal nerve root of the spinal cord (**Figure 8.19**). The ganglion is an enlargement of the nerve root. Under microscopic inspection, it can be seen to include the cell bodies of the neurons, as well as bundles of fibers that are the posterior nerve root (**Figure 8.20**).
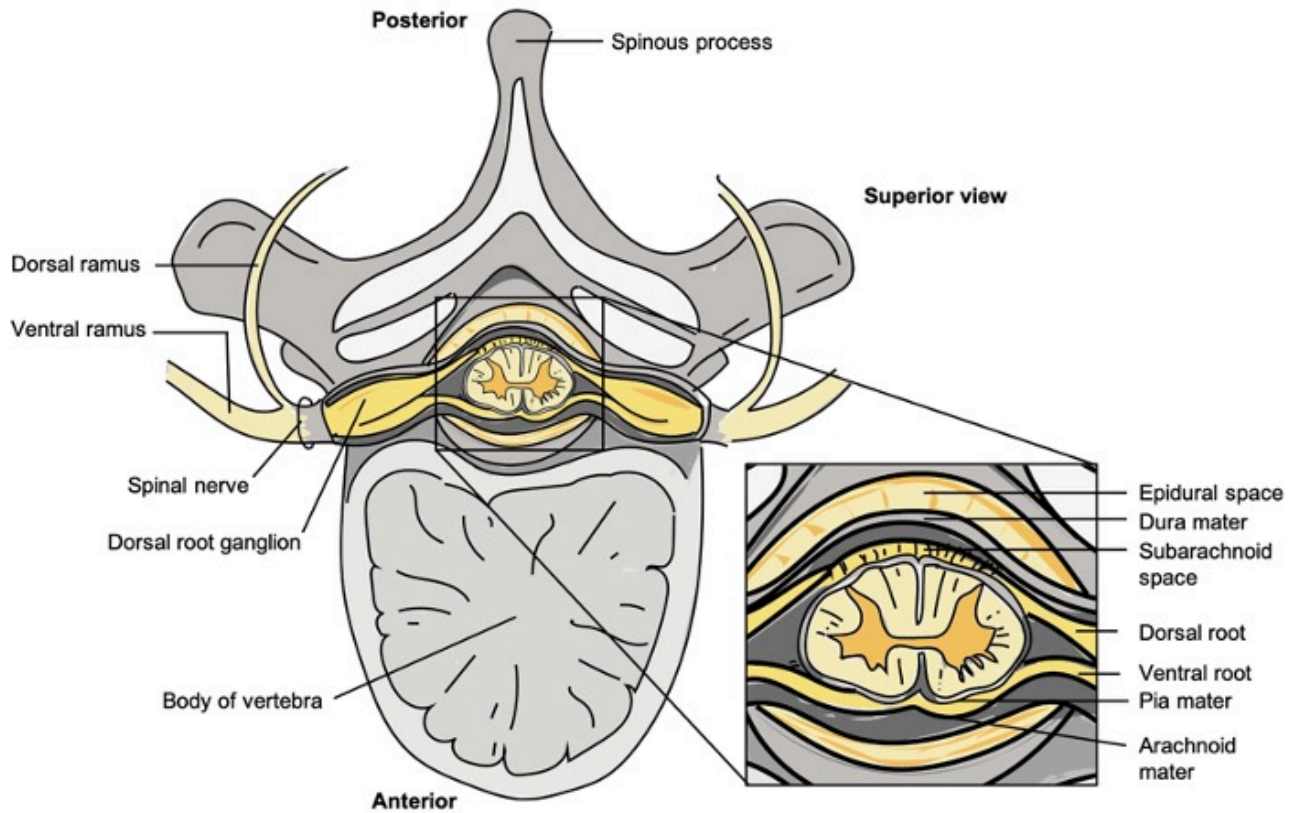
Figure 8.19 Spinal cord within vertebra. The superior view of a cross section of spinal cord within the vertebra shows the dorsal and ventral roots emerging from the spinal cord and fusing to form the spinal nerve. On the dorsal root, a dorsal root ganglion contain sensory neurons. The spinal cord is wrapped in meninges, as shown in the figure enlargement. (Image credit: "Spinal Cord within Vertebra" by Chiara Mazzasette is a derivative from the original work of Daniel Donnelly and is licensed by CC BY 4.0)
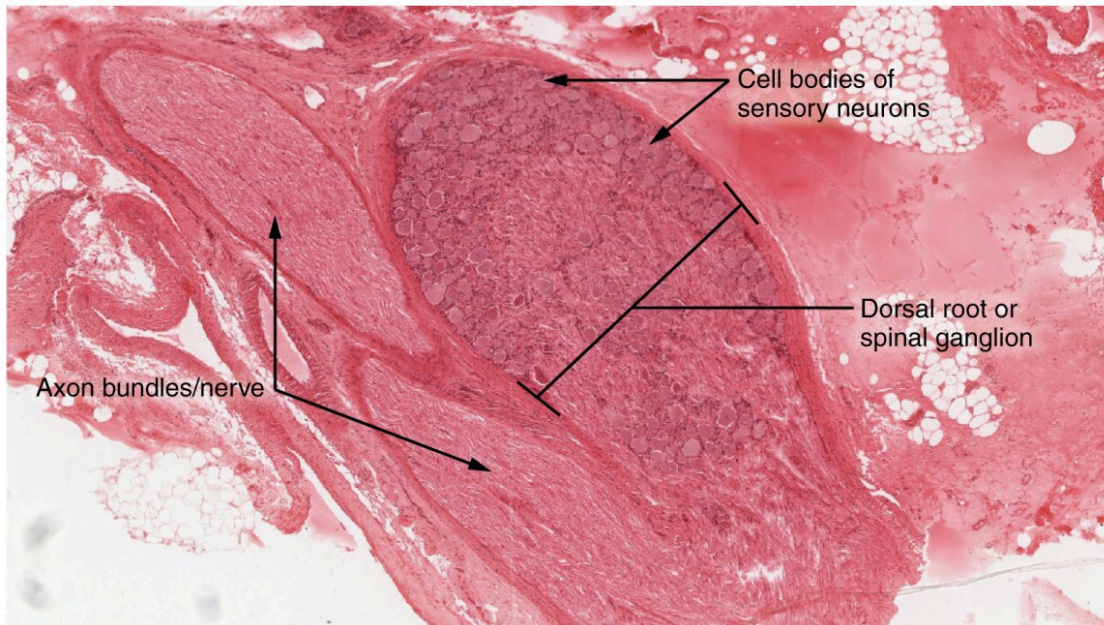
Figure 8.20 Dorsal Root Ganglion. The cell bodies of sensory neurons, which are unipolar neurons by shape, are seen in this photomicrograph. Also, the fibrous region is composed of the axons of these neurons that are passing through the ganglion to be part of the dorsal nerve root (tissue source: canine). LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Another type of sensory ganglion is a **cranial nerve ganglion**. This is analogous to the dorsal root ganglion, except that it is associated with a **cranial nerve** instead of a **spinal nerve**, which is what the dorsal root ganglion is associated with. The roots of cranial nerves are within the cranium, whereas the ganglia are outside the skull.

The other major category of ganglia are those of the autonomic nervous system, which is divided into the sympathetic and parasympathetic nervous systems. The **sympathetic chain ganglia** constitute a row of ganglia along the vertebral column that receive central input from the lateral horn of the thoracic and upper lumbar spinal cord. There are also surrounding paravertebral ganglia and prevertebral ganglia, which are located outside of the chain but have similar functions. The neurons of the chain, paravertebral, and prevertebral ganglia then project to organs in the head and neck, thoracic, abdominal, and pelvic cavities to regulate the sympathetic aspect of homeostatic mechanisms.

Another group of autonomic ganglia are the **terminal ganglia** that receive input from cranial nerves or sacral spinal nerves and are responsible for regulating the parasympathetic aspect of homeostatic mechanisms. These two sets of ganglia, sympathetic and parasympathetic, often project to the same organs—one input from the chain ganglia and one input from a terminal ganglion—to regulate the overall function of an organ. For example, the heart receives two inputs such as these; one increases heart rate, and the other decreases it.

Nerves

Bundles of axons in the PNS are referred to as nerves. These structures in the periphery are different than the central counterpart, called a tract. Nerves are composed of more than just nervous tissue. They have connective tissues invested in their structure, as well as blood vessels supplying the tissues with nourishment. The outer

surface of a nerve is a surrounding layer of fibrous connective tissue called the **epineurium**. Within the nerve, axons are further bundled into **fascicles**, which are each surrounded by their own layer of fibrous connective tissue called **perineurium**. Finally, individual axons are surrounded by loose connective tissue called the **endoneurium** (**Figure 8.21**). These three layers are similar to the connective tissue sheaths for muscles. Nerves are associated with the region of the CNS to which they are connected, either as cranial nerves connected to the brain or spinal nerves connected to the spinal cord.
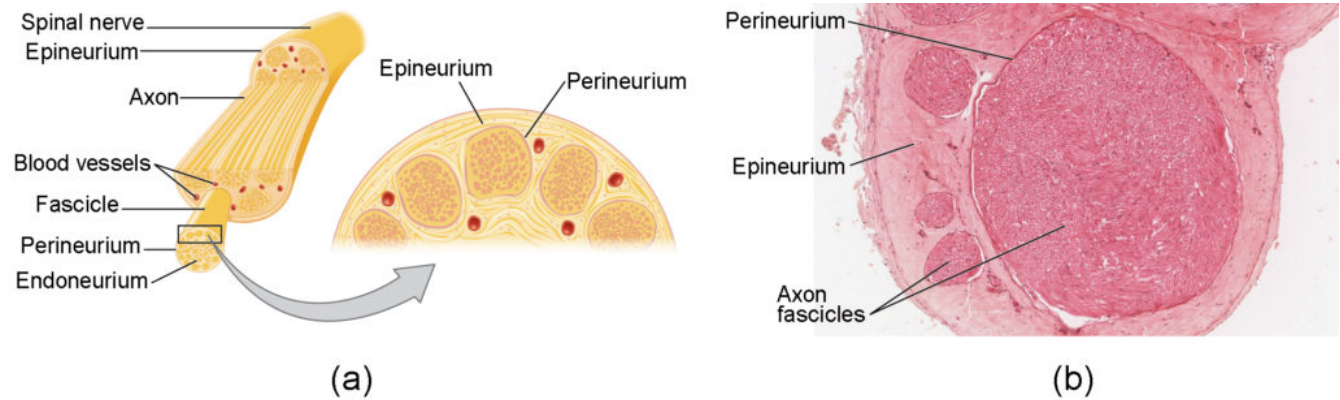
Figure 8.21. Nerve Structure. The structure of a nerve is organized by the layers of connective tissue on the outside, around each fascicle, and surrounding the individual nerve fibers (tissue source: simian). LM × 40. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Cranial Nerves

The nerves attached to the brain are the **cranial nerves**, which are primarily responsible for the sensory and motor functions of the head and neck (one of these nerves targets organs in the thoracic and abdominal cavities as part of the parasympathetic nervous system). There are twelve cranial nerves, which are designated CN I through CN XII for "Cranial Nerve," using Roman numerals for 1 through 12 (**Figure 8.22**). They can be classified as **sensory nerves**, **motor nerves**, or a **combination of both**, meaning that the axons in these nerves originate out of sensory ganglia external to the cranium or motor nuclei within the brain stem. Sensory axons enter the brain to synapse in a nucleus. Motor axons connect to skeletal muscles of the head or neck. Three of the nerves are solely composed of sensory fibers; five are strictly motor; and the remaining four are mixed nerves.
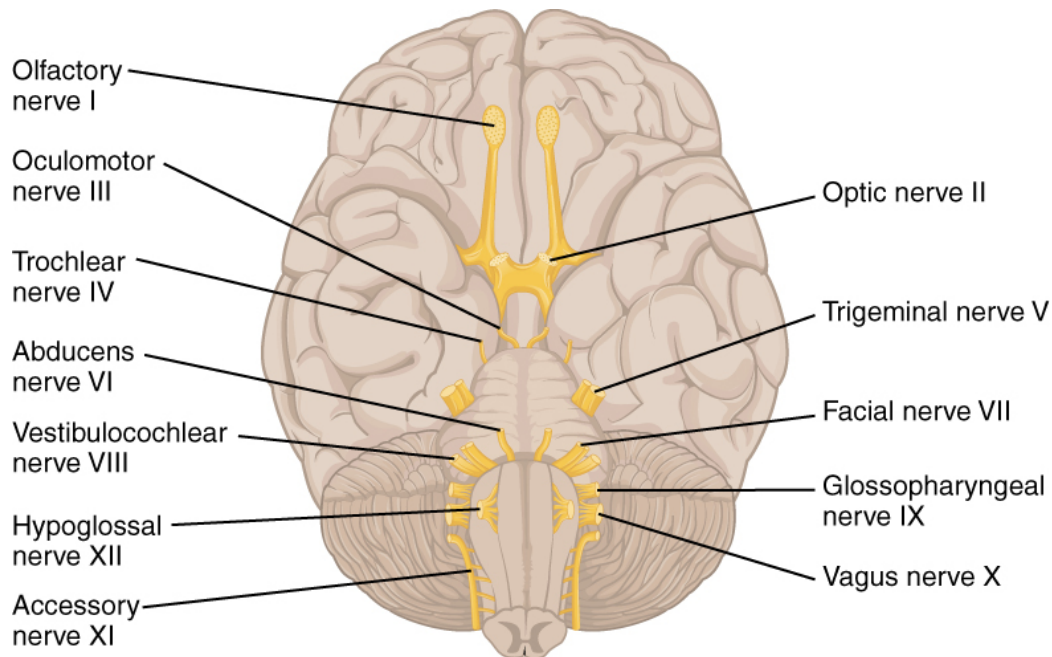
Figure 8.18 The Cranial Nerves The anatomical arrangement of the roots of the cranial nerves observed from an inferior view of the brain.

Learning the cranial nerves is a tradition in anatomy courses, and students have always used mnemonic devices to remember the nerve names. A traditional mnemonic is the rhyming couplet, "On Old Olympus' Towering Tops/A Finn And German Viewed Some Hops," in which the initial letter of each word corresponds to the initial letter in the name of each nerve. The names of the nerves have changed over the years to reflect current usage and more accurate naming. An exercise to help learn this sort of information is to generate a mnemonic using words that have personal significance. The names of the cranial nerves are listed in **Table 8.2** along with a brief description of their function, their source (sensory ganglion or motor nucleus), and their target (sensory nucleus or skeletal muscle).

The **olfactory nerve** and **optic nerve** are responsible for the sense of smell and vision, respectively. The **oculomotor nerve** is responsible for eye movements by controlling four of the extraocular muscles. It is also responsible for lifting the upper eyelid when the eyes point up, and for pupillary constriction. The **trochlear nerve** and the **abducens nerve** are both responsible for eye movement, but do so by controlling different extraocular muscles. The **trigeminal nerve** is responsible for cutaneous sensations of the face and controlling the muscles of mastication. The **facial nerve** is responsible for the muscles involved in facial expressions, as well as part of the sense of taste and the production of saliva. The **vestibulocochlear nerve** is responsible for the senses of hearing and balance. The **glossopharyngeal nerve** is responsible for controlling muscles in the oral cavity and upper throat, as well as part of the sense of taste and the production of saliva. The **vagus nerve** is responsible for contributing to homeostatic control of the organs of the thoracic and upper abdominal cavities. The **accessory nerve** is responsible for controlling the muscles of the neck, along with cervical spinal nerves. The **hypoglossal nerve** is responsible for controlling the muscles of the lower throat and tongue.

Four of the cranial nerves also contain autonomic fibers. The oculomotor, facial, and glossopharyngeal nerves contain fibers that contact autonomic ganglia. The oculomotor fibers initiate pupillary constriction, whereas the

facial and glossopharyngeal fibers both initiate salivation. The vagus nerve primarily targets autonomic ganglia in the thoracic and upper abdominal cavities.

Another important aspect of the cranial nerves that lends itself to a mnemonic is the functional role each nerve plays. The nerves fall into one of three basic groups. They are sensory, motor, or both (see **Table 8.2**). The sentence, "Some Say Marry Money But My Brother Says Brains Beauty Matter More," corresponds to the basic function of each nerve. The first, second, and eighth nerves are purely sensory: the olfactory (CNI), optic (CNII), and vestibulocochlear (CNVIII) nerves. The three eye-movement nerves are all motor: the oculomotor (CNIII), trochlear (CNIV), and abducens (CNVI). The accessory (CNXI) and hypoglossal (CNXII) nerves are also strictly motor. The remainder of the nerves contain both sensory and motor fibers. They are the trigeminal (CNV), facial (CNVII), glossopharyngeal (CNIX), and vagus (CNX) nerves. The nerves that convey both are often related to each other. The trigeminal and facial nerves both concern the face; one concerns the sensations and the other concerns the muscle movements. The facial and glossopharyngeal nerves are both responsible for conveying gustatory, or taste, sensations as well as controlling salivary glands. The vagus nerve is involved in visceral responses to taste, namely the gag reflex. This is not an exhaustive list of what these combination nerves do, but there is a thread of relation between them.

Table 8.2. Cranial Nerves

Mnemonic	#	Name	Function (S/M/B)	Central connection (nuclei)	Peripheral connection (ganglion or muscle)
On	I	Olfactory	Smell (S)	Olfactory bulb	Olfactory epithelium
Old	II	Optic	Vision (S)	Hypothalamus/thalamus/midbrain	Retina (retinal ganglion cells)
Olympus	III	Oculomotor	Eye movements (M)	Oculomotor nucleus	Extraocular muscles (other 4), levator palpebrae superioris, ciliary ganglion (autonomic)
Towering	IV	Trochlear	Eye movements (M)	Trochlear nucleus	Superior oblique muscle
Tops	V	Trigeminal	Sensory/motor—face (B)	Trigeminal nuclei in the midbrain, pons, and medulla	Trigemal
A	VI	Abducens	Eye movements (M)	Abducens nucleus	Lateral rectus muscle
Finn	VII	Facial	Motor—face, Taste (B)	Facial nucleus, solitary nucleus, superior salivatory nucleus	Facial muscles, Geniculate ganglion, Pterygopalatine ganglion (autonomic)
And	VIII	Vestibulocochlear	Hearing/balance (S)	Cochlearn nucleus, Vestibular nucleus/cerebellum	Spiral ganglion (hearing), Vestibular ganglion (balance)
German	IX	Glossopharyngeal	Motor—throat Taste (B)	Solitary nucleus, inferior salivatory nucleus, nucleus ambiguus	Pharyngeal muscles, Geniculate ganglion, Otic ganglion (autonomic)
Viewed	X	Vagus	Motor/sensory—viscera (autonomic)	Medulla	Terminal ganglia serving thoracic and upper abdominal organs (heart and small intestines)
Some	XI	Accessory	Motor—head and neck (M)	Spinal accessory nucleus	Neck muscles
Hops	XII	Hypoglossal	Motor—lower throat (M)	Hypoglossal nucleus	Muscles of the larynx and lower pharynx

Spinal Nerves

The nerves connected to the spinal cord are the spinal nerves. The arrangement of these nerves is much more regular than that of the cranial nerves. All of the spinal nerves are combined sensory and motor axons that separate into two nerve roots. The sensory axons enter the spinal cord as the dorsal nerve root. The motor fibers, both somatic and autonomic, emerge as the ventral nerve root. The dorsal root ganglion for each nerve is an enlargement of the spinal nerve (see **Figure 8.19**).

There are 31 spinal nerves, named for the level of the spinal cord at which each one emerges. There are eight pairs of cervical nerves designated C1 to C8, twelve thoracic nerves designated T1 to T12, five pairs of lumbar nerves designated L1 to L5, five pairs of sacral nerves designated S1 to S5, and one pair of coccygeal nerves. The

nerves are numbered from the superior to inferior positions, and each emerges from the vertebral column through the intervertebral foramen at its level.

Spinal nerves extend outward from the vertebral column to enervate the periphery. The nerves in the periphery are not straight continuations of the spinal nerves, but rather the reorganization of the axons in those nerves to follow different courses. Axons from different spinal nerves will come together into a systemic nerve. This occurs at four places along the length of the vertebral column, each identified as a **nerve plexus**, whereas the other spinal nerves directly correspond to nerves at their respective levels. In this instance, the word plexus is used to describe networks of nerve fibers with no associated cell bodies.

Of the four nerve plexuses, two are found at the cervical level, one at the lumbar level, and one at the sacral level (**Figure 8.23**). The **cervical plexus** is composed of axons from spinal nerves C1 through C5 and branches into nerves in the posterior neck and head, as well as the **phrenic nerve**, which connects to the diaphragm at the base of the thoracic cavity. The other plexus from the cervical level is the **brachial plexus**. Spinal nerves C4 through T1 reorganize through this plexus to give rise to the nerves of the arms, as the name brachial suggests. A large nerve from this plexus is the **radial nerve** from which the **axillary nerve** branches to go to the armpit region. The radial nerve continues through the arm and is paralleled by the **ulnar nerve** and the **median nerve**. The **lumbar plexus** arises from all the lumbar spinal nerves and gives rise to nerves enervating the pelvic region and the anterior leg. The **femoral nerve** is one of the major nerves from this plexus.The **sacral plexus** comes from the lower lumbar nerves L4 and L5 and the sacral nerves S1 to S4. The most significant systemic nerve to come from this plexus is the **sciatic nerve**, which is a combination of the **tibial nerve** and the **fibular nerve**.

These plexuses are described as arising from spinal nerves and giving rise to certain systemic nerves, but they contain fibers that serve sensory functions or fibers that serve motor functions. This means that some fibers extend from cutaneous or other peripheral sensory surfaces and send action potentials into the CNS. Those are axons of sensory neurons in the dorsal root ganglia that enter the spinal cord through the dorsal nerve root. Other fibers are the axons of motor neurons of the anterior horn of the spinal cord, which emerge in the ventral nerve root and send action potentials to cause skeletal muscles to contract in their target regions. For example, the radial nerve contains fibers of cutaneous sensation in the arm, as well as motor fibers that move muscles in the arm.

Spinal nerves of the thoracic region, T2 through T11, are not part of the plexuses but rather emerge and give rise to the **intercostal nerves** found between the ribs, which articulate with the vertebrae surrounding the spinal nerve.
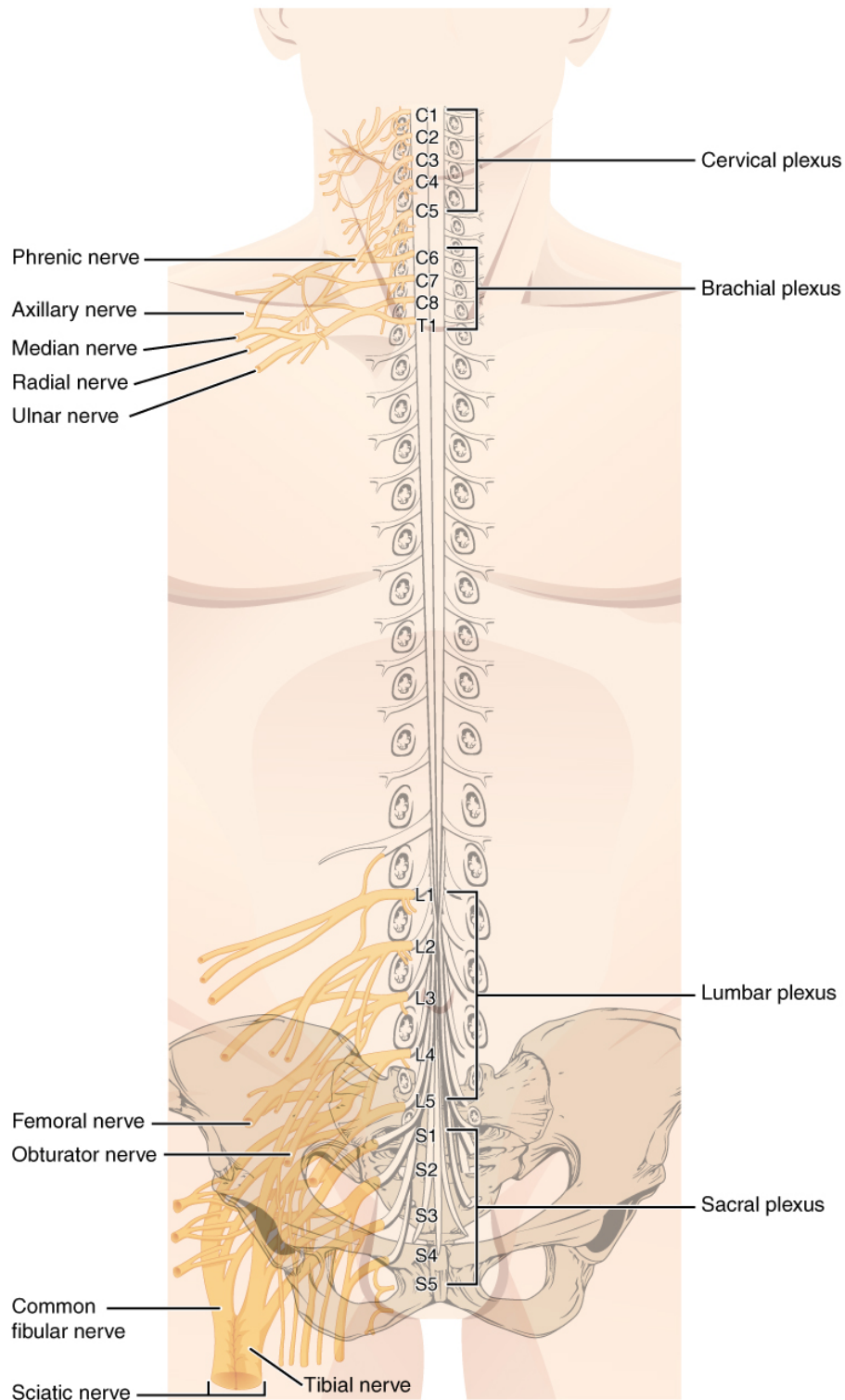
Figure 8.23. Nerve Plexuses of the Body There are four main nerve plexuses in the human body. The cervical plexus supplies nerves to the posterior head and neck, as well as to the diaphragm. The brachial plexus supplies nerves to the arm. The lumbar plexus supplies nerves to the anterior leg. The sacral plexus supplies nerves to the posterior leg.

Lab 9: Nervous system II - Special Senses

Special senses

> ### Learning Objectives
>
> When you are prepared for the **Test on Week 9 Learning Objectives** in Week 10, you will be able to:
>
> - Identify structures of the eye and their functions.
> - Identify layers of the retina.
> - Identify the extrinsic eye muscles, their actions, and innervations.
> - Identify structures of the ear and their functions.
> - Identify structures of the cochlea.

Senses

A major role of sensory receptors is to help us learn about the environment around us, or about the state of our internal environment. Stimuli from varying sources, and of different types, are received and changed into the electrochemical signals of the nervous system. This occurs when a stimulus changes the cell membrane potential of a sensory neuron. The stimulus causes the sensory cell to produce an action potential that is relayed into the central nervous system (CNS), where it is integrated with other sensory information—or sometimes higher cognitive functions—to become a conscious perception of that stimulus. The central integration may then lead to a motor response.

Describing sensory function with the term sensation or perception is a deliberate distinction. Sensation is the activation of sensory receptor cells at the level of the stimulus. Perception is the central processing of sensory stimuli into a meaningful pattern. Perception is dependent on sensation, but not all sensations are perceived. Receptors are the cells or structures that detect sensations.

Sensory Receptors

Stimuli in the environment activate specialized receptor cells in the peripheral nervous system. Different types of stimuli are sensed by different types of receptor cells. One way to categorize sensory receptors is through a functional classification: which type of stimulus the receptor can detect and how it transduces the stimulus into a nervous signal.

Chemoreceptors can detect ions and macromolecules (chemicals), which leads to an interpretation of taste or

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smell. **Nociceptors** detect chemicals from tissue damage or other intense stimuli, which leads to an interpretation of pain. Physical stimuli, such as pressure and vibration, as well as the sensation of sound and body position (balance), are interpreted through a **mechanoreceptor**. Another physical stimulus that has its own type of receptor is temperature, which is sensed through a **thermoreceptor** that is either sensitive to temperatures above (heat) or below (cold) normal body temperature. Other stimuli include the electromagnetic radiation from visible light and are detected by **photoreceptors**. For humans, the only electromagnetic energy that is perceived by our eyes is visible light. Some other organisms have receptors that humans lack, such as the heat sensors of snakes, the ultraviolet light sensors of bees, or magnetic receptors in migratory birds.

Gustation (taste)

Gustation is the special sense associated with the tongue. The surface of the tongue, along with the rest of the oral cavity, is lined by a stratified squamous epithelium. Raised bumps called **papillae** (singular = papilla) contain the structures for gustatory transduction. There are four types of papillae, based on their appearance (**Figure 9.1**): circumvallate, foliate, filiform, and fungiform. Within the structure of the papillae are **taste buds** that contain specialized **gustatory receptor cells** for the transduction of taste stimuli. These receptor cells are sensitive to the chemicals contained within foods that are ingested, and they release neurotransmitters based on the amount of the chemical in the food. Neurotransmitters from the gustatory cells can activate sensory neurons in the facial, glossopharyngeal, and vagus cranial nerves.
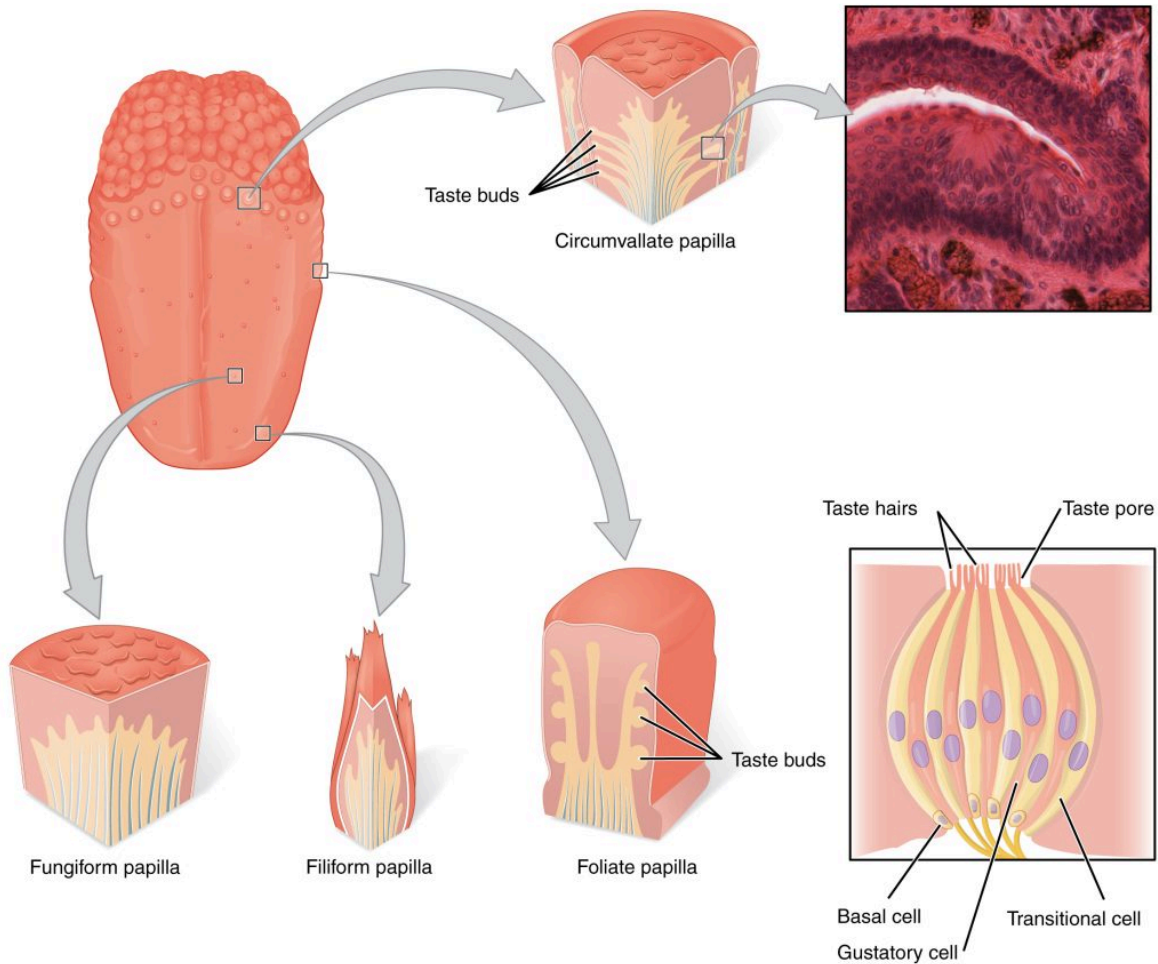
Figure 9.1 The Tongue The tongue is covered with small bumps, called papillae, which contain taste buds that are sensitive to chemicals in ingested food or drink. Different types of papillae are found in different regions of the tongue. The taste buds contain specialized gustatory receptor cells that respond to chemical stimuli dissolved in the saliva. These receptor cells activate sensory neurons that are part of the facial and glossopharyngeal nerves. LM × 1600. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Only a few recognized submodalities exist within the sense of taste, or **gustation**. Until recently, only four tastes were recognized: sweet, salty, sour, and bitter. Research at the turn of the 20th century led to recognition of the fifth taste, umami, during the mid-1980s. **Umami** is a Japanese word that means "delicious taste," and is often translated to mean savory. Very recent research has suggested that there may also be a sixth taste for fats, or lipids.

Olfaction (Smell)

Like taste, the sense of smell, or **olfaction**, is also responsive to chemical stimuli. The olfactory receptor neurons are located in a small region within the superior nasal cavity (**Figure 9.2**). This region is referred to as the **olfactory epithelium** and contains bipolar sensory neurons. Each **olfactory sensory neuron** has dendrites that extend from the apical surface of the epithelium into the mucus lining the cavity. As airborne molecules are inhaled through the

nose, they pass over the olfactory epithelial region and dissolve into the mucus. These **odorant molecules** bind to proteins that keep them dissolved in the mucus and help transport them to the olfactory dendrites.
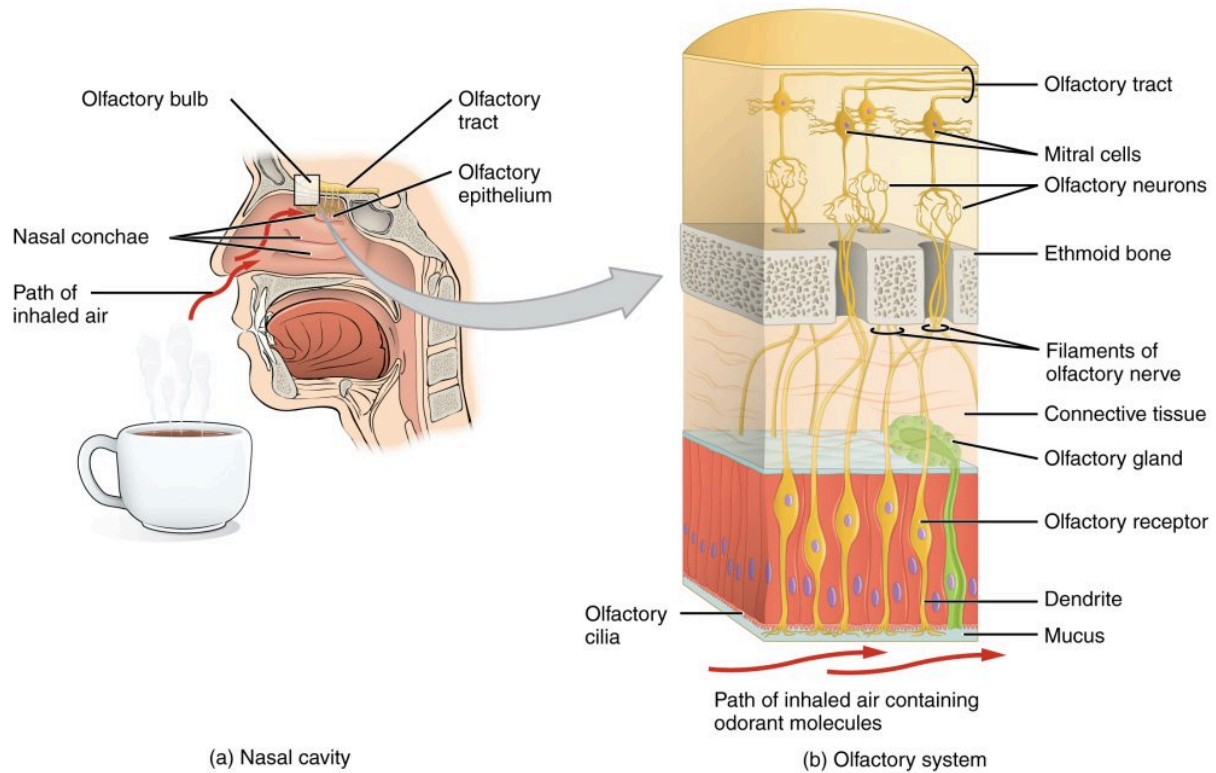
(a) Nasal cavity

(b) Olfactory system
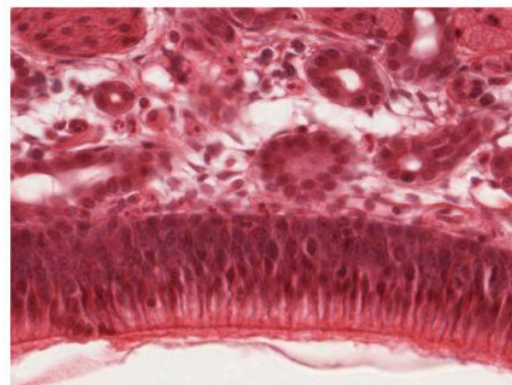
(c) Olfactory epithelium

Figure 9.2 The Olfactory System (a) The olfactory system begins in the peripheral structures of the nasal cavity. (b) The olfactory receptor neurons are within the olfactory epithelium. (c) Axons of the olfactory receptor neurons project through the cribriform plate of the ethmoid bone and synapse with the neurons of the olfactory bulb (tissue source: simian). LM × 812. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The axon of an olfactory neuron extends from the basal surface of the epithelium, through an olfactory foramen in the cribriform plate of the ethmoid bone, and into the brain. The group of axons called the olfactory tract connect to the **olfactory bulb** on the ventral surface of the frontal lobe. From there, the axons split to travel to several brain regions. Some travel to the cerebrum, specifically to the primary olfactory cortex that is located in the inferior

and medial areas of the temporal lobe. Others project to structures within the limbic system and hypothalamus, where smells become associated with long-term memory and emotional responses. This is how certain smells trigger emotional memories, such as the smell of food associated with one's birthplace. Smell is the one sensory modality that does not synapse in the thalamus before connecting to the cerebral cortex. This intimate connection between the olfactory system and the cerebral cortex is one reason why smell can be a potent trigger of memories and emotion.

Audition (Hearing)

Hearing, or **audition**, is the transduction of sound waves into a neural signal that is made possible by the structures of the ear (**Figure 9.3**). The large, fleshy structure on the lateral aspect of the head is known as the **auricle**. Some sources will also refer to this structure as the pinna, though that term is more appropriate for a structure that can be moved, such as the external ear of a cat. The C-shaped curves of the auricle direct sound waves toward the auditory canal. The canal enters the skull through the external auditory meatus of the temporal bone. At the end of the auditory canal is the **tympanic membrane**, or ear drum, which vibrates after it is struck by sound waves. The auricle, ear canal, and tympanic membrane are often referred to as the **external ear**. The **middle ear** consists of a space spanned by three small bones called the **ossicles**. The three ossicles are the **malleus**, **incus**, and **stapes**, which are Latin names that roughly translate to hammer, anvil, and stirrup. The malleus is attached to the tympanic membrane and articulates with the incus. The incus, in turn, articulates with the stapes. The stapes is then attached to the **inner ear**, where the sound waves will be transduced into a neural signal. The middle ear is connected to the pharynx through the Eustachian tube, which helps equilibrate air pressure across the tympanic membrane. The tube is normally closed but will pop open when the muscles of the pharynx contract during swallowing or yawning.
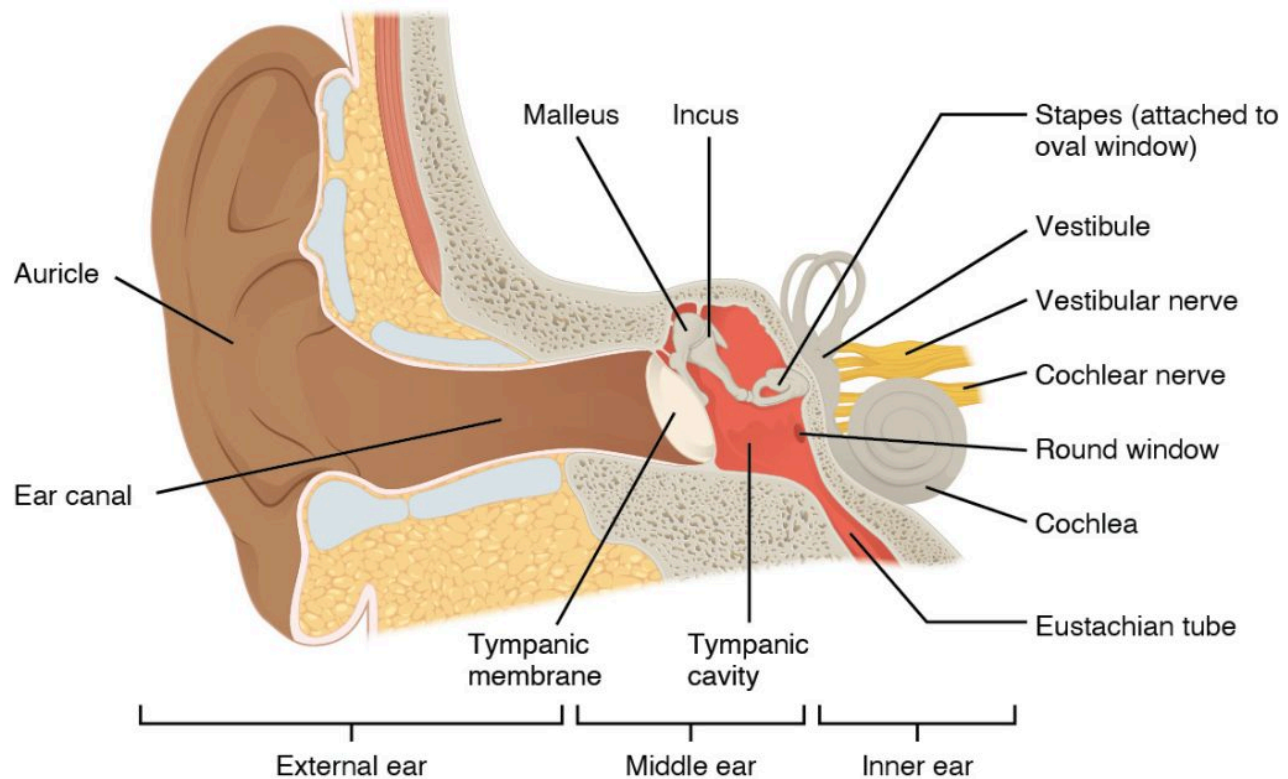
Figure 9.3 Structures of the Ear The external ear contains the auricle, ear canal, and tympanic membrane. The middle ear contains the ossicles and is connected to the pharynx by the Eustachian tube. The inner ear contains the cochlea and vestibule, which are responsible for audition and equilibrium, respectively.

The inner ear is often described as a bony labyrinth, as it is composed of a series of canals embedded within the temporal bone. It has two separate regions, the **cochlea** and the **vestibule**, which are responsible for hearing and balance, respectively. The neural signals from these two regions are relayed to the brain stem through separate fiber bundles. However, these two distinct bundles travel together from the inner ear to the brain stem as the vestibulocochlear nerve. Sound is transduced into neural signals within the cochlear region of the inner ear, which contains the sensory neurons of the spiral ganglia. These ganglia are located within the spiral-shaped cochlea of the inner ear. The cochlea is attached to the stapes through the **oval window**.

The oval window is located at the beginning of a fluid-filled tube within the cochlea called the **scala vestibuli**. The scala vestibuli extends from the oval window, travelling above the **cochlear duct**, which is the central cavity of the cochlea that contains the sound-transducing neurons. At the uppermost tip of the cochlea, the scala vestibuli curves over the top of the cochlear duct. The fluid-filled tube, now called the **scala tympani**, returns to the base of the cochlea, this time travelling under the cochlear duct. The scala tympani ends at the **round window**, which is covered by a membrane that contains the fluid within the scala. As vibrations of the ossicles travel through the oval window, the fluid of the scala vestibuli and scala tympani moves in a wave-like motion. The frequency of the fluid waves match the frequencies of the sound waves (**Figure 9.4**). The membrane covering the round window will bulge out or pucker in with the movement of the fluid within the scala tympani.
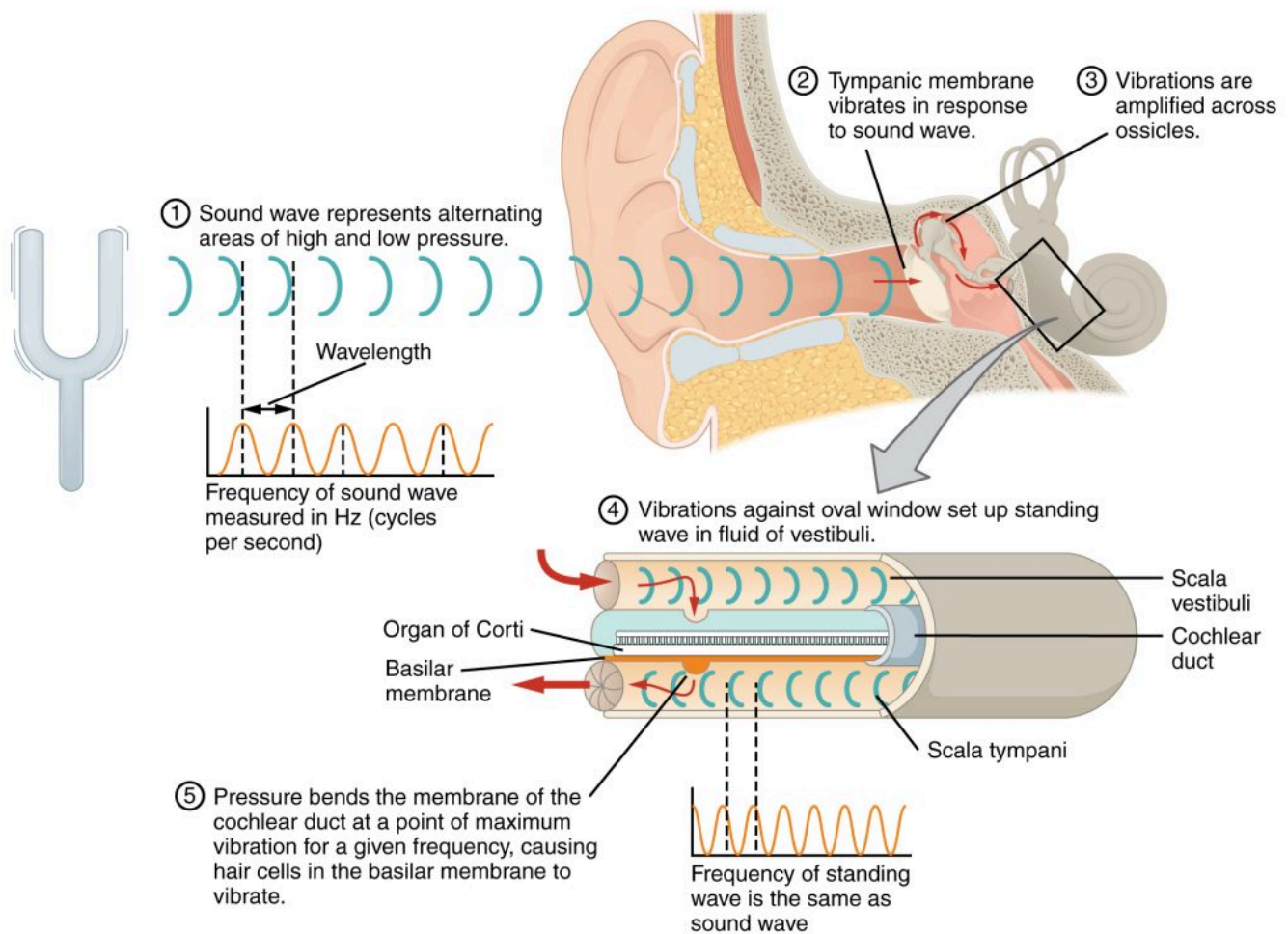
Figure 9.4 Transmission of Sound Waves to Cochlea A sound wave causes the tympanic membrane to vibrate. This vibration is amplified as it moves across the malleus, incus, and stapes. The amplified vibration is picked up by the oval window causing pressure waves in the fluid of the scala vestibuli and scala tympani. The complexity of the pressure waves is determined by the changes in amplitude and frequency of the sound waves entering the ear.

A cross-sectional view of the cochlea shows that the scala vestibuli and scala tympani run along both sides of the cochlear duct (**Figure 9.5**). The cochlear duct contains several **organs of Corti**, which transduce the wave motion of the two scala into neural signals. The organs of Corti lie on top of the **basilar membrane**, which is the side of the cochlear duct located between the organs of Corti and the scala tympani. As the fluid waves move through the scala vestibuli and scala tympani, the basilar membrane moves at a specific spot, depending on the frequency of the waves. Higher frequency waves move the region of the basilar membrane that is close to the base of the cochlea. Lower frequency waves move the region of the basilar membrane that is near the tip of the cochlea.
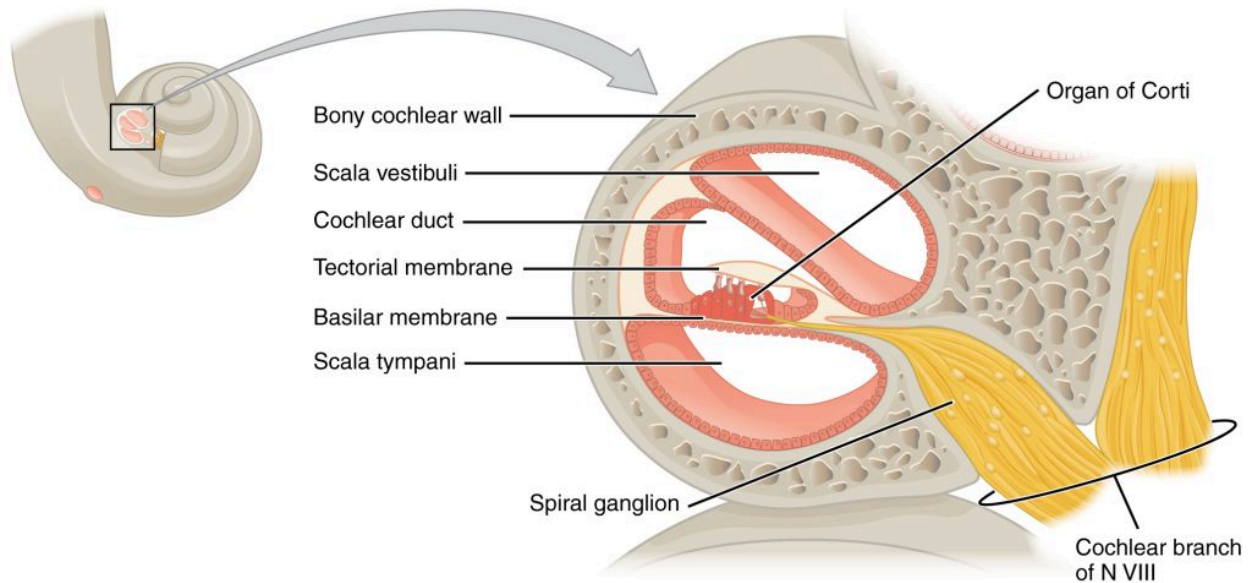
Figure 9.5 Cross Section of the Cochlea The three major spaces within the cochlea are highlighted. The scala tympani and scala vestibuli lie on either side of the cochlear duct. The organ of Corti, containing the mechanoreceptor hair cells, is adjacent to the scala tympani, where it sits atop the basilar membrane.

The organs of Corti contain **hair cells**, which are named for the hair-like **stereocilia** extending from the cell's apical surfaces (**Figure 9.6**). The stereocilia are an array of microvilli-like structures arranged from tallest to shortest. Protein fibers tether adjacent hairs together within each array, such that the array will bend in response to movements of the basilar membrane. The stereocilia extend up from the hair cells to the overlying **tectorial membrane**, which is attached medially to the **organ of Corti** (**Figure 9.7**). When the pressure waves from the scala move the basilar membrane, the tectorial membrane slides across the stereocilia. This bends the stereocilia either toward or away from the tallest member of each array. When the stereocilia bend toward the tallest member of their array, tension in the protein tethers opens ion channels in the hair cell membrane. This will depolarize the hair cell membrane, triggering nerve impulses that travel down the afferent nerve fibers attached to the hair cells.
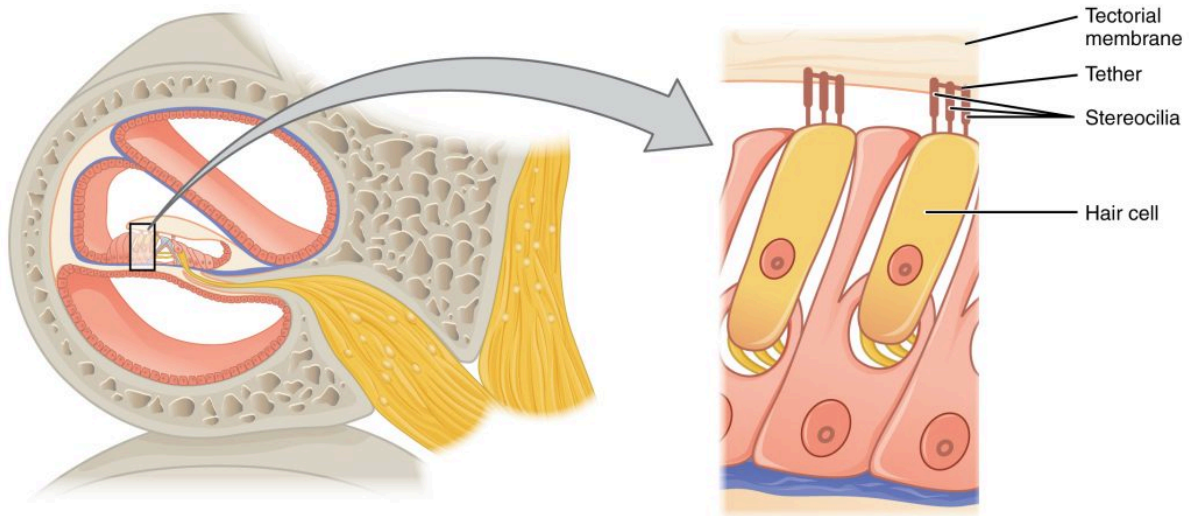
Figure 9.6 Hair Cell The hair cell is a mechanoreceptor with an array of stereocilia emerging from its apical surface. The stereocilia are tethered together by proteins that open ion channels when the array is bent toward the tallest member of their array, and closed when the array is bent toward the shortest member of their array.
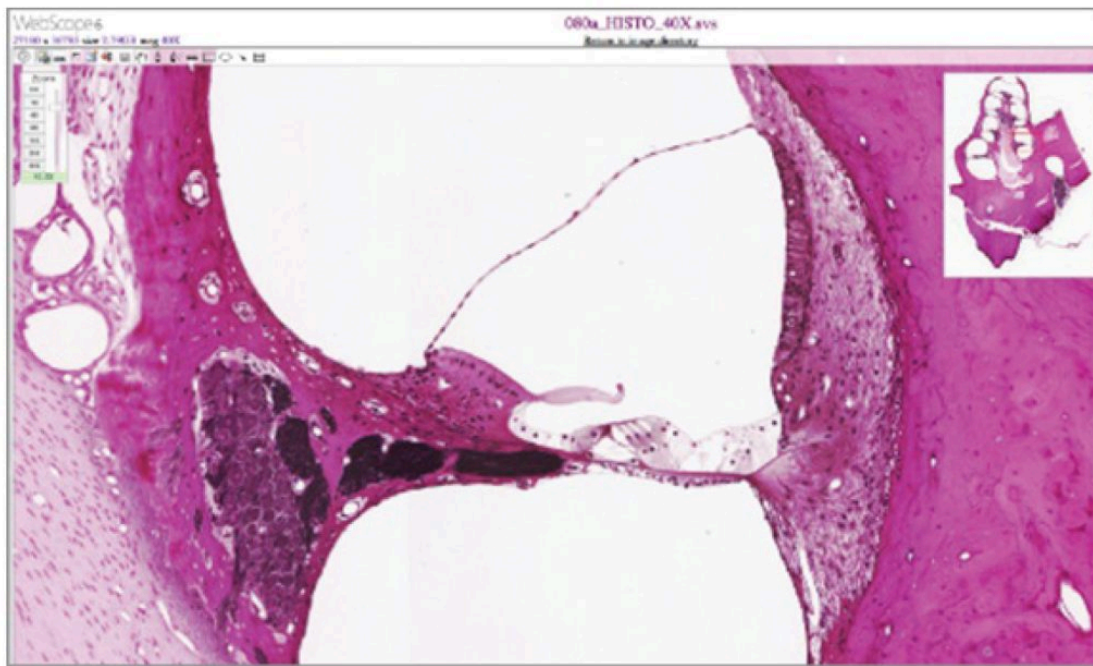
Figure 9.7 Cochlea and Organ of Corti LM × 412. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Equilibrium (Balance)

Along with audition, the inner ear is responsible for encoding information about **equilibrium**, the sense of balance.

A similar mechanoreceptor—a hair cell with stereocilia—senses head position, head movement, and whether our bodies are in motion. These cells are located within the vestibule of the inner ear. Head position is sensed by the **utricle** and **saccule**, whereas head movement is sensed by the **semicircular canals**. The neural signals generated in the vestibular ganglion are transmitted through the vestibulocochlear nerve to the brain stem and cerebellum.

Vision

Vision is the special sense of sight that is based on the transduction of light stimuli received through the eyes. The eyes are located within either orbit in the skull. The bony orbits surround the eyeballs, protecting them and anchoring the soft tissues of the eye (**Figure 9.8**). The eyelids, with lashes at their leading edges, help to protect the eye from abrasions by blocking particles that may land on the surface of the eye. The inner surface of each lid is a thin membrane known as the **palpebral conjunctiva**. The conjunctiva extends over the white areas of the eye (the sclera), connecting the eyelids to the eyeball. Tears are produced by the **lacrimal gland**, located just inside the orbit, superior and lateral to the eyeball. Tears produced by this gland flow through the **lacrimal duct** to the medial corner of the eye, where the tears flow over the conjunctiva, washing away foreign particles.
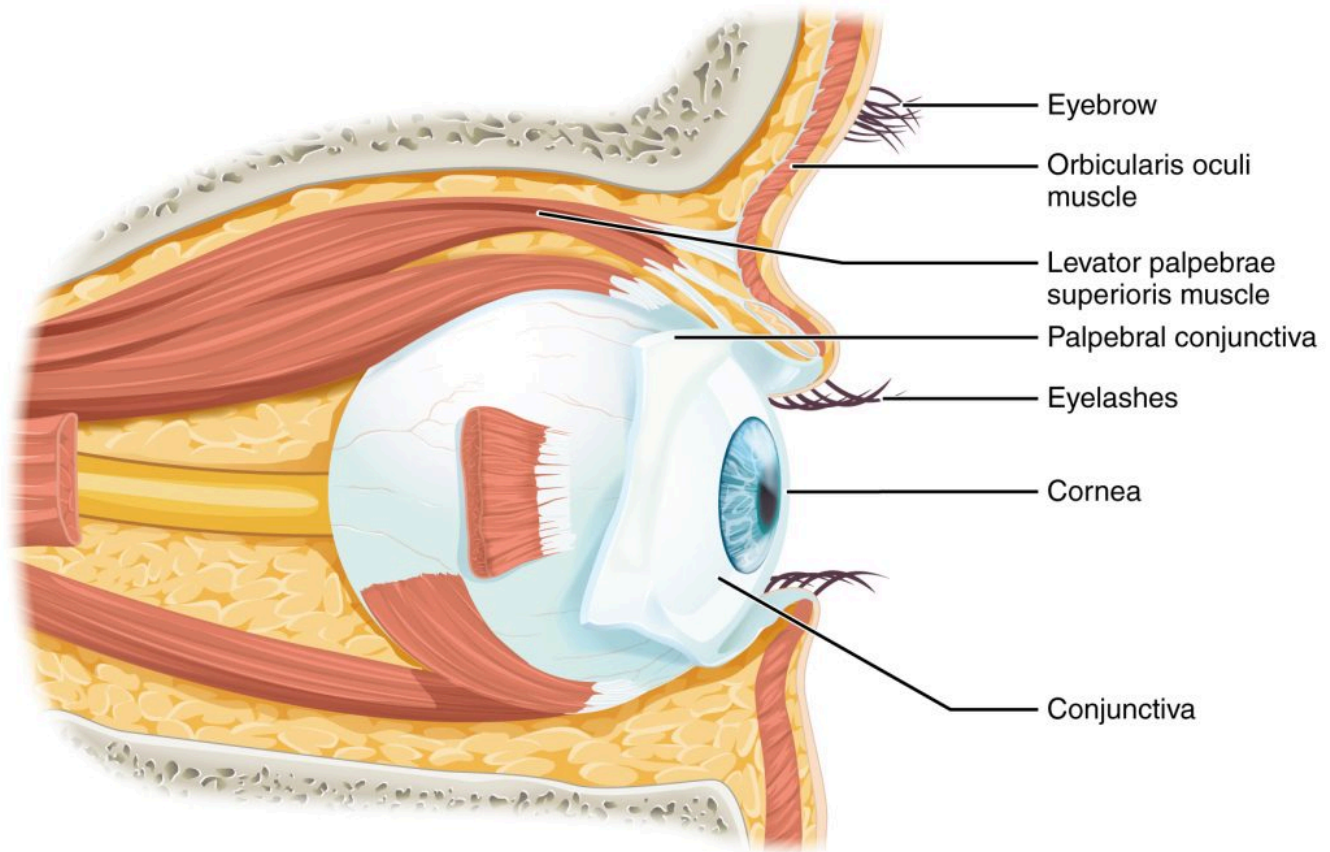
Figure 9.8 The Eye in the Orbit The eye is located within the orbit and surrounded by soft tissues that protect and support its function. The orbit is surrounded by cranial bones of the skull.

Movement of the eye within the orbit is accomplished by the contraction of six **extraocular muscles** that originate from the bones of the orbit and insert into the surface of the eyeball (**Figure 9.9**). Four of the muscles are arranged

at the cardinal points around the eye and are named for those locations. They are the **superior rectus**, **medial rectus**, **inferior rectus**, and **lateral rectus**. When each of these muscles contract, the eye moves toward the contracting muscle. For example, when the superior rectus contracts, the eye rotates to look up. The **superior oblique** originates at the posterior orbit, near the origin of the four rectus muscles. However, the tendon of the oblique muscles threads through a pulley-like piece of cartilage known as the **trochlea**. The tendon inserts obliquely into the superior surface of the eye. The angle of the tendon through the trochlea means that contraction of the superior oblique rotates the eye laterally. The **inferior oblique** muscle originates from the floor of the orbit and inserts into the inferolateral surface of the eye. When it contracts, it laterally rotates the eye, in opposition to the superior oblique. Rotation of the eye by the two oblique muscles is necessary because the eye is not perfectly aligned on the sagittal plane. When the eye looks up or down, the eye must also rotate slightly to compensate for the superior rectus pulling at approximately a 20-degree angle, rather than straight up. The same is true for the inferior rectus, which is compensated by contraction of the inferior oblique. A seventh muscle in the orbit is the **levator palpebrae superioris**, which is responsible for elevating and retracting the upper eyelid, a movement that usually occurs in concert with elevation of the eye by the superior rectus (see Figure 14.13).
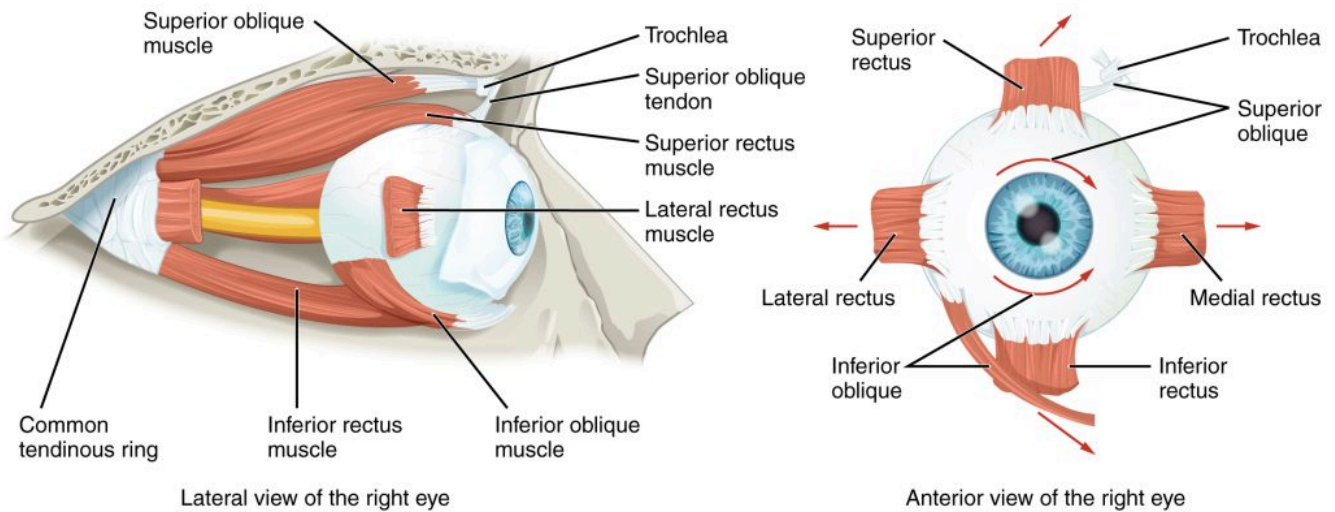
Figure 9.9 Extraocular Muscles The extraocular muscles move the eye within the orbit.

The extraocular muscles are innervated by three cranial nerves. The lateral rectus, which causes abduction of the eye, is innervated by the abducens nerve. The superior oblique is innervated by the trochlear nerve. All of the other muscles are innervated by the oculomotor nerve, as is the levator palpebrae superioris. The motor nuclei of these cranial nerves connect to the brain stem, which coordinates eye movements.

The eye itself is a hollow sphere composed of three layers of tissue. The outermost layer is the **fibrous tunic**, which includes the white **sclera** and clear **cornea (Figure 9.10)**. The sclera accounts for five sixths of the surface of the eye, most of which is not visible, though humans are unique compared with many other species in having so much of the "white of the eye" visible. The transparent cornea covers the anterior tip of the eye and allows light to enter the eye. The middle layer of the eye is the **vascular tunic**, which is mostly composed of the choroid, ciliary body, and iris. The **choroid** is a layer of highly vascularized connective tissue that provides a blood supply to the eyeball. The choroid is posterior to the **ciliary body**, a muscular structure that is attached to the **lens** by suspensory ligaments, or **zonule fibers**. These two structures bend the lens, allowing it to focus light on the back of the eye. Overlaying the ciliary body, and visible in the anterior eye, is the **iris**—the colored part of the eye. The iris is a smooth muscle that opens or closes the **pupil**, which is the hole at the center of the eye that allows light

to enter. The iris constricts the pupil in response to bright light and dilates the pupil in response to dim light. The innermost layer of the eye is the **neural tunic**, or **retina**, which contains the nervous tissue responsible for photoreception.

The eye is also divided into two cavities: the anterior cavity and the posterior cavity. The anterior cavity is the space between the cornea and lens, including the iris and ciliary body. It is filled with a watery fluid called the **aqueous humor**. The posterior cavity is the space behind the lens that extends to the posterior side of the interior eyeball, where the retina is located. The posterior cavity is filled with a more viscous fluid called the **vitreous humor**.

The retina is composed of several layers and contains specialized cells for the initial processing of visual stimuli. The photoreceptors (rods and cones) change their membrane potential when stimulated by light energy. The change in membrane potential alters the amount of neurotransmitter that the photoreceptor cells release onto **bipolar cells** in the **outer synaptic layer**. It is the bipolar cell in the retina that connects a photoreceptor to a **retinal ganglion cell (RGC)** in the **inner synaptic layer**. There, **amacrine cells** additionally contribute to retinal processing before an action potential is produced by the RGC. The axons of RGCs, which lie at the innermost layer of the retina, collect at the **optic disc** and leave the eye as the **optic nerve** (see Figure 9.10). Because these axons pass through the retina, there are no photoreceptors at the very back of the eye, where the optic nerve begins. This creates a "blind spot" in the retina, and a corresponding blind spot in our visual field.
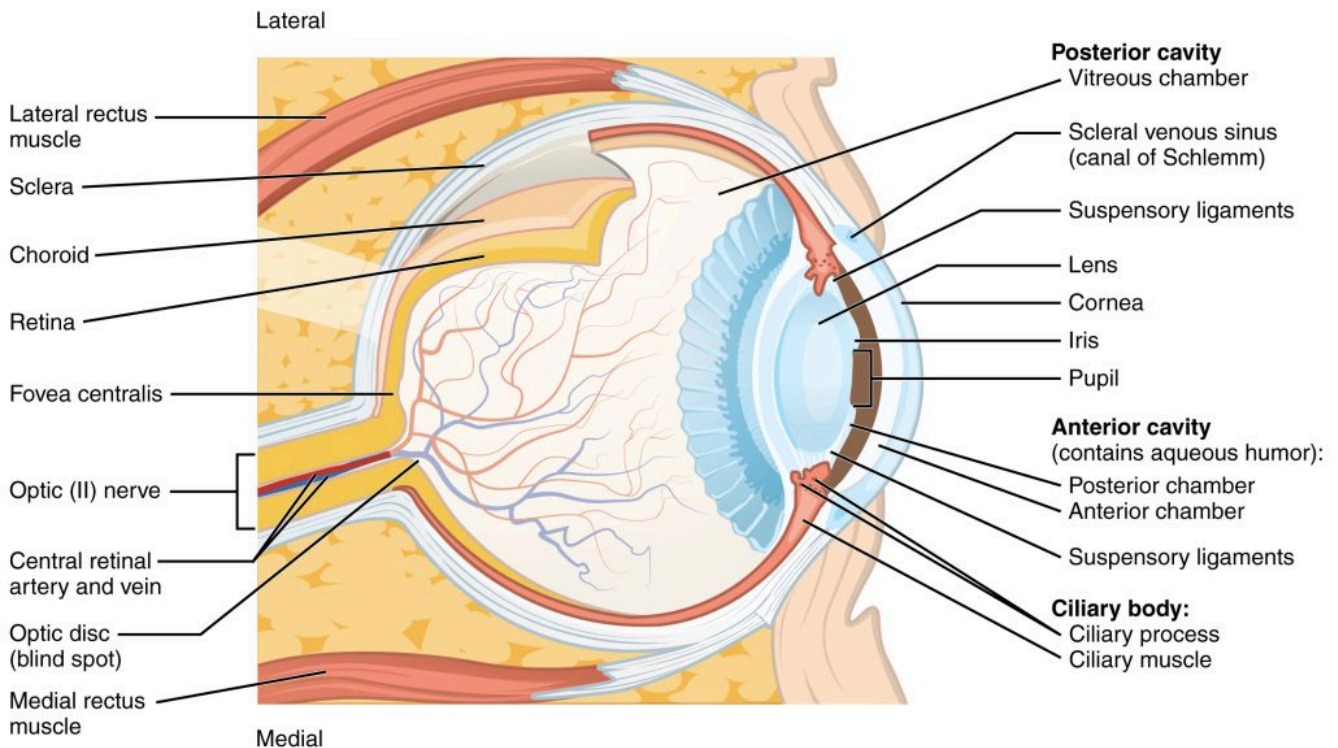
Figure 9.10 Structure of the Eye The sphere of the eye can be divided into anterior and posterior chambers. The wall of the eye is composed of three layers: the fibrous tunic, vascular tunic, and neural tunic. Within the neural tunic is the retina, with three layers of cells and two synaptic layers in between. The center of the retina has a small indentation known as the fovea.

Note that the photoreceptors in the retina (rods and cones) are located behind the axons, RGCs, bipolar cells,

and retinal blood vessels (**Figure 9.11**). A significant amount of light is absorbed by these structures before the light reaches the photoreceptor cells. However, at the exact center of the retina is a small area known as the **fovea**. At the fovea, the retina lacks the supporting cells and blood vessels, and only contains photoreceptors. Therefore, **visual acuity**, or the sharpness of vision, is greatest at the fovea. This is because the fovea is where the least amount of incoming light is absorbed by other retinal structures (see Figure 9.10). As one moves in either direction from this central point of the retina, visual acuity drops significantly. The difference in visual acuity between the fovea and peripheral retina is easily evidenced by looking directly at a word in the middle of this paragraph. The visual stimulus in the middle of the field of view falls on the fovea and is in the sharpest focus. Without moving your eyes off that word, notice that words at the beginning or end of the paragraph are not in focus. The images in your peripheral vision are focused by the peripheral retina, and have vague, blurry edges and words that are not as clearly identified. As a result, a large part of the neural function of the eyes is concerned with moving the eyes and head so that important visual stimuli are centered on the fovea.
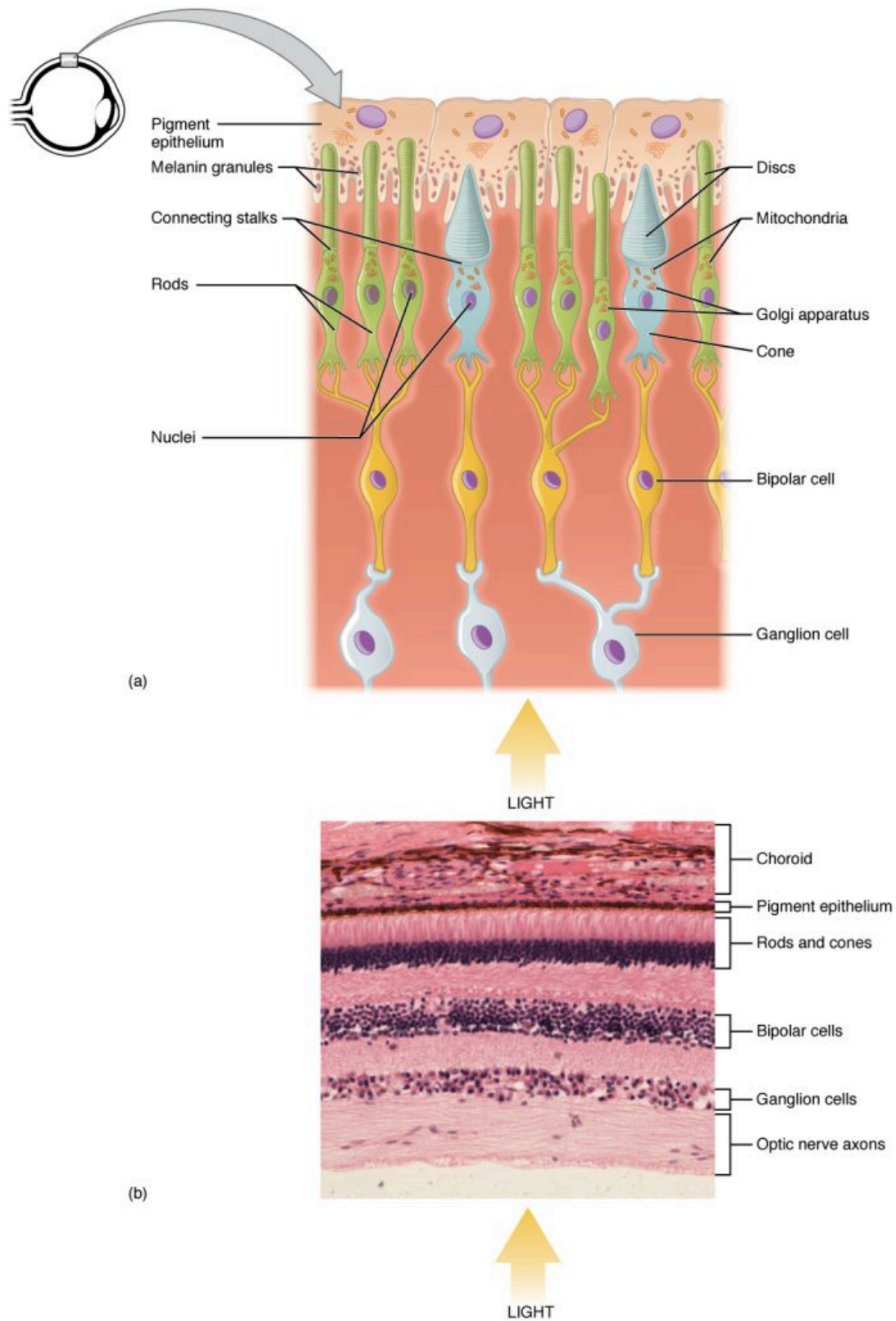
Figure 9.11 Photoreceptor (a) All photoreceptors have inner segments containing the nucleus and other important organelles and outer segments with membrane arrays containing the photosensitive opsin molecules. Rod outer segments are long columnar shapes with stacks of

membrane-bound discs that contain the rhodopsin pigment. Cone outer segments are short, tapered shapes with folds of membrane in place of the discs in the rods. (b) Tissue of the retina shows a dense layer of nuclei of the rods and cones. LM × 800. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Lab 10: Cardiovascular System I - Blood and the Heart

Blood tissue and the Heart

Blood

Blood is a connective tissue made up of cellular elements and an extracellular matrix. The cellular elements are referred to as the **formed elements and** include **red blood cells (RBCs)**, **white blood cells (WBCs)**, and **platelets**. The extracellular matrix, called **plasma**, makes blood unique among connective tissues because it is fluid. This fluid, which is mostly water, perpetually suspends the formed elements and enables them to circulate throughout the body within the cardiovascular system.In the laboratory, blood samples are often centrifuged in order to separate the components of blood from one another (**Figure 10.1**). Erythrocytes are the heaviest elements in blood and settle at the very bottom of the tube. Above the erythrocyte layer we see the **buffy coat**, a pale, thin layer of leukocytes and platelets, which together make up less than 1% of the sample of whole blood. Above the buffy coat is the blood plasma, normally a pale, straw-colored fluid, which constitutes the remainder of the sample.

Plasma:
- Water, proteins, nutrients, hormones, etc.

Buffy coat:
- White blood cells, platelets

Hematocrit:
- Red blood cells

Normal Blood:
♀ 37%–47% hematocrit
♂ 42%–52% hematocrit

Anemia:
Depressed
hematocrit %

Polycythemia:
Elevated
hematocrit %
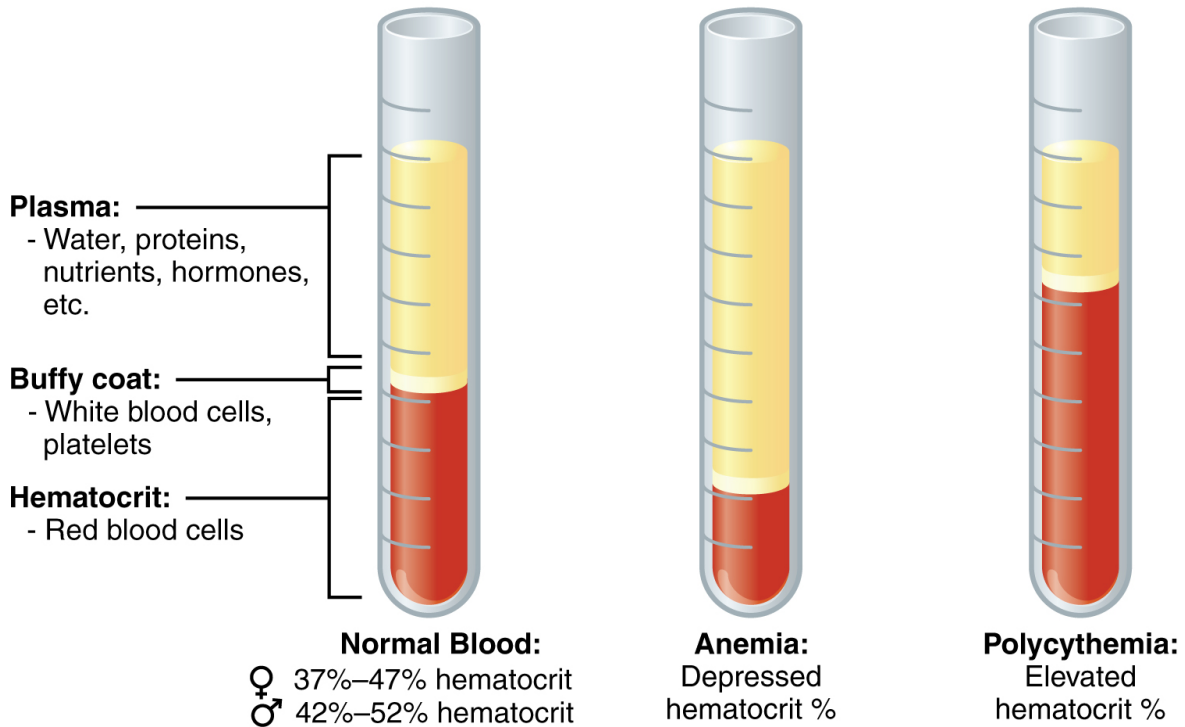
Figure 10.1 Composition of Blood. The cellular elements of blood include a vast number of erythrocytes and comparatively fewer leukocytes and platelets. Plasma is the fluid in which the formed elements are suspended. A sample of blood spun in a centrifuge reveals that plasma is the lightest component. It floats at the top of the tube separated from the heaviest elements, the erythrocytes, by a buffy coat of leukocytes and platelets. Hematocrit is the percentage of the total sample that is comprised of erythrocytes. Depressed and elevated hematocrit levels are shown for comparison.

In normal blood, about 45 percent of a sample is erythrocytes, which is referred to as the hematocrit. The hematocrit of any one sample can vary significantly, however, about 36–50 percent, according to gender and other factors. Not counting the buffy coat, which makes up less than 1% of the blood, we can estimate the mean plasma percentage to be the percent of blood that is not erythrocytes: approximately 55% (**Table 10.1**).

Table 10.1 Major Blood Components. This table displays the components of blood and their associated functions.

COMPONENT AND % OF BLOOD	SUBCOMPONENT AND % OF COMPONENT	TYPE AND % (WHERE APPROPRIATE)	SITE OF PRODUCTION	MAJOR FUNCTION(S)
Plasma **46 – 63% of blood**	Water; 92% of plasma	Fluid	Absorbed by intestinal tract or produced by metabolism	Transport medium
	Plasma proteins; 7% of plasma	Albumin; 54 – 60% of plasma proteins	Liver	Maintain osmotic concentration, transport lipid molecules
		Globulins; 35 – 38% of plasma proteins	Alpha globulins – liver	Transport, maintain osmotic concentration
			Beta globulins – liver	Transport, maintain osmotic concentration
			Gamma globulins (immunoglobulins) – plasma cells	Immune responses
		Fibrinogen 4 – 7 percent	Liver	Blood clotting in hemostasis
	Regulatory proteins; <1% of plasma	Hormones and enzymes	Various sources	Regulate various body functions
	Other solutes; 1% of plasma	Nutrients, gases, and wastes	Absorbed by intestinal tract, exchanged in respiratory system, or produced by cells	Numerous and varied
Formed elements **37 – 54% of blood**	**Erythrocytes**; 99% of formed elements	**Erythrocytes**	Red bone marrow	Transport gases, primarily oxygen and some carbon dioxide
	Leukocytes; <1% of formed elements	Granular Leukocytes: **neutrophils eosinophils basophils**	Red bone marrow	Nonspecific immunity
		Agranular leukocytes: **lymphocytes monocytes**	Lymphocytes: bone marrow and lymphatic tissue	Lymphocytes: specific immunity
			Monocytes: red bone marrow	Monocytes: nonspecific immunity
	Platelets; <1% of formed elements	n/a	Megakaryocytes: Red Bone Marrow	Hemostasis

Functions of Blood

Although carrying oxygen and nutrients to cells and removing wastes from cells is the main function of blood, it is important to realize that blood also serves in defense, distribution of heat, and maintenance of homeostasis.

Transportation

- Nutrients from the foods you eat are absorbed in the digestive tract. Most of these travel in the bloodstream directly to the liver, where they are processed and released back into the bloodstream for delivery to body cells.
- Oxygen from the air you breathe diffuses into the blood, which moves from the lungs to the heart, which then pumps it out to the rest of the body.
- Endocrine glands scattered throughout the body release their products, called hormones, into the bloodstream, which carries them to distant target cells.
- Blood also picks up cellular wastes and byproducts, and transports them to various organs for removal. For instance, blood moves carbon dioxide to the lungs for exhalation from the body, and various waste products are transported to the kidneys and liver for excretion from the body in the form of urine or bile.

Defense

- Leukocytes protect the organism from disease-causing bacteria, cells with mutated DNA that could multiply to become cancerous, or body cells infected with viruses.
- When damage to the vessels results in bleeding, blood platelets and certain proteins dissolved in the plasma, interact to block the ruptured areas of the blood vessels involved. This protects the body from further blood loss.

Homeostasis

- If you were exercising on a warm day, your rising core body temperature would trigger several homeostatic mechanisms, including increased transport of blood from your core to your body periphery, which is typically cooler. As blood passes through the vessels of the skin, heat would be dissipated to the environment, and the blood returning to your body core would be cooler. In contrast, on a cold day, blood is diverted away from the skin to maintain a warmer body core. In extreme cases, this may result in frostbite.
- Blood helps to regulate the water content of body cells.
- Blood also helps to maintain the chemical balance of the body. Proteins and other compounds in blood act as buffers, which thereby help to regulate the pH of body tissues. The pH of blood ranges from 7.35 to 7.45.

Components of Blood
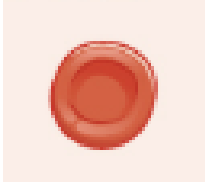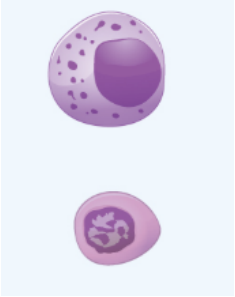
Blood Plasma

Like other fluids in the body, plasma is composed primarily of water. In fact, it is about 92% water. Dissolved or suspended within this water is a mixture of substances, most of which are proteins. The major components of plasma and their functions are summarized in the table above.

Formed Elements

The formed elements of blood include red blood cells (RBCs), white blood cells (WBCs), and platelets. **Table 10.2** summarizes the main facts about the formed elements in blood.

Table 10.2 Summary of Formed Elements in Blood.

FORMED ELEMENT	NUMBER PRESENT PER MICROLITER (µL) AND MEAN (RANGE)	APPEARANCE IN A STANDARD BLOOD SMEAR	SUMMARY OF FUNCTIONS	COMMENTS
Erythrocytes (red blood cells) Red Blood Cell	5.2 million (4.4-5.0 million)	Flattened biconcave disk; no nucleus; pale red colour	Transport oxygen and some carbon dioxide between tissues and lungs	Lifespan of approximately 120 days
Leukocytes (white blood cells) 	7000 (5000 – 10,000)	Obvious dark-staining nucleus	All function in body defenses	Exit capillaries and move into tissues; lifespan of usually a few hours or days
Platelets Platelete Cells	350,000 (150,000 – 500,000)	Cellular fragments surrounded by a plasma membrane and containing granules; purple stain	Hemostasis plus release growth factors for repair and healing of tissue	Formed from megakaryocytes that remain in the red bone marrow and shed platelets into circulation

Erythrocytes

The most abundant formed elements in blood, **erythrocytes,** are basically sacs packed with an oxygen-carrying compound called **hemoglobin**. They are flattened, biconcave discs and relatively small, which allows them to travel through small-diameter capillaries. The primary functions of erythrocytes are to pick up inhaled oxygen from the lungs and transport it to the body's tissues. At maturity, erythrocytes lose their nucleus and most of their organelles, which means there is more interior space for the presence of the hemoglobin molecules that transport gases. The biconcave shape also provides a greater surface area across which gas exchange can occur, relative to its volume; a sphere of a similar diameter would have a lower surface area-to-volume ratio (**Figure 10.2**).

Production of erythrocytes in the red bone marrow occurs at the staggering rate of more than 2 million cells per second. For this production to occur, raw materials including iron, copper, zinc, B-vitamins, glucose, lipids, and amino acids must be present in adequate amounts. Erythrocytes live only 120 days on average, and thus must be continually replaced. Worn-out erythrocytes are phagocytized by macrophages and their hemoglobin is broken down. The breakdown products are recycled or removed as wastes.
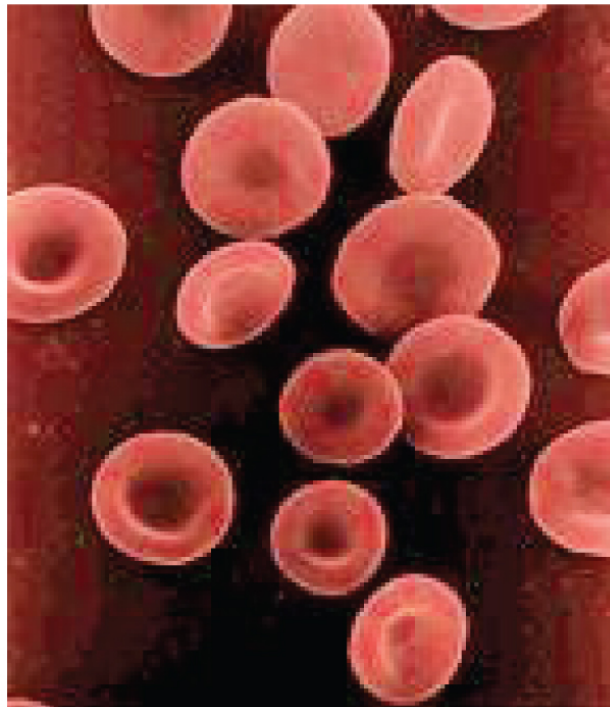
Figure 10.2 Shape of Red Blood Cells. Erythrocytes are biconcave discs with very shallow centers. This shape optimizes the ratio of surface area to volume, facilitating gas exchange. It also enables them to fold up as they move through narrow blood vessels.

Changes in the levels of RBCs can have significant effects on the body's ability to effectively deliver oxygen to the tissues. The size, shape, and number of erythrocytes, and the number of hemoglobin molecules can have a major impact on a person's health. When the number of RBCs or hemoglobin is deficient, the general condition is called **anemia**. There are more than 400 types of anemia.

Anemia can be broken down into three major groups: those caused by blood loss, those caused by excessive destruction of RBCs, and those caused by faulty or decreased RBC production. Of those types of anemia caused by faulty or decreased RBC production, the most common type is **iron deficiency anemia**, which results when the amount of available iron is insufficient to allow production of sufficient hemoglobin. Another dietary deficiency that can lead to various types of anemia is insufficient vitamin B12 and/or folate. Faulty RBC production can be caused by **sickle cell anemia**, a genetic disorder involving the production of an abnormal type of hemoglobin which delivers less oxygen to tissues and causes erythrocytes to assume a sickle (or crescent) shape (**Figure 10.3**).
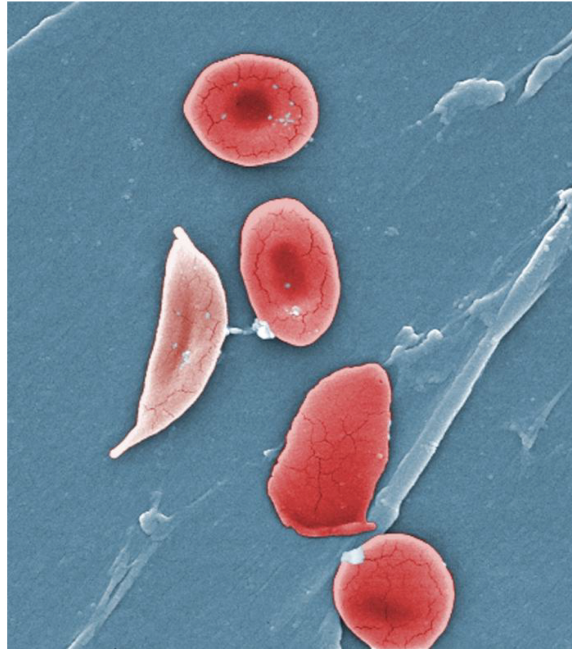
Figure 10.3 Sickle Cells. (credit: Janice Haney Carr).

In addition to these causes, various disease processes also can lead to anemias. These include chronic kidney diseases often associated with a decreased production of EPO (a hormone that signals RBC production), hypothyroidism, some forms of cancer, lupus, and rheumatoid arthritis.

Polycythemia is an elevated RBC count. It can occur transiently in a person who is dehydrated; when water intake is inadequate or water losses are excessive, the plasma volume falls. As a result, the hematocrit rises. A mild form of polycythemia is chronic but normal in people living at high altitudes. Some elite athletes train at high elevations specifically to induce this phenomenon. Finally, a type of bone marrow disease called polycythemia vera causes an excessive production of immature erythrocytes. Polycythemia vera can dangerously elevate the viscosity of blood, raising blood pressure and making it more difficult for the heart to pump blood throughout the body. It is a relatively rare disease that occurs more often in men than women, and is more likely to be present in elderly patients those over 60 years of age.

Leukocytes

The **leukocyte**, commonly known as a white blood cell (or WBC), is a major component of the body's defenses against disease. Leukocytes protect the body against invading microorganisms and body cells with mutated DNA, and they clean up debris. They are typically 1.5-3x larger than erythrocytes and are the only formed elements that are complete cells, possessing a nucleus and organelles. And although there is just one type of erythrocyte, there are many types of leukocytes (**Figure 10.4**).

Key

| Basophil | Eosinophil | Neutrophil | Monocyte | Lymphocyte |
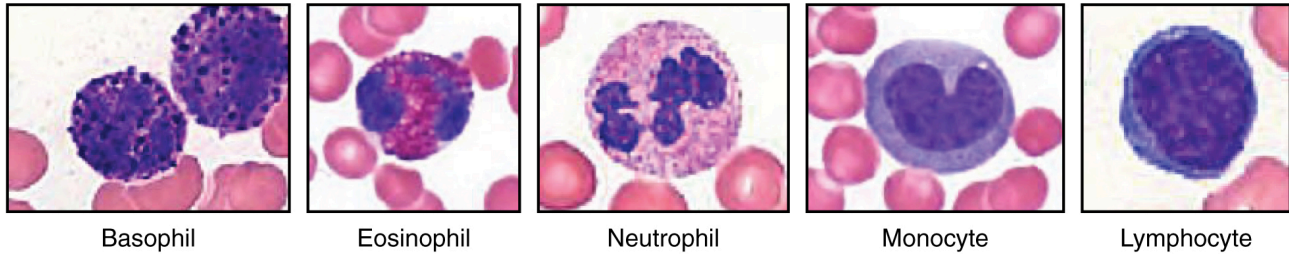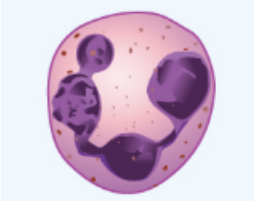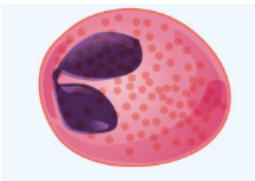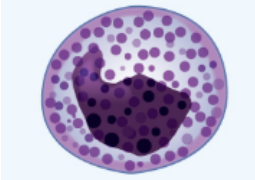
Figure 10.4 Leukocytes. (Micrographs provided by the Regents of University of Michigan Medical School © 2012).
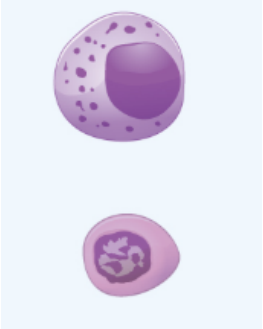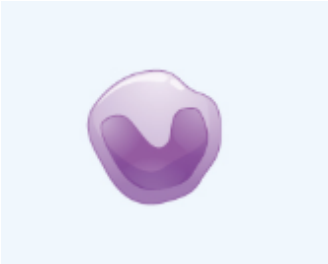
When scientists first began to observe stained blood slides, it quickly became evident that leukocytes could be divided into two groups, according to whether their cytoplasm contained highly visible granules:

- **Granular** leukocytes contain abundant granules within the cytoplasm. They typically have a lobed nucleus and classified by which type of stain best highlights their granules. They include **neutrophils**, **eosinophils**, and **basophils**.
- While granules are not totally lacking in **agranular** leukocytes, they are far fewer and less obvious. Agranular leukocytes include **monocytes**, which mature into macrophages that are phagocytic, and lymphocytes, which arise from the lymphoid stem cell line.

Each white blood cell type has a distinctive appearance and fulfills a different role in the immune system response (**Table 10.3**). If a pathogen is detected, the body increases production of the WBC type(s) that are specialized for that particular pathogen. Because of this, counting relative abundances of WBCs in a patient and comparing them to the typical abundance you would expect in a healthy individual can be useful during diagnosis.

Table 10.3 Types of Leukocytes

Name	Type	Typical Abundance in a WBC count	Appearance	Functions	Conditions related to high counts	Notes
Neutrophils 	Granulocytes	50-70%	– "Neutral" (pale lilac) colored granules – Light purple cytoplasm – Most segmented nucleus (2-5 lobes)	Phagocytic; particularly effective against bacteria. Release cytotoxic chemicals from granules	Infection (particularly bacterial), inflammation, burns, unusual stress	Most common leukocyte; lifespan of minutes to days
Eosinophils 		1-4%	– Dark pink/orange/red granules – Bi-lobed nucleus	Phagocytic cells; particularly effective with antigen-antibody complexes. Release antihistamines. Increase in allergies and parasitic infections	Allergies, parasitic worm infestations, some autoimmune diseases	Lifespan of minutes to days
Basophils 		0.5-1%	– Dark blue/purple granules that obscure nucleus and cytoplasm – Bi-lobed nucleus	Promotes inflammation; Release histamines and heparin during allergic reactions	Allergies, hypothyroidism	Least common leukocyte; lifespan unknown

Lymphocytes	**Agranulocytes**	20-40%	-Spherical cells with a single, often large nucleus occupying much of the cell's volume -stains purple -see in large (natural killer cells) and small (B and T cells) variants	Attack pathogens and virus-infected cells; coordinate body's immune response. T cells directly attack other cells (cellular immunity). B cells release antibodies (humoral immunity); natural killer cells are similar to T cells but nonspecific	Viral infections, some cancers	Initial cells originate in bone marrow, but secondary production occurs in lymphatic tissue; several distinct subtypes; memory cells form after exposure to a pathogen and rapidly increase responses to subsequent exposure; lifespan of many years
Monocytes		2-8%	-Largest leukocyte (2-3x size of RBC) -indented or horseshoe-shaped nucleus	Very effective phagocytic cells engulfing pathogens or worn out cells; also serve as antigen-presenting cells (APCs) for other components of the immune system	Viral or fungal infections, tuberculosis, some forms of leukemia, other chronic diseases	Produced in red bone marrow; referred to as macrophages after leaving circulation

Leukocytes routinely leave the bloodstream to perform their **defensive** functions in the body's tissues, where they are often given distinct names, such as **macrophage** or **microglia**, depending on their function. They leave the capillaries—the smallest blood vessels—or other small vessels through a process known as emigration or diapedesis in which they squeeze through adjacent cells in a blood vessel wall (**Figure 10.5**).

Once they have exited the capillaries, some leukocytes will take up fixed positions in lymphatic tissue, bone marrow, the spleen, the thymus, or other organs. Others will move about through the tissue spaces, sometimes wandering freely, and sometimes moving toward the direction in which they are drawn by chemical signals.

① Leukocytes in the blood respond to chemical attractants released by pathogens and chemical signals from nearby injured cells.

Eosinophil

Capillary epithelial cells

Injured/infected cells secrete chemical signals into the blood.

Monocyte

Neutrophil

Pathogens
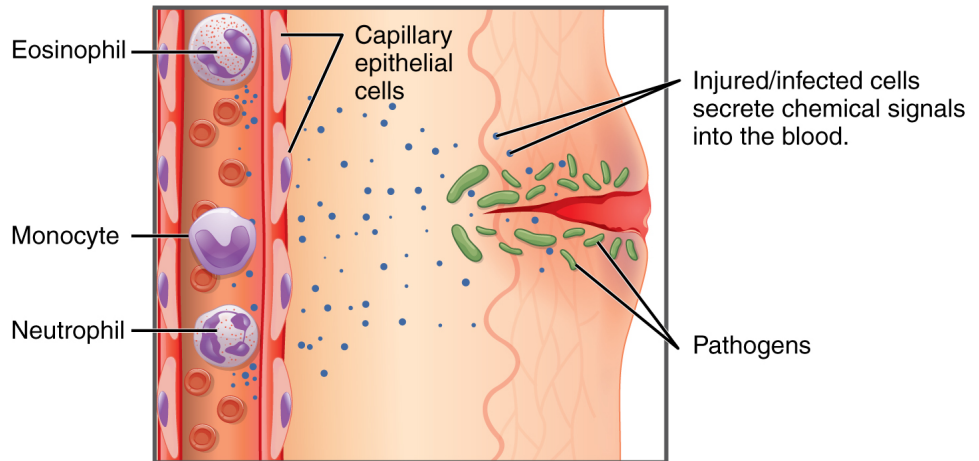
② The leukocytes squeeze between the cells of the capillary wall as they follow the chemical signals to where they are most concentrated (positive chemotaxis).

Leukocytes emigrate to site of injury and infection.
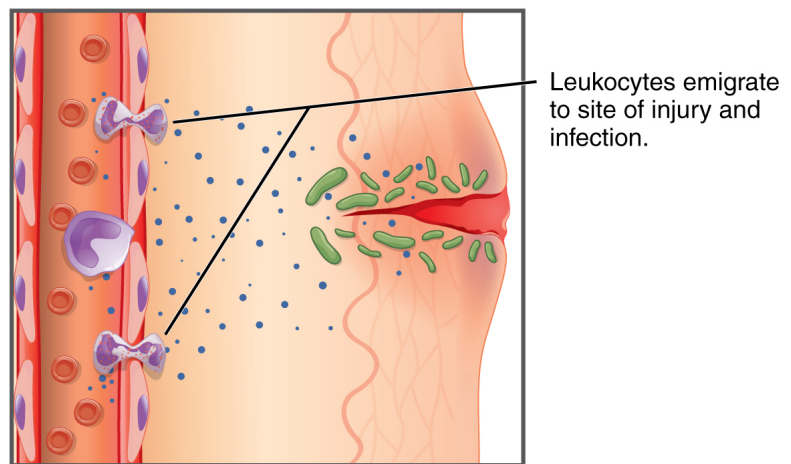
③ Within the damaged tissue, monocytes differentiate into macrophages that phagocytize the pathogens. The eosinophils and neutrophils release chemicals that break apart pathogens. They are also capable of phagocytosis.

Eosinophil releases cytotoxic chemicals from granules into tissue.

Macrophage engulfs pathogen.
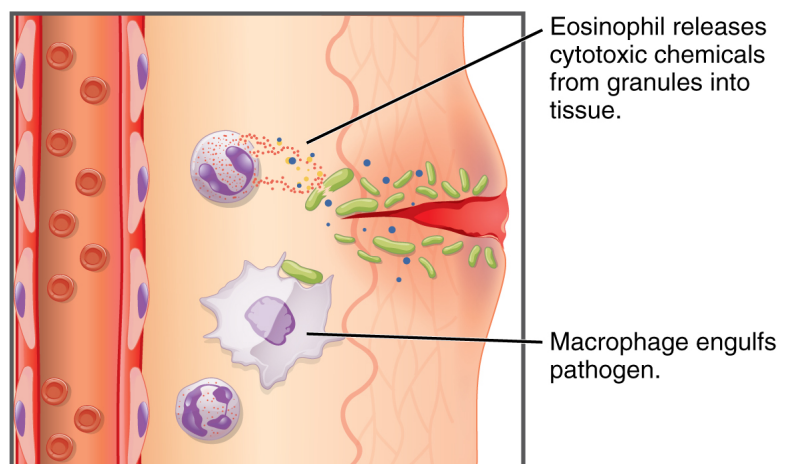
Figure 10.5 Emigration. Leukocytes exit the blood vessel and then move through the connective tissue of the dermis toward the site of a wound. Some leukocytes, such as the eosinophil and neutrophil, are characterized as granular leukocytes. They release chemicals from their granules that destroy pathogens; they are also capable of phagocytosis. The monocyte differentiates into a macrophage that then hagocytizes the pathogens.

Platelets

A platelet is not a cell but rather a fragment of the cytoplasm of a cell called a megakaryocyte that is surrounded by a plasma membrane. Platelets are much smaller than RBCs, but numerous. After entering the circulation, approximately one-third of the newly-formed platelets migrate to the spleen for storage for later release in response to any rupture in a blood vessel. They then become activated to perform their primary function, which is to limit blood loss. Platelets remain only about 10 days, then are phagocytized by macrophages.

Platelets are key players in **hemostasis**, the process by which the body seals a ruptured blood vessel and prevents further loss of blood. Although rupture of larger vessels usually requires medical intervention, hemostasis is quite effective in dealing with small, simple wounds. There are three steps to the process: vascular spasm, the formation of a platelet plug, and coagulation (blood clotting) (**Figure 10.6**). Failure of any of these steps will result in **hemorrhage.**
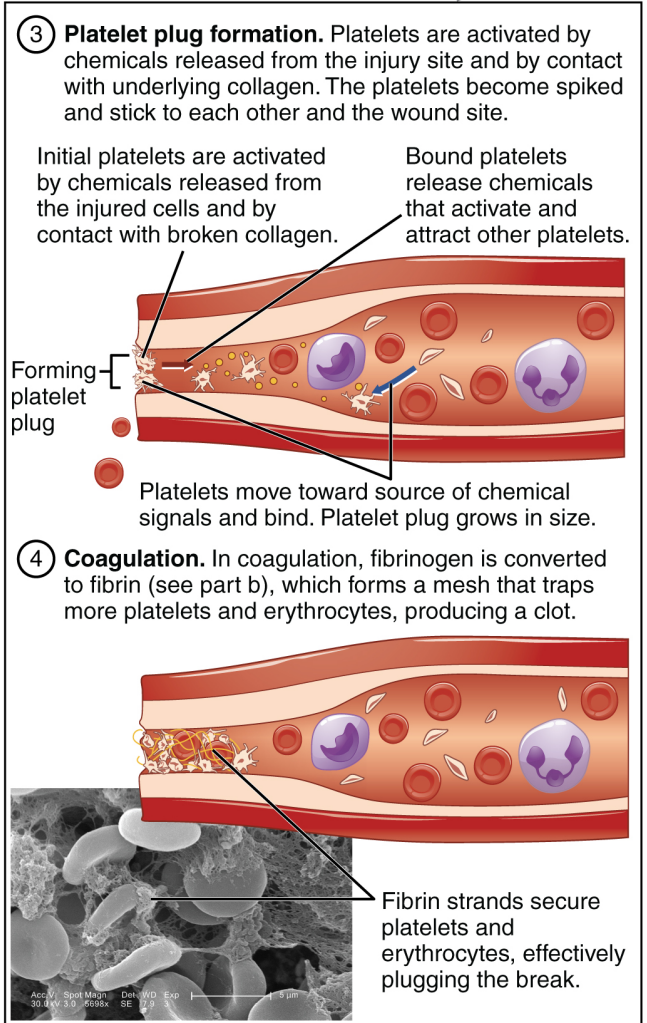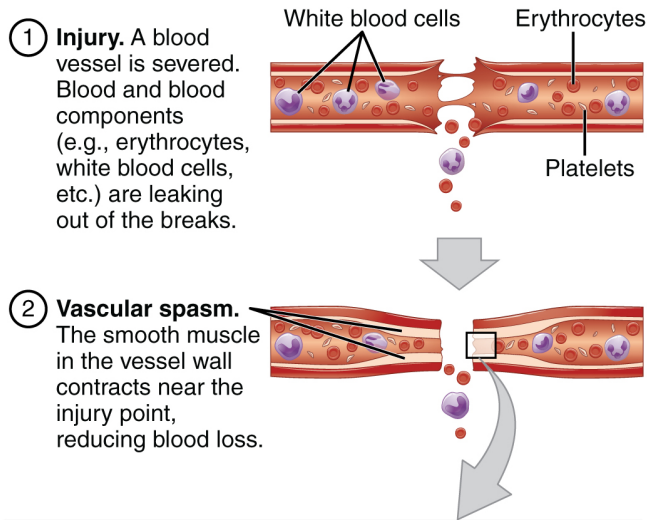
(a) The general steps of clotting

① Injury. A blood vessel is severed. Blood and blood components (e.g., erythrocytes, white blood cells, etc.) are leaking out of the breaks.

White blood cells

Erythrocytes

Platelets

② Vascular spasm. The smooth muscle in the vessel wall contracts near the injury point, reducing blood loss.

③ Platelet plug formation. Platelets are activated by chemicals released from the injury site and by contact with underlying collagen. The platelets become spiked and stick to each other and the wound site.

Initial platelets are activated by chemicals released from the injured cells and by contact with broken collagen.

Bound platelets release chemicals that activate and attract other platelets.

Forming platelet plug

Platelets move toward source of chemical signals and bind. Platelet plug grows in size.

④ Coagulation. In coagulation, fibrinogen is converted to fibrin (see part b), which forms a mesh that traps more platelets and erythrocytes, producing a clot.

Fibrin strands secure platelets and erythrocytes, effectively plugging the break.

(b) Fibrin synthesis cascade

INTRINSIC PATHWAY

Damaged vessel wall

EXTRINSIC PATHWAY

Trauma to extravascular cells

XII → XII$_a$

III

XI → XI$_a$

IX → IX$_a$

VII$_a$ ← VII

VIII$_a$ IX$_a$ complex

VII$_a$ III complex

X → X$_a$ ← X

V$_a$

FINAL COMMON PATHWAY

Prothrombin (II) → Thrombin (II$_a$)

Fibrinogen (I) → Fibrin (I$_a$)

XIII$_a$

Cross-linked fibrin clot

⬭ Factor: inactive state

✦ Factor: active state

Figure 10.6 Hemostasis. (a) An injury to a blood vessel initiates the process of hemostasis. Blood clotting involves three steps. First, vascular spasm constricts the flow of blood. Next, a platelet plug forms to temporarily seal small openings in the vessel. Coagulation then enables the repair of the vessel wall once the leakage of blood has stopped. (b) The

synthesis of fibrin in blood clots involves either an intrinsic pathway or an extrinsic pathway, both of which lead to a common pathway. (credit a: Kevin MacKenzie).

Fibrinolysis is the process in which a clot is degraded in a healing vessel. An **anticoagulant** is any substance that opposes coagulation. Several circulating plasma anticoagulants play a role in limiting the coagulation process to the region of injury and restoring a normal, clot-free condition of blood.

Hemopoiesis/Hematopoiesis

The lifespan of the formed elements is very brief. Although one type of leukocyte (memory cells) can survive for years, most erythrocytes, leukocytes, and platelets normally live only a few hours to a few weeks. Thus, the body must form new blood cells and platelets quickly and continuously, a process known as **hemopoiesis,** or **hematopoiesis**. In children, hemopoiesis can occur in the medullary cavity of long bones; in adults, the process is largely restricted to the red bone marrow in the cranial and pelvic bones, the vertebrae, the sternum, and the proximal epiphyses of the femur and humerus.

All formed elements arise from stem cells of the red bone marrow, called **hemopoietic stem cell**, or **hemocytoblast**. Hemopoiesis begins when the hemopoietic stem cell is exposed to appropriate chemical stimuli collectively called **emopoietic growth factors**, which prompt it to divide and differentiate. One daughter cell remains a hemopoietic stem cell, allowing hemopoiesis to continue. The other daughter cell becomes either of two types of more specialized stem cells (**Figure 10.7**).

After division, some cells remain stem cells.

Multipotent hematopoietic stem cell (hemocytoblast)

The remaining cell goes down one of two paths depending on the chemical signals received.

Myeloid stem cell

Lymphoid stem cell

Megakaryoblast   Proerythroblast   Myeloblast   Monoblast

Lymphoblast

Reticulocyte

Megakaryocyte   Erythrocyte   Basophil   Neutrophil   Eosinophil   Monocyte

Natural killer cell (large granular lymphocyte)

Small lymphocyte

Platelets

T lymphocyte   B lymphocyte

Figure 10.7 Hematopoietic System of Bone Marrow. Hemopoiesis is the proliferation and differentiation of the formed elements of blood. From Betts, et al., 2013. Licensed under CC BY 4.0. [Image description.]

The Heart

The heart is a fist-sized vital organ that has *one* job: to pump blood. If one assumes an average heart rate of 75 beats per minute, a human heart would beat approximately 108,000 times in one day, more than 39 million times in one year, and nearly 3 billion times during a 75-year lifespan. At rest, each of the major pumping chambers of the heart ejects approximately 70 mL blood per contraction in an adult. This would be equal to 5.25 liters of blood per minute and approximately 14,000 liters per day. Over one year, that would equal 10,000,000 liters of blood sent through roughly 100,000 km of blood vessels. In order to understand how that happens, it is necessary to understand the anatomy and physiology of the heart.

Anatomy of the Heart

Location

The human heart is located within the thoracic cavity, between the lungs in the space known as the **mediastinum (Figure 10.8).** Within the mediastinum, the heart is separated from the other mediastinal structures by a tough membrane known as the **pericardium**, or pericardial sac, and sits in its own space called the **pericardial cavity**. The great vessels, which carry blood to and from the heart, are attached to the superior surface of the heart, which is called the base. The base of the heart is located at the level of the third costal cartilage. The inferior tip of the heart, the apex, lies just to the left of the sternum between the junction of the fourth and fifth ribs.
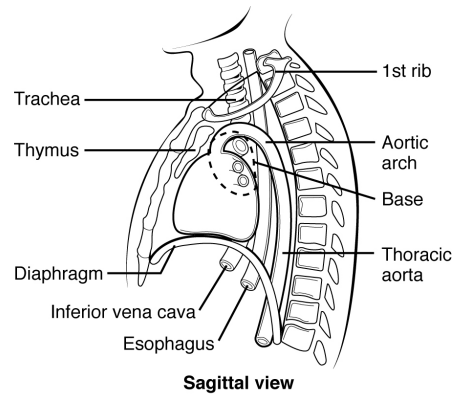
Figure 10.8 Position of the Heart in the Thorax. The heart is located within the thoracic cavity, medially between the lungs in the mediastinum. It is about the size of a fist, is broad at the top, and tapers toward the base.
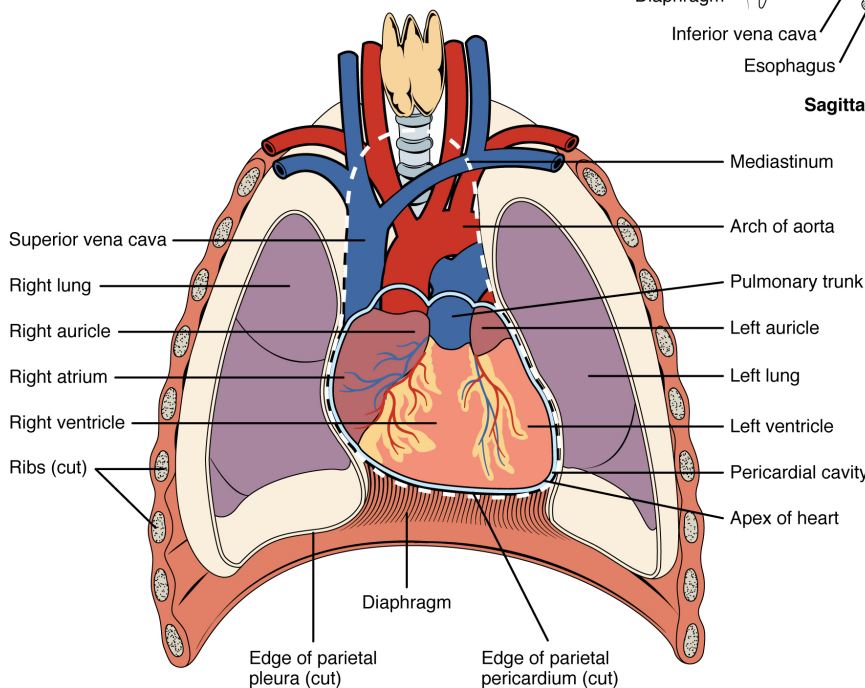
Membranes and Layers of the Heart Walls

The heart and the roots of the great vessels are surrounded by a membrane known as the **pericardium** or **pericardial sac**. The pericardium consists of two distinct sub layers (**Figure 10.9**):

- The sturdy outer fibrous pericardium is made of tough, dense connective tissue that protects the heart and holds it in position.
- Separated by the **pericardial cavity** and containing pericardial fluid the inner serous pericardium consists of

two layers:
- ◦ the outer **parietal pericardium**, which is fused to the fibrous pericardium.
- ◦ the inner **visceral pericardium**, or **epicardium**, which is fused to the heart and forms the outer layer of the heart wall.

The walls of the heart consist of three layers (**Figure 10.9**):

- The outer **epicardium**, which is another name for the visceral pericardium mentioned above.
- The thick, middle **myocardium**, which is made of muscle tissue and gives the heart its ability to contract.
- The inner **endocardium**, which lines the heart chambers and is the main component of the heart valves.
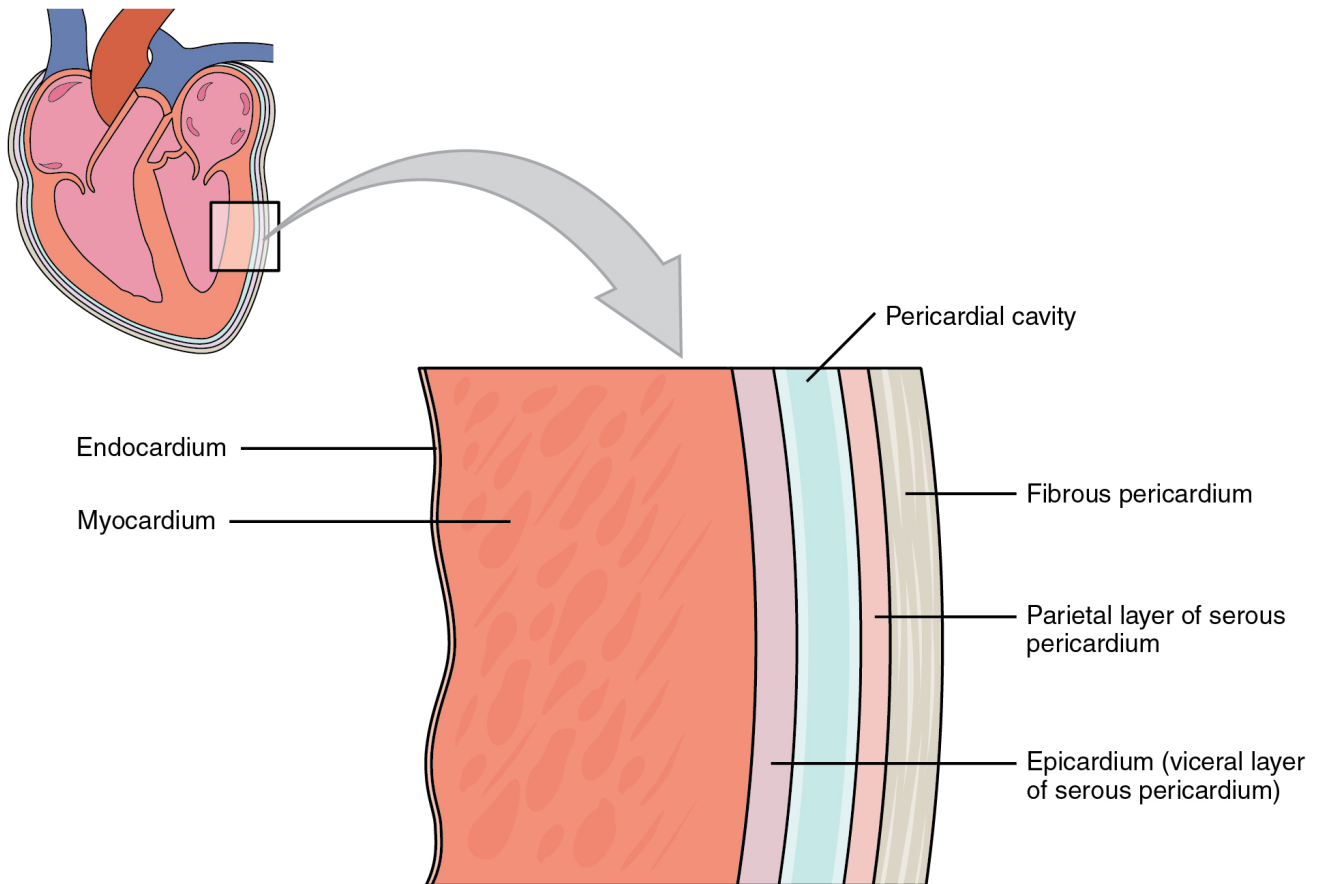
Figure 10.9 Pericardial Membranes and Layers of the Heart Wall. The pericardial membrane that surrounds the heart consists of three layers and the pericardial cavity. The heart wall also consists of three layers. The pericardial membrane and the heart wall share the epicardium

Surface Features of the Heart

Inside the pericardium, the surface features of the heart are visible, including the four chambers. There is a superficial leaf-like extension of the atria near the superior surface of the heart, one on each side, called

an **auricle**—a name that means "ear like"—because its shape resembles the external ear of a human (**Figure 10.10**). Auricles are relatively thin-walled structures that can fill with blood and empty into the atria or upper chambers of the heart. You may also hear them referred to as atrial appendages. Also prominent is a series of fat-filled grooves, each of which is known as a **sulcus** (plural = sulci), along the superior surfaces of the heart. Major coronary blood vessels are located in these sulci. The deep coronary sulcus is located between the atria and ventricles. Located between the left and right ventricles are two additional sulci that are not as deep as the coronary sulcus. The **anterior interventricular sulcus** is visible on the anterior surface of the heart, whereas the **posterior interventricular sulcus** is visible on the posterior surface of the heart. **Figure 10.10** illustrates anterior and posterior views of the surface of the heart.
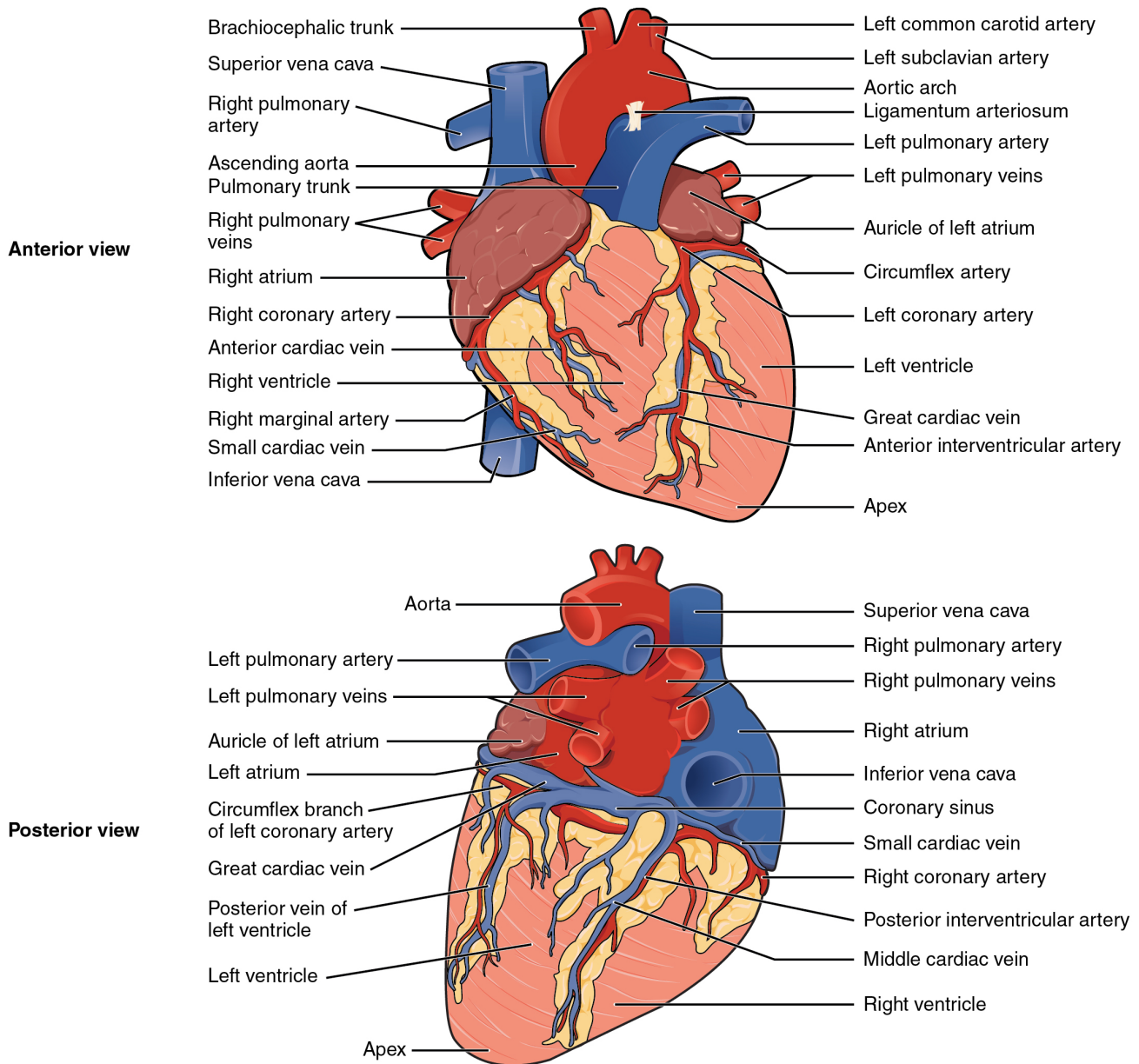
Figure 10.10 External Anatomy of the Heart Inside the pericardium, the surface features of the heart are visible.

Internal Structures of the Heart

The human heart consists of four chambers: The left side and the right side each have one **atrium** and one **ventricle**. Each of the upper chambers, the right atrium (plural = atria) and the left atrium, acts as a receiving chamber and contracts to push blood into the lower chambers, the right ventricle and the left ventricle. The ventricles serve as the primary pumping chambers of the heart, propelling blood to the lungs or to the rest of the body. The majority of the internal heart structures discussed in this section are illustrated in **Figure 10.11**.

Aorta

Superior vena cava

Right pulmonary artery

Pulmonary trunk

Right pulmonary veins

Right atrium

Fossa ovalis

Tricuspid valve

Right ventricle

Chordae tendineae

Trabeculae carneae

Moderator band

Inferior vena cava

Left pulmonary artery

Left atrium

Left pulmonary veins

Mitral (bicuspid) valve

Aortic valve

Pulmonary valve

Left ventricle

Papillary muscle

Interventricular septum

Epicardium

Myocardium

Endocardium

Anterior view

Figure 10.11 Internal Structures of the Heart This anterior view of the heart shows the four chambers, the major vessels and their early branches, as well as the valves. The presence of the pulmonary trunk and aorta covers the interatrial septum, and the atrioventricular septum is cut away to show the atrioventricular valves.

The right atrium is separated from the left atrium by a wall called the interatrial septum. Normally in an adult heart, the interatrial septum bears an oval-shaped depression known as the fossa ovalis, a remnant of an opening in the fetal heart known as the foramen ovale. The foramen ovale allowed blood in the fetal heart to pass directly from the right atrium to the left atrium, allowing some blood to bypass the pulmonary circuit. Between the two ventricles is a second septum known as the interventricular septum. It is substantially thicker than the interatrial septum, since the ventricles generate far greater pressure when they contract.

The septum between the atria and ventricles is known as the **atrioventricular septum**. It is marked by

the presence of four openings that allow blood to move from the atria into the ventricles and from the ventricles into the pulmonary trunk and aorta. Located in each of these openings between the atria and ventricles is a **valve**, a specialized structure that ensures one-way flow of blood. The valves between the atria and ventricles are known generically as **atrioventricular valves**. The valves at the openings that lead to the pulmonary trunk and aorta are known generically as **semilunar valves**. A transverse section through the heart slightly above the level of the atrioventricular septum reveals all four heart valves along the same plane (**Figure 10.12**).

Posterior

Tricuspid valve

Bicuspid (mitral) valve

Right side of heart

Left side of heart

Aortic valve

Pulmonary valve

Anterior
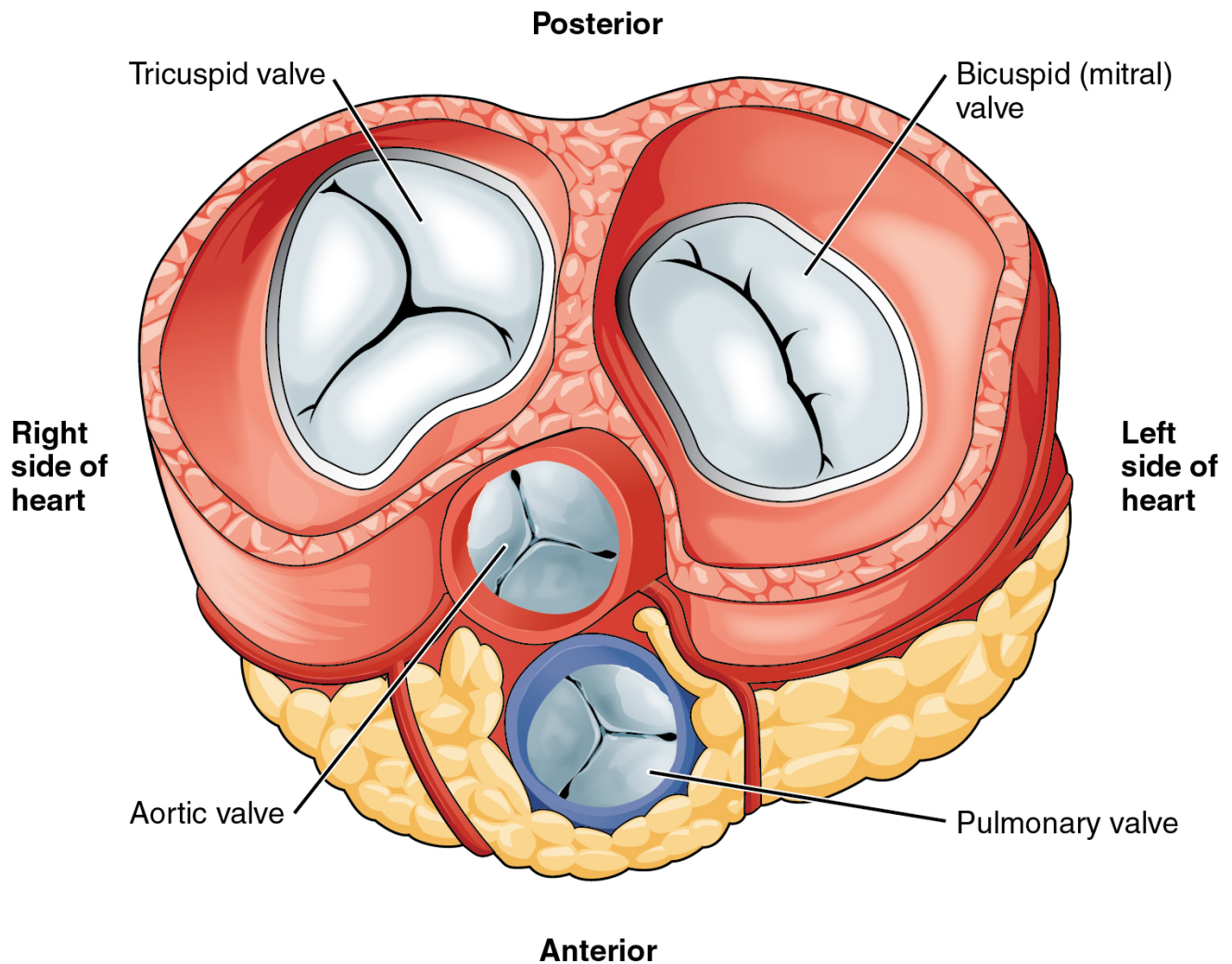
Figure 10.12 Heart Valves With the atria and major vessels removed, all four valves are clearly visible, although it is difficult to distinguish the three separate cusps of the tricuspid valve.

Right atrium

The **right atrium**serves as the receiving chamber for blood returning to the heart from the **systemic circulation**. The two major systemic veins, the **superior and inferior venae cavae**, and the large coronary vein called the **coronary sinus** that drains the heart myocardium empty into the right atrium.

While the bulk of the internal surface of the right atrium is smooth, the depression of the fossa ovalis is medial, and the anterior surface demonstrates prominent ridges of muscle called the **pectinate muscles**. The right auricle also has pectinate muscles. The left atrium does not have pectinate muscles except in the auricle. The right atrioventricular valve, or **tricuspid valve,** separates the right atrium and right ventricle.

Right ventricle

The right ventricle receives blood from the right atrium through the tricuspid valve. Each flap of the valve is attached to strong strands of connective tissue, the **chordae tendineae**, literally "tendinous cords," or sometimes more poetically referred to as "heart strings." They connect each of the flaps to a **papillary muscle** that extends from the inferior ventricular surface. There are three papillary muscles in the right ventricle, called the anterior, posterior, and septal muscles, which correspond to the three sections of the valves.

When the myocardium of the ventricle contracts, pressure within the ventricular chamber rises. Blood, like any fluid, flows from higher pressure to lower pressure areas, in this case, toward the pulmonary trunk and the atrium. To prevent any potential backflow, the papillary muscles also contract, generating tension on the chordae tendineae. This prevents the flaps of the valves from being forced into the atria and regurgitation of the blood back into the atria during ventricular contraction. **Figure 10.13** shows papillary muscles and chordae tendineae attached to the tricuspid valve.
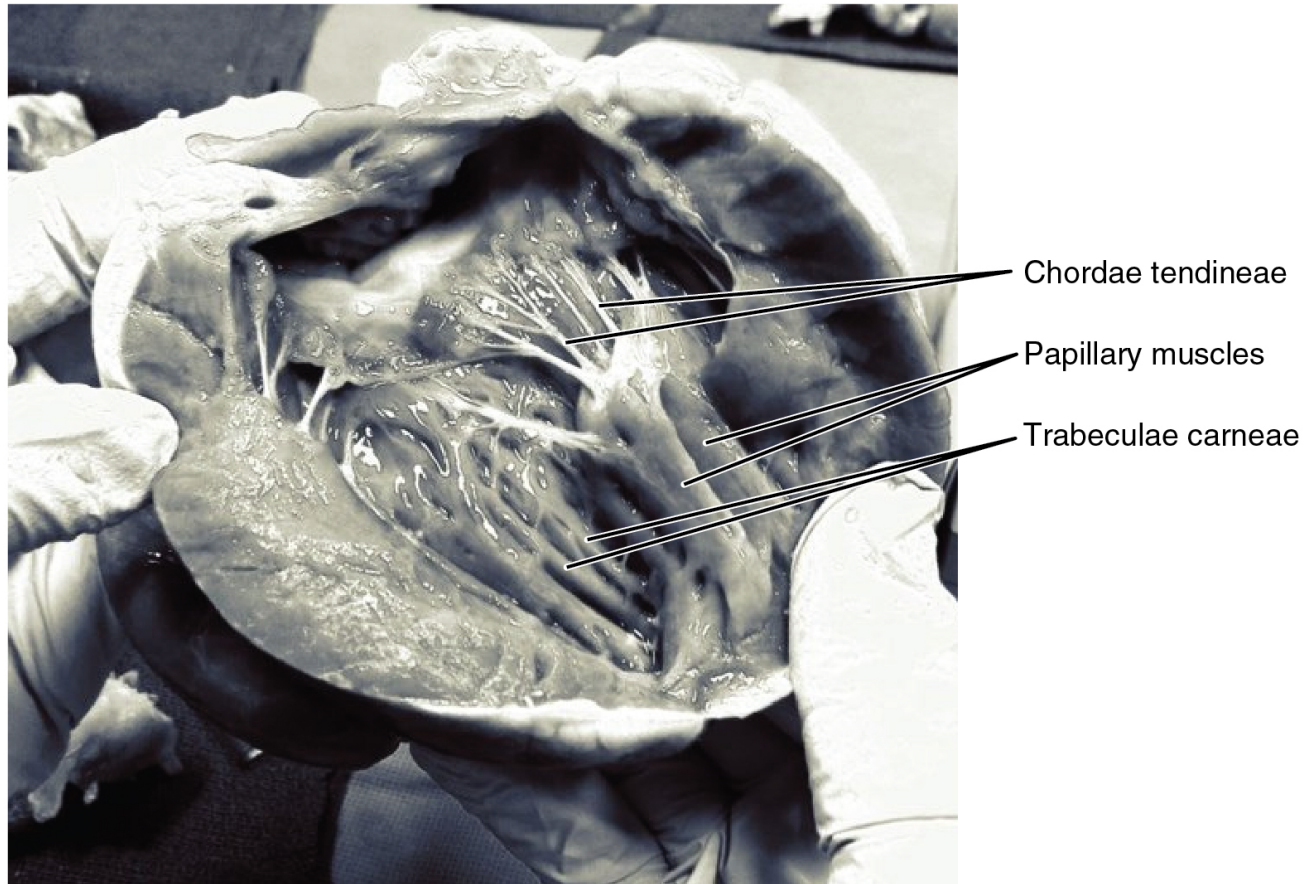
Figure 10.13 Chordae Tendineae and Papillary Muscles In this frontal section, you can see papillary muscles attached to the tricuspid valve on the right as well as the mitral valve on the left via chordae tendineae. (credit: modification of work by "PV KS"/flickr.com)

The walls of the ventricle are lined with **trabeculae carneae**, ridges of cardiac muscle covered by endocardium. When the right ventricle contracts, it ejects blood into the pulmonary trunk, which branches into the left and right pulmonary arteries that carry it to each lung. At the base of the pulmonary trunk is the **pulmonary semilunar valve** that prevents backflow from the pulmonary trunk.

Left Atrium

After exchange of gases in the pulmonary capillaries, blood returns to the left atrium high in oxygen via one of the four pulmonary veins. Blood flows nearly continuously from the pulmonary veins back into the atrium, which acts as the receiving chamber, and from here through an opening into the left ventricle.

The left atrioventricular valve, or **bicuspid valve**, separates the left atrium and left ventricle. This valve is also called the **mitral valve**. In **Figure 10.14a**, the two atrioventricular valves are open and the two semilunar valves are closed. This occurs when both atria and ventricles are relaxed and when the atria

contract to pump blood into the ventricles. **Figure 10.14b** shows a frontal view. Although only the left side of the heart is illustrated, the process is virtually identical on the right.
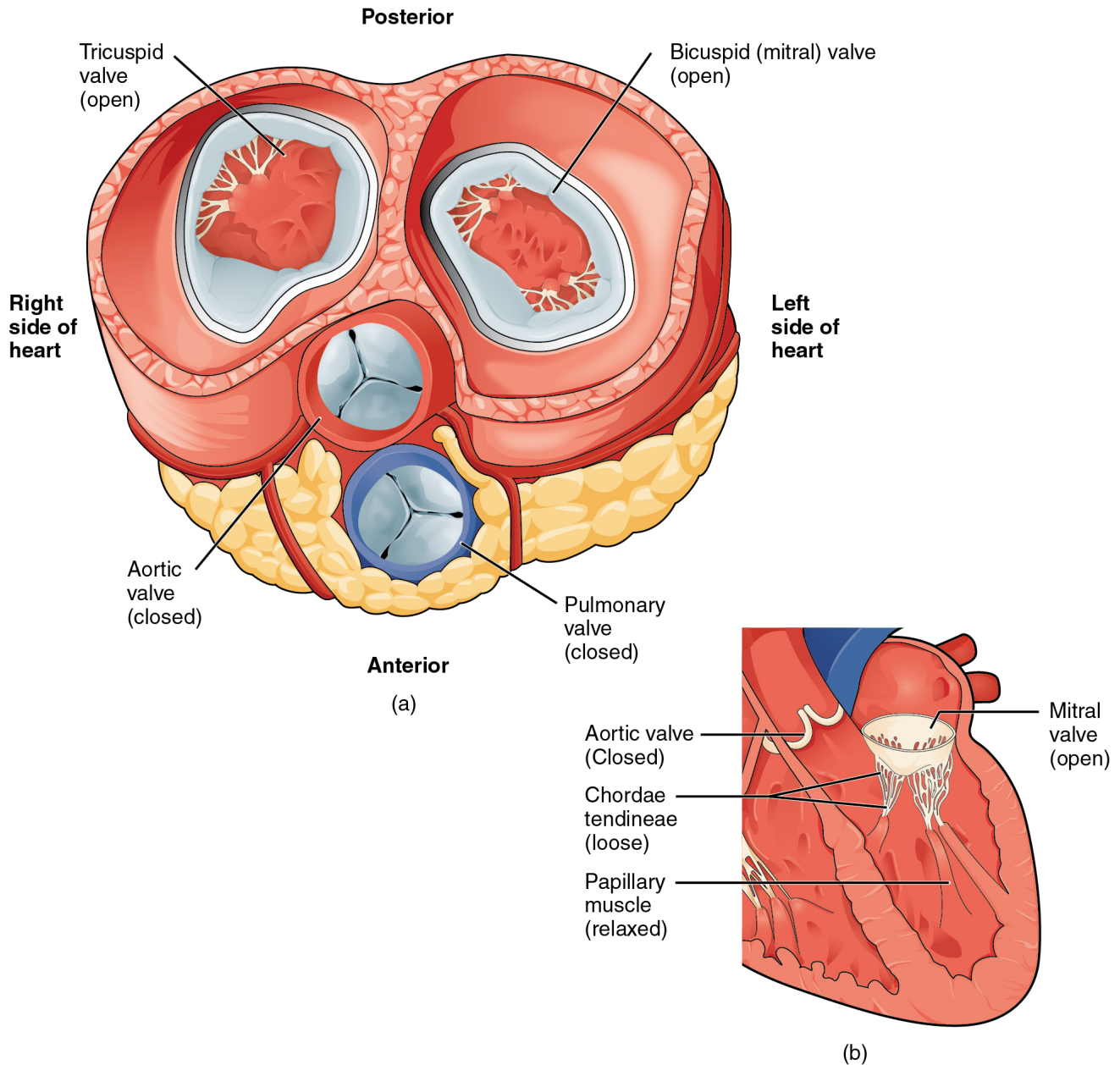
Figure 10.14 Blood Flow from the Left Atrium to the Left Ventricle (a) A transverse section through the heart illustrates the four heart valves. The two atrioventricular valves are open; the two semilunar valves are closed. The atria and vessels have been removed. (b) A frontal section through the heart illustrates blood flow through the mitral valve. When the mitral valve is open, it allows blood to move from the left atrium to the left ventricle. The aortic semilunar valve is closed to prevent backflow of blood from the aorta to the left ventricle.

Left ventricle

The left ventricle receives blood from the left atrium through the bicuspid valve. Like in the right ventricle,

the bicuspid valve is connected to papillary muscles via chordae tendineae to prevent prolapse. There are two papillary muscles on the left—the anterior and posterior—as opposed to three on the right.

The left ventricle is the major pumping chamber for the systemic circuit; it ejects blood into the aorta through the aortic semilunar valve.

Although the ventricles on the right and left sides pump the same amount of blood per contraction, the muscle of the left ventricle is much thicker and better developed than that of the right ventricle. In order to overcome the high resistance required to pump blood into the long systemic circuit, the left ventricle must generate a great amount of pressure. The right ventricle does not need to generate as much pressure, since the pulmonary circuit is shorter and provides less resistance. **Figure 10.15** illustrates the differences in muscular thickness needed for each of the ventricles.

Relaxed   **Contracted**
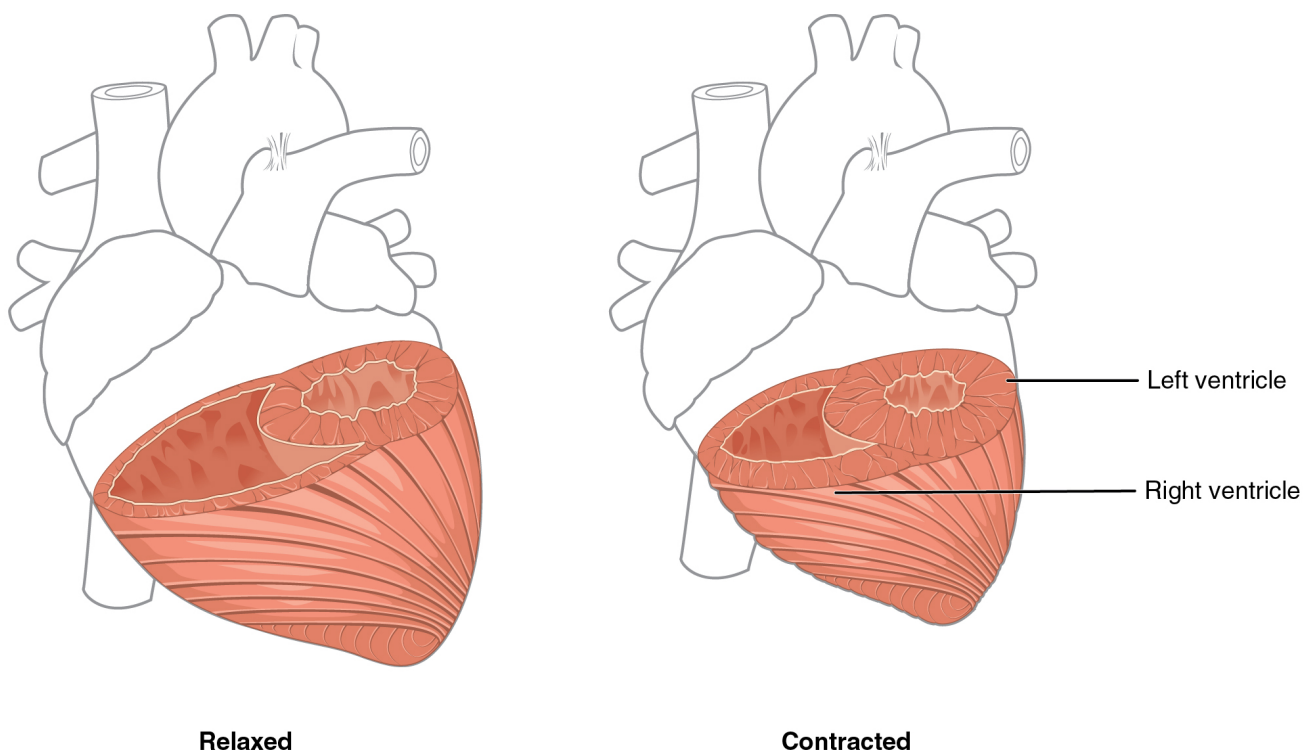
Figure 10.15 Differences in Ventricular Muscle Thickness The myocardium in the left ventricle is significantly thicker than that of the right ventricle. Both ventricles pump the same amount of blood, but the left ventricle must generate a much greater pressure to overcome greater resistance in the systemic circuit. The ventricles are shown in both relaxed and contracting states. Note the differences in the relative size of the lumens, the region inside each ventricle where the blood is contained.

The Coronary Blood Supply

Myocardial cells require their own blood supply to carry out their function of contracting and relaxing the heart in order to pump blood. Their own blood supply provides nutrients and oxygen and carry away carbon dioxide and waste. These functions are provided by the coronary arteries and coronary veins.

Coronary arteries supply blood to the myocardium and other components of the heart (**Figure 10.16**). The first

portion of the aorta after it arises from the left ventricle gives rise to the **left and right coronary arteries**. The **left coronary artery** distributes blood to the left side of the heart, the left atrium and ventricle, and the interventricular septum. The **circumflex artery** arises from the left coronary artery and follows the coronary sulcus to the left. The larger **anterior interventricular artery**, also known as the left anterior descending artery (LAD), is the second major branch arising from the left coronary artery. It follows the anterior interventricular sulcus. The **right coronary artery** proceeds along the coronary sulcus and distributes blood to the right atrium, portions of both ventricles, and the heart conduction system. Smaller arteries branch off of these main ones so that all of the heart wall is supplied.
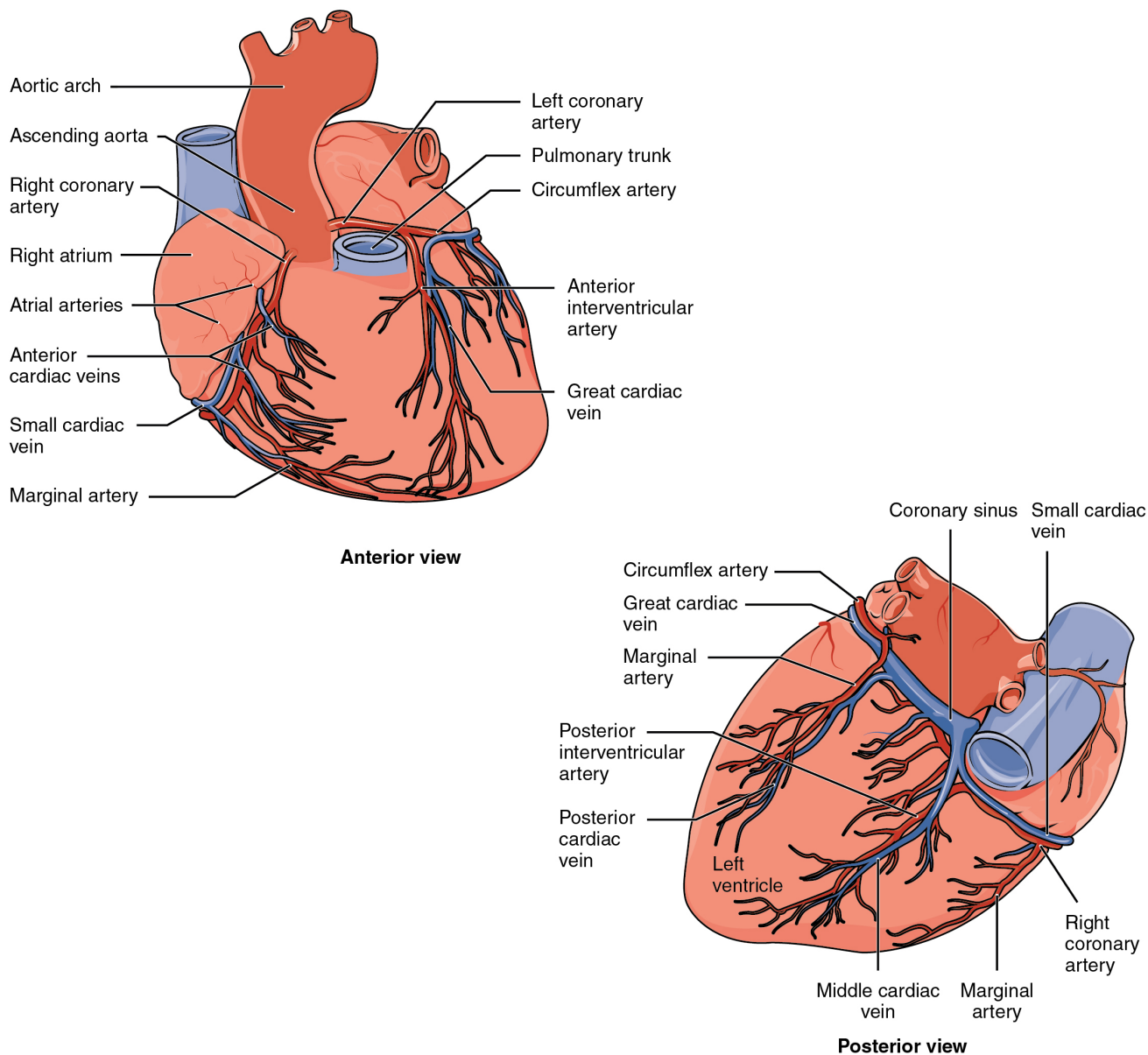
Figure 10.16 Coronary Circulation The anterior view of the heart shows the prominent coronary surface vessels. The posterior view of the heart shows the prominent coronary surface vessels.

Coronary veins drain the heart and generally parallel the large surface arteries. These veins drain the areas of the

heart supplied by the coronary arteries and bring the deoxygenated blood to the **coronary sinus** on the posterior surface of the heart. The coronary sinus is a large, thin-walled vein on the posterior surface of the heart lying within the atrioventricular sulcus and emptying directly into the right atrium.

Pathway of Blood Through the Heart

The process of pumping and circulating blood is active, coordinated and rhythmic. Each heartbeat represents one cycle of the heart receiving blood and ejecting blood. The heart pumps blood to two distinct but linked circulatory systems called the pulmonary and systemic circuits. The **pulmonary circuit** transports blood to and from the lungs, where it picks up oxygen and drops off carbon dioxide. The **systemic circuit** transports freshly oxygenated blood to virtually all of the tissues of the body and returns relatively deoxygenated blood and carbon dioxide to the heart to be sent back to the pulmonary circulation (**Figure 10.17**).
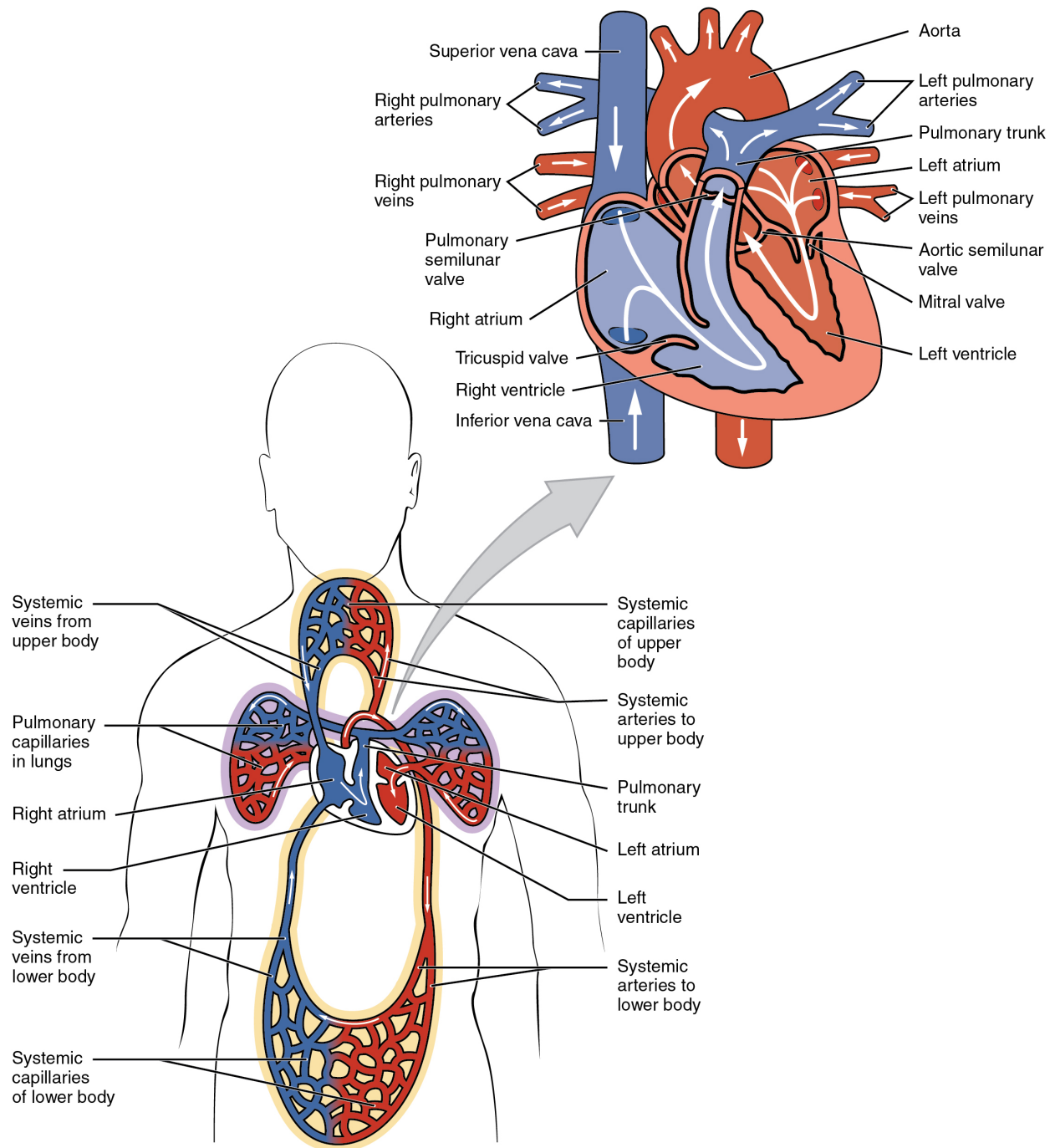
Figure 10.17 Dual System of the Human Blood Circulation. Blood flows from the right atrium to the right ventricle, where it is pumped into the pulmonary circuit. The blood in the pulmonary artery branches is low in oxygen but relatively high in carbon dioxide. Gas exchange occurs in the pulmonary capillaries (oxygen into the blood, carbon dioxide out), and blood high in oxygen and low in carbon dioxide is returned to the left atrium. From here, blood enters the left ventricle, which pumps it into the systemic circuit. Following exchange in the systemic capillaries (oxygen and nutrients out of the capillaries and carbon dioxide and wastes in), blood returns to the right atrium and the cycle is repeated.

The right and left sides of the heart fill and empty simultaneously in the cardiac cycle (see below), but to

understand the flow of blood through the heart, it is helpful to first follow the pathway that one molecule of blood would take through the heart as it is reoxygenated:

1. Deoxygenated blood that is carrying carbon dioxide and waste products from the body tissues is returned to the **right atrium** via the **superior vena cava** and **the inferior vena cava**.
2. From the right atrium, the deoxygenated blood moves through the **tricuspid valve** into the right ventricle.
3. The **right ventricle** pumps deoxygenated blood through the **pulmonary semilunar valve** into the **pulmonary trunk**, which splits into the **right and left pulmonary arteries**, leading toward the lungs. These arteries branch many times before reaching the **pulmonary capillaries**, where gas exchange occurs: carbon dioxide exits the blood and oxygen enters. The pulmonary arteries are the only arteries in the postnatal body that carry deoxygenated blood. Did you notice that they are often coloured blue on diagrams of the heart?
4. Freshly oxygenated blood returns from the lungs to the **left atrium** via the **pulmonary veins**. These veins are the only postnatal veins in the body that carry highly oxygenated blood, and are often coloured red on heart images.
5. From the left atrium, the blood moves through the **bicuspid** (**mitral) valve** into the **left ventricle.**
6. The left ventricle pumps blood through the **aortic semilunar valve**, into the **aorta**, delivering oxygenated blood to all parts of the body.

Cardiac Cycle

The period of time that begins with contraction of the atria and ends with ventricular relaxation is known as the cardiac cycle (**Figure 10.18**). **Diastole** is the portion of the cycle in which the heart is relaxed and the atria and ventricles are filling with blood. The atrioventricular (tricuspid and bicuspid) valves are open, so that blood can move from the atria to the ventricles. **Systole** is the portion of the cycle in which the heart contracts, the atrioventricular valves slam shut, and the ventricles eject blood to the lungs and to the body through the open semilunar valves. Once this phase ends, the semilunar valves close, in preparation for another filling phase. Both the atria and ventricles undergo systole and diastole, and it is essential that these components be carefully regulated and coordinated to ensure blood is pumped efficiently to the body.
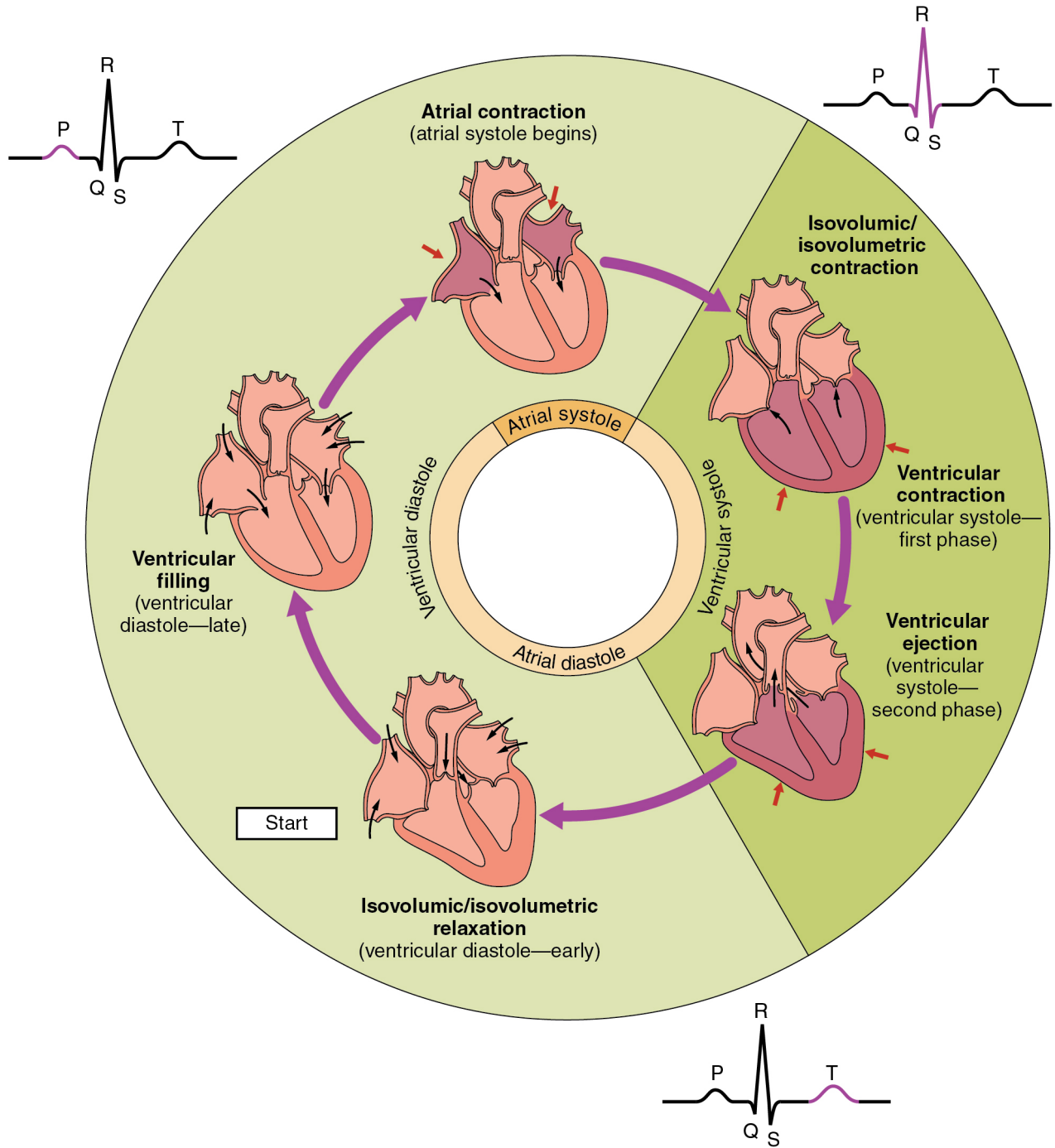
Figure 10.18 Overview of the Cardiac Cycle The cardiac cycle begins with atrial systole and progresses to ventricular systole, atrial diastole, and ventricular diastole, when the cycle begins again. Correlations to the ECG are highlighted.

Lab 11: Cardiovascular system II - Blood Vessels
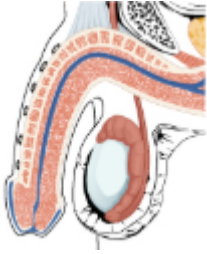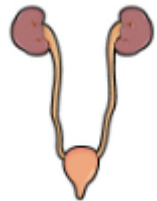
Blood vessels

Blood Vessels

Our large, complex bodies need blood to deliver nutrients to and remove wastes from our trillions of cells. The heart, as discussed in the previous chapter, pumps blood throughout the body in a network of blood vessels. Together, these three components—blood, heart, and vessels—makes up the cardiovascular system.

Virtually every cell, tissue, organ, and system in the body is impacted by the circulatory system. This includes the generalized and more specialized functions of transport of materials, capillary exchange, maintaining health by transporting white blood cells and various immunoglobulins (antibodies), hemostasis, regulation of body temperature, and helping to maintain acid-base balance. **Table 11.1** summarizes the important relationships between the circulatory system and the other body systems.

Table 11.1 Interaction of the Circulatory System with Other Body Systems. A table depicting the various body systems and the role of the circulatory system in each.

SYSTEM	ROLE OF CIRCULATORY SYSTEM
Digestive Digestive System	Absorbs nutrients and water; delivers nutrients (except most lipids) to liver for processing by hepatic portal vein; provides nutrients essential for hematopoiesis and building hemoglobin.
Endocrine Endocrine System	Delivers hormones: atrial natriuretic hormone (peptide) secreted by the heart atrial cells to help regulate blood volumes and pressures; epinephrine, ANH, angiotensin II, ADH, and thyroixine to help regulate blood pressure; estrogen to promote vascular health in women and men.
Integumentary Integumentary System	Carries clotting factors, platelets, and white blood cells for hemostasis, fighting infection, and repairing damage; regulates temperature by controlling blood flow to the surface, where heat can be dissipated; provides some coloration of integument; acts as a blood reservoir.
Lymphatic Lymphatic System	Transports various white blood cells, including those produced by lymphatic tissue, and immunoglobulins (antibodies) throughout the body to maintain health; carries excess tissue fluid not able to be reabsorbed by the vascular capillaries back to the lymphatic system for processing.

SYSTEM	ROLE OF CIRCULATORY SYSTEM
Muscular Muscular System	Provides nutrients and oxygen for contraction; removes lactic acid and distributes heat generated by contraction; muscular pumps aid in venous return; exercise contributes to cardiovascular health and helps to prevent atherosclerosis.
Nervous Nervous System	Produces cerebrospinal fluid (CSF) within choroid plexuses;contributes to blood-brain barrier; cardiac and vasomotor centers regulate cardiac output and blood flow through vessels via the autonomic system.
Reproductive Reproductive System	Aids in erection of genitalia in both sexes during sexual arousal; transports gonadotropic hormones that regulate reproductive functions.
Respiratory Respiratory System	Provides blood for critical exchange of gases to carry oxygen needed for metabolic reactions and carbon dioxide generated as byproducts of these processes.

SYSTEM	ROLE OF CIRCULATORY SYSTEM
Skeletal Skeletal System	Provides calcium,phosphate, and other minerals critical for bone matrix; transports hormones regulating buildup and absorption of matrix including growth hormone (somatotropin), thyroid hormone, calcitronins, and parathryoid hormones; erythropoietin stimulates myeloid cell hematopoiesis; some level of protection for select vessels by bony structures.
Urinary Urinary System	Delivers 20% of resting circulation to kidneys for filtering, reabsorption of useful products, and secretion of excesses; regulates blood volume and pressure by regulating fluid loss in the form of urine and by releasing the enzyme renin that is essential in the renin-angiotensin-aldosterone mechanism.

Types of Blood Vessels

Blood is carried through the body via blood vessels. An artery is a blood vessel that carries blood away from the heart, eventually reaching a capillary bed, where nutrients and wastes are exchanged. The blood then is returned to the heart in veins, vessels that bring blood towards the heart. Depending on the diameter of the vessel, they can be further classified:

- **Arteries** transport blood away from the heart and branch into smaller vessels, forming arterioles.
- **Arterioles** are smaller in diameter and distribute blood to capillary beds, the sites of exchange with the body tissues.
- A **capillary** is a microscopic channel that supplies blood to the tissues themselves, a process called perfusion.
  - Exchange of gases and other substances occurs in the capillaries between the blood and the surrounding cells and their tissue fluid (interstitial fluid).
  - For capillaries to function, their walls must be leaky, allowing substances to pass through.
  - Capillaries lead back to small vessels known as venules.
- **Venules** are small veins that converge into larger veins.
- A **vein** is a blood vessel that conducts blood toward the heart
  - Compared to arteries, veins are thin-walled vessels with large and irregular lumens

- Larger veins are commonly equipped with **valves** that promote the unidirectional flow of blood toward the heart and prevent backflow toward the capillaries caused by the inherent low blood pressure in veins as well as the pull of gravity (**Figure 11.1**)
- Other ways in which the body assists the transport of venous blood back to the heart involve contractions of skeletal muscles in the extremities (**Figure 11.1**), as well as pressure variations caused by breathing motion in the chest.
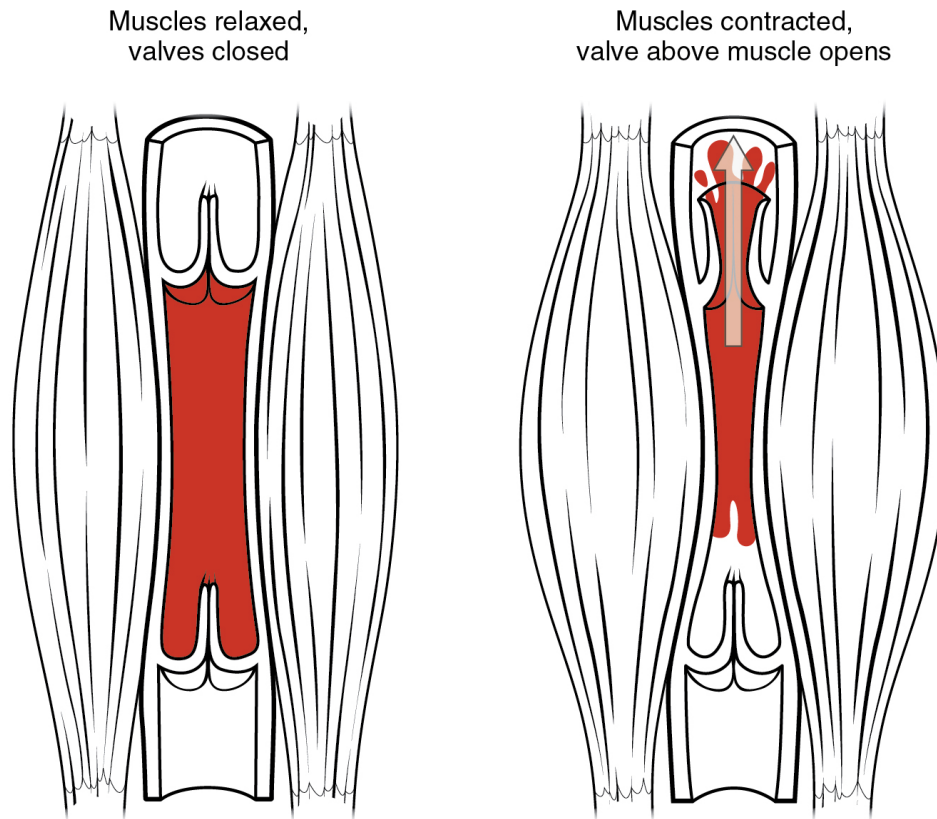

Muscles relaxed,
valves closed

Muscles contracted,
valve above muscle opens

Figure 11.1 Skeletal Muscle Pump. The contraction of skeletal muscles surrounding a vein compresses the blood and increases the pressure in that area. This action forces blood closer to the heart where venous pressure is lower. Note the importance of the one-way valves to assure that blood flows only in the proper direction.

Shared Structures of blood vessels

Different types of blood vessels vary slightly in their structures, but they share the same general features. Arteries and arterioles have thicker walls than veins and venules because they are closer to the heart and receive blood that is surging at a far greater pressure (**Figure 11.2**). Each type of vessel has a **lumen**—a hollow passageway through which blood flows. Arteries have smaller lumens than veins, a characteristic that helps to maintain the pressure of blood moving through the system. Together, their thicker walls and smaller diameters give arterial lumens a more rounded appearance in cross section than the lumens of veins. in comparison to arteries, venules and veins withstand a much lower pressure from the blood that flows through them. Their walls are considerably thinner and their lumens are correspondingly larger in diameter, allowing more blood to flow with

less vessel resistance. In addition, many veins of the body, particularly those of the limbs, contain valves that assist the unidirectional flow of blood toward the heart. This is critical because blood flow becomes sluggish in the extremities, as a result of the lower pressure and the effects of gravity.

Both arteries and veins have the same three distinct tissue layers, called **tunics**, for the garments first worn by ancient Romans. From the most interior layer to the outer, these tunics are the **tunica intima,** the **tunica media**, and the **tunica externa** (**Figure 11.2**).

Artery

- Tunica externa
- Tunica media
- Tunica intima
- Smooth muscle
- Internal elastic membrane
- Vasa vasorum
- External elastic membrane
- Nervi vasorum
- Endothelium
- Elastic fiber

(a)

Vein

- Tunica externa
- Tunica media
- Tunica intima
- Vasa vasorum
- Smooth muscle
- Endothelium

(b)

Vein

Artery

(c)
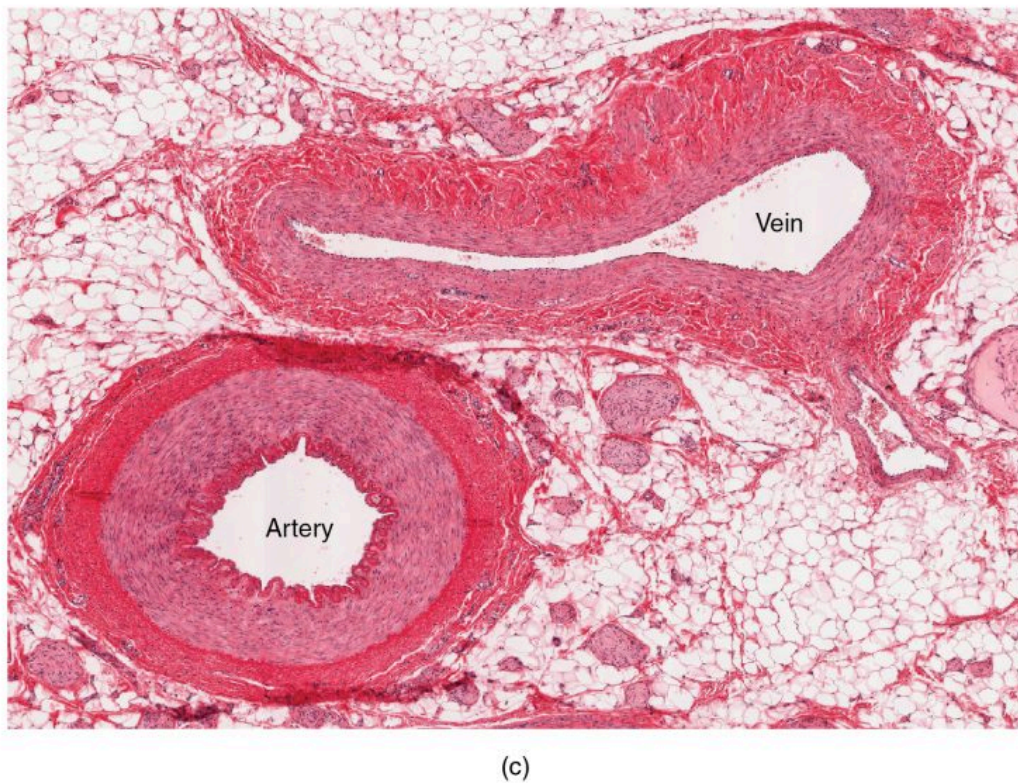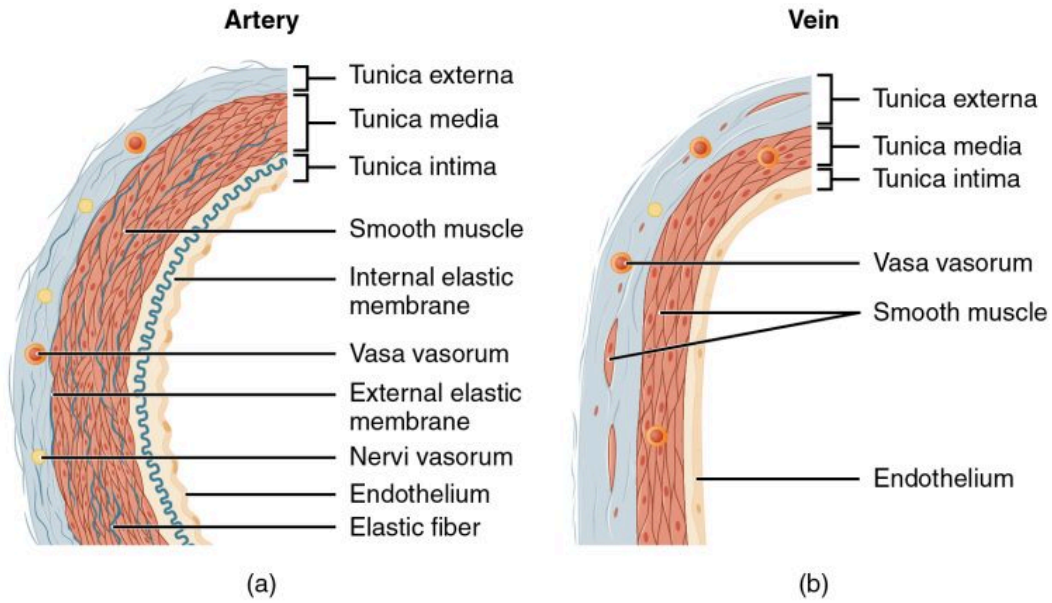
Figure 11.2 Structure of Blood Vessels (a) Arteries and (b) veins share the same general features, but the walls of arteries are much thicker because of the higher pressure of the blood that flows through them. (c) A micrograph shows the relative differences in thickness. LM × 160. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

The **tunica intima** (also called the tunica interna) is composed of epithelial and connective tissue layers. Lining

the tunica intima is the specialized simple squamous epithelium called the endothelium, which is continuous throughout the entire vascular system, including the lining of the chambers of the heart.

The **tunica media** is the substantial middle layer of the vessel wall. It is generally the thickest layer in arteries, and it is much thicker in arteries than it is in veins. The tunica media consists of layers of smooth muscle supported by connective tissue. Contraction of the smooth muscle allows arteries to **vasoconstrict,** which decreases blood flow and increases blood pressure. Similarly, **vasodilation** increases blood flow as the smooth muscle relaxes, allowing the lumen to widen and blood pressure to drop.

The outer tunic, the **tunica externa** (also called the tunica adventitia), is a substantial sheath of connective tissue composed primarily of collagenous fibers with some bands of elastic fibers. This is normally the thickest tunic in veins and may be thicker than the tunica media in some larger arteries.

Circulatory Pathways

Arteries and veins transport blood in two distinct circuits: the systemic circuit and the pulmonary circuit (**Figure 11.3**). Systemic arteries provide blood rich in oxygen to the body's tissues. The blood returned to the heart through systemic veins has less oxygen, since much of the oxygen carried by the arteries has been delivered to the cells. In contrast, in the pulmonary circuit, arteries carry blood low in oxygen exclusively to the lungs for gas exchange. Pulmonary veins then return freshly oxygenated blood from the lungs to the heart to be pumped back out into systemic circulation.
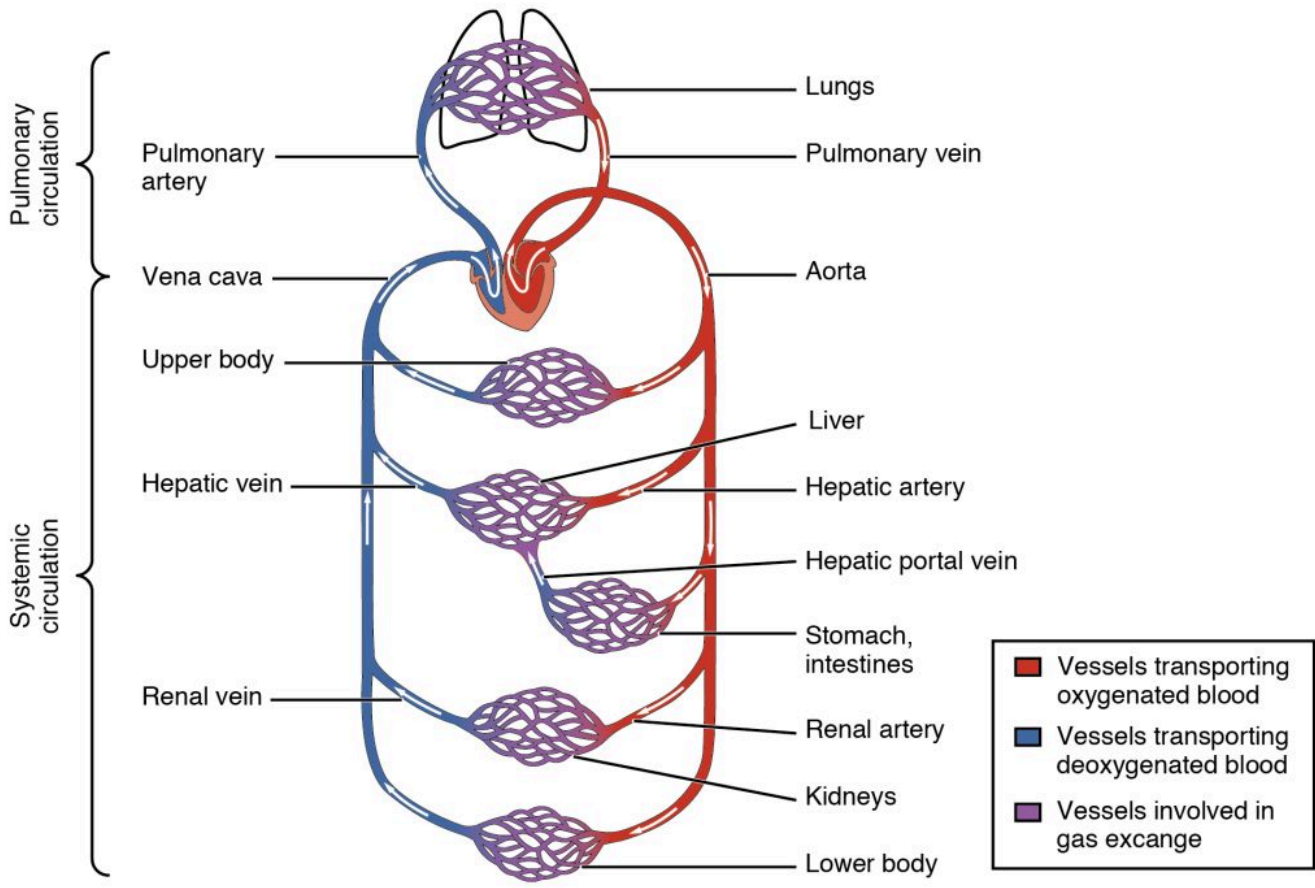
Figure 11.3 Cardiovascular Circulation The pulmonary circuit moves blood from the right side of the heart to the lungs and back to the heart. The systemic circuit moves blood from the left side of the heart to the head and body and returns it to the right side of the heart to repeat the cycle. The arrows indicate the direction of blood flow, and the colors show the relative levels of oxygen concentration.

As you learn about the vessels of the systemic and pulmonary circuits, notice that many arteries and veins share the same names, parallel one another throughout the body, and are very similar on the right and left sides of the body. For example, you will find a pair of femoral arteries and a pair of femoral veins, with one vessel on each side of the body. In contrast, some vessels closer to the midline of the body, such as the aorta, are unique. Moreover, some superficial veins, such as the great saphenous vein in the femoral region, have no arterial counterpart. Another phenomenon that can make the study of vessels challenging is that names of vessels can change with location. Like a street that changes name as it passes through an intersection, an artery or vein can change names as it passes an anatomical landmark. For example, the left subclavian artery becomes the axillary artery as it passes through the body wall and into the axillary region, and then becomes the brachial artery as it flows from the axillary region into the upper arm (or brachium).

As you read about circular pathways, notice that there is an occasional, very large artery referred to as a **trunk,** a term indicating that the vessel gives rise to several smaller arteries. For example, the celiac trunk gives rise to the left gastric, common hepatic, and splenic arteries.

As you study circulatory pathways, imagine you are on a "Voyage of Discovery" similar to Lewis and Clark's expedition in 1804−1806, which followed rivers and streams through unfamiliar territory, seeking a water route

from the Atlantic to the Pacific Ocean. You might envision being inside a miniature boat, exploring the various branches of the circulatory system. This simple approach has proven effective for many students in mastering these major circulatory patterns. Another approach that works well for many students is to create simple line drawings similar to the ones provided, labeling each of the major vessels. It is beyond the scope of this course to name every vessel in the body. However, we will attempt to discuss the major pathways for blood and acquaint you with the major named arteries and veins in the body.

Pulmonary Circulation

Blood returning from the systemic circuit enters the right atrium (**Figure 11.4**) via the superior and inferior venae cavae and the coronary sinus, which drains the blood supply of the heart muscle. This blood is relatively low in oxygen and relatively high in carbon dioxide, since much of the oxygen has been extracted for use by the tissues and the waste gas carbon dioxide was picked up to be transported to the lungs for elimination. From the right atrium, blood moves into the right ventricle, which pumps it to the lungs for gas exchange. This system of vessels is referred to as the **pulmonary circuit**.
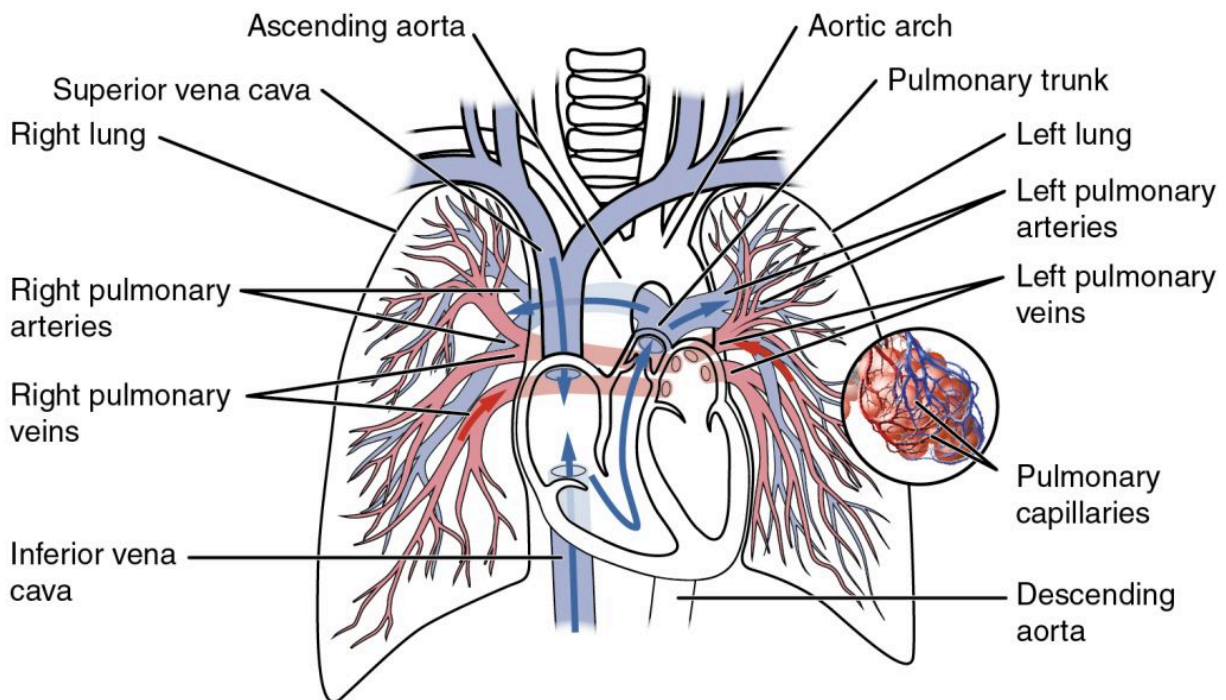
Figure 11.4 Pulmonary Circuit Blood exiting from the right ventricle flows into the pulmonary trunk, which bifurcates into the two pulmonary arteries. These vessels branch to supply blood to the pulmonary capillaries, where gas exchange occurs within the lung alveoli. Blood returns via the pulmonary veins to the left atrium.

The single vessel exiting the right ventricle is the **pulmonary trunk.** At the base of the pulmonary trunk is the pulmonary semilunar valve, which prevents backflow of blood into the right ventricle during ventricular diastole. The pulmonary trunk divides into two branches, the **left pulmonary artery** going to the left lung and the **right pulmonary artery** going to the right lung. The pulmonary arteries divide into smaller branches within the lungs, eventually leading to the **pulmonary capillaries**, which surround lung structures known as alveoli that are the sites of oxygen and carbon dioxide exchange. Oxygenated blood flows from the pulmonary capillaries into

a series of pulmonary venules that eventually lead to two **left pulmonary veins** and two **right pulmonary veins**, which return blood to the left atrium.

Overview of Systemic Arteries

Blood relatively high in oxygen concentration is returned from the pulmonary circuit to the left atrium via the four pulmonary veins. From the left atrium, blood moves into the left ventricle, which pumps blood into the aorta. The aorta and its branches—the systemic arteries—send blood to virtually every organ of the body (**Figure 11.5**).
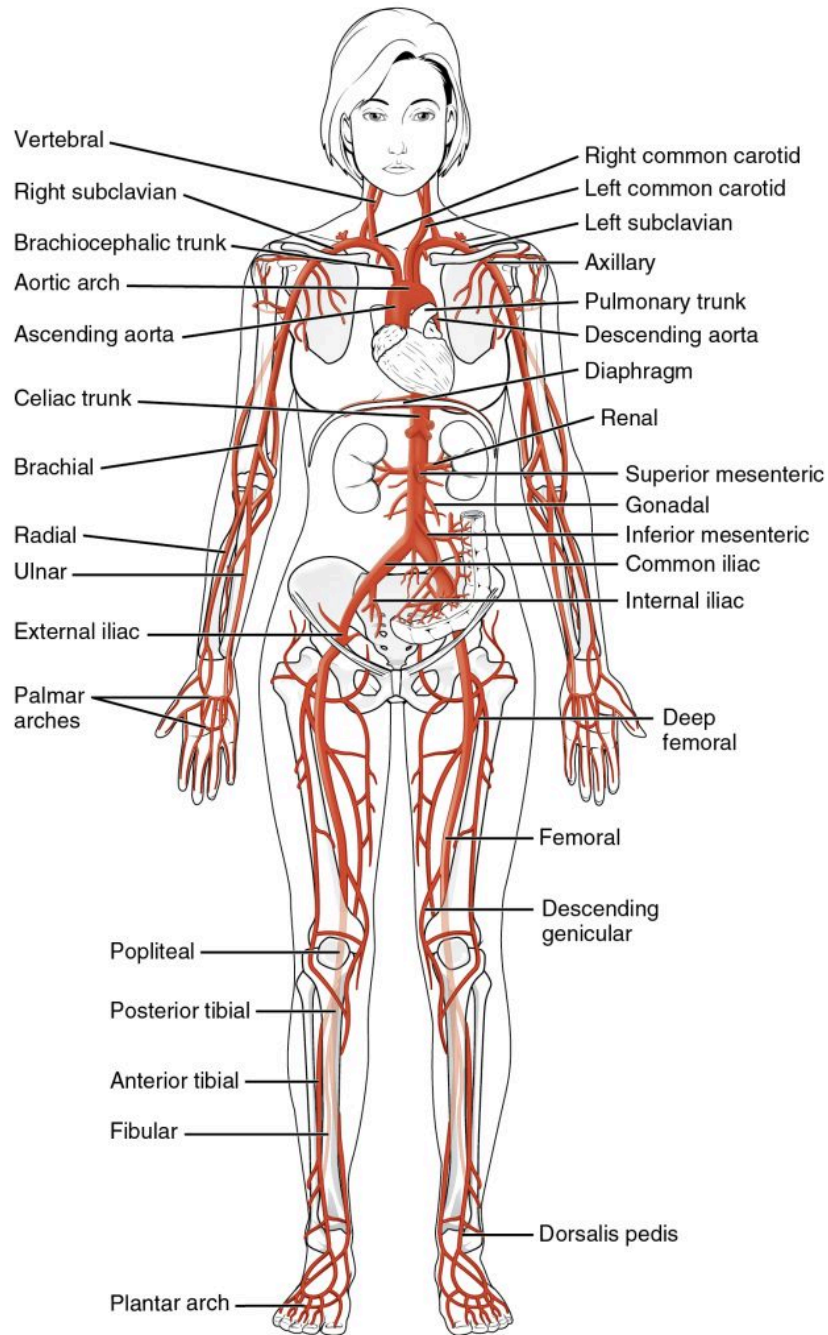
Figure 11.5 Systemic Arteries The major systemic arteries shown here deliver oxygenated blood throughout the body.

The Aorta and its superior branches

The **aorta** is the largest artery in the body (Figure #). It arises from the left ventricle; at the base of the aorta is the aortic semilunar valve that prevents backflow of blood into the left ventricle while the heart is relaxing. The aorta consists of the **ascending aorta**, the **aortic arch**, and the **descending aorta** (**thoracic aorta**), which passes through the diaphragm and becomes the **abdominal aorta**. The abdominal aorta terminates when it bifurcates into the

two **common iliac arteries** at the level of the fourth lumbar vertebra. Arteries originating from the aorta ultimately distribute blood to virtually all tissues of the body.

The first vessels that branch from the ascending aorta are the paired **coronary arteries** (**Figure 11.6**). The coronary arteries encircle the heart, forming a ring-like structure that divides into the next level of branches that supplies blood to the heart tissues. This was discussed in greater detail in the previous chapter on the heart.
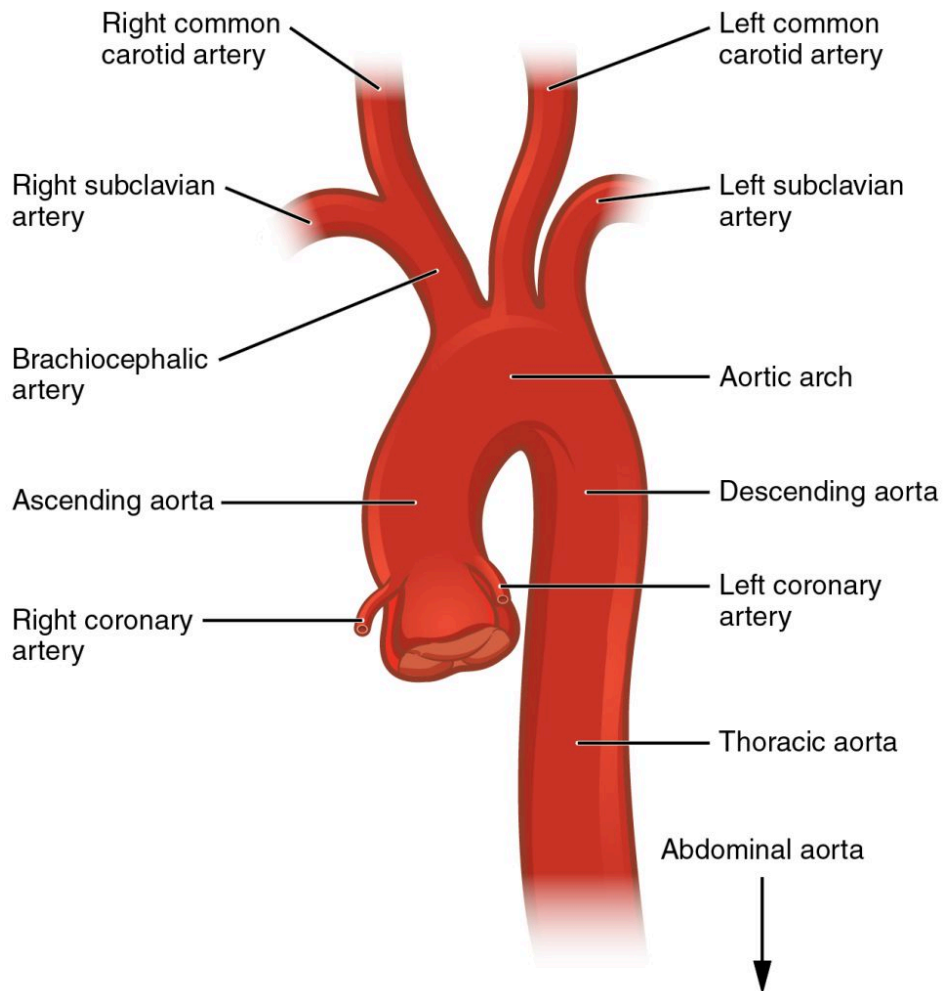
Figure 11.6 Aorta The aorta has distinct regions, including the ascending aorta, aortic arch, and the descending aorta, which includes the thoracic and abdominal regions.

There are three major branches of the aortic arch: the **brachiocephalic artery (trunk)**, the **left common carotid artery**, and the **left subclavian** (literally "under the clavicle") artery. The brachiocephalic artery is located only on the right side of the body; there is no corresponding artery on the left. The brachiocephalic artery branches into the right subclavian artery and the right common carotid artery. The left subclavian and left common carotid arteries arise independently from the aortic arch but otherwise follow a similar pattern and distribution to the corresponding arteries on the right side.The **common carotid arteries** divide into internal and external carotid arteries. The **internal carotid arteries** along with the vertebral arteries are the two primary suppliers of blood to the human brain. The internal carotid artery continues through the carotid canal of the temporal bone and enters

the base of the brain through the carotid foramen where it gives rise to several branches (**Figures 11.7-11.8**). The **external carotid artery** supplies blood to numerous structures within the face, lower jaw, neck, esophagus, and larynx. Each **subclavian artery** supplies blood to the arms, chest, shoulders, back, and central nervous system.
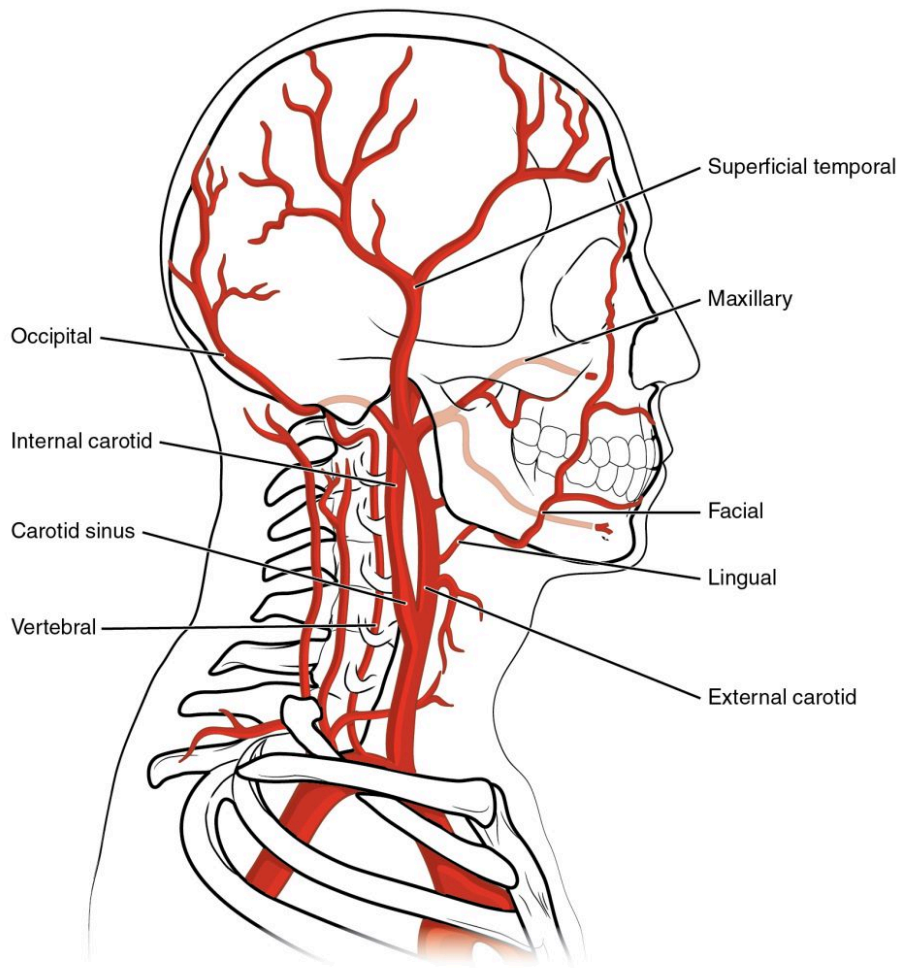

Figure 11.7 Arteries Supplying the Head and Neck The common carotid artery gives rise to the external and internal carotid arteries. The external carotid artery remains superficial and gives rise to many arteries of the head. The internal carotid artery first forms the carotid sinus and then reaches the brain via the carotid canal and carotid foramen, emerging into the cranium via the foramen lacerum. The vertebral artery branches from the subclavian artery and passes through the transverse foramen in the cervical vertebrae, entering the base of the skull at the vertebral foramen. The subclavian artery continues toward the arm as the axillary artery.
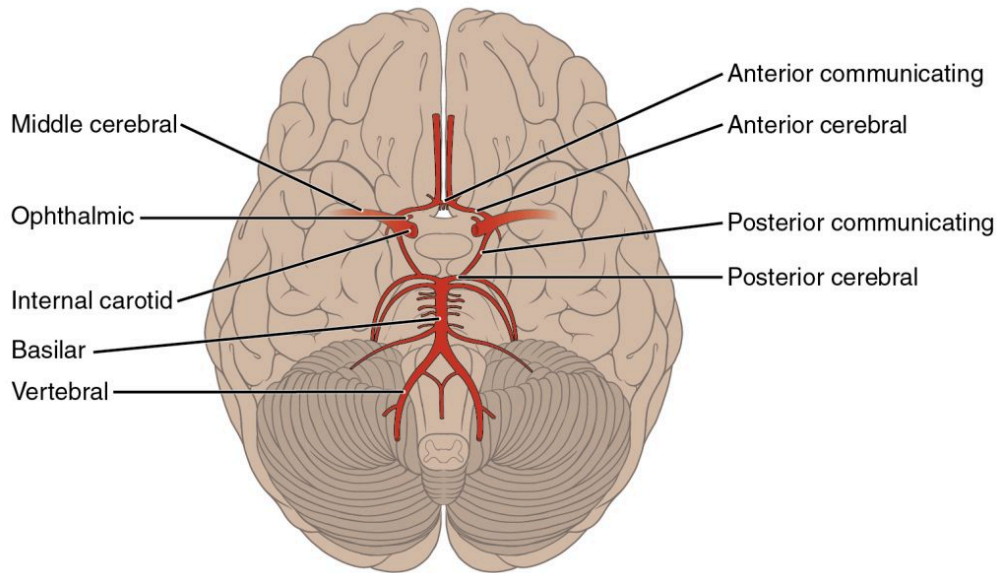
Figure 11.8 Arteries Serving the Brain This inferior view shows the network of arteries serving the brain. The structure is referred to as the arterial circle or circle of Willis.

Arteries serving the upper limbs

As the subclavian artery exits the thorax into the axillary region (armpit), it is renamed the **axillary artery**. It then continues into the upper arm, or brachium, and becomes the brachial artery (**Figure 11.9**). The **brachial artery** supplies blood to much of the brachial region and divides at the elbow into several smaller branches, including the radial and ulnar arteries, which continue into the forearm, or antebrachium. The **radial artery** and **ulnar artery** parallel their namesake bones, giving off smaller branches until they reach the wrist, or carpal region. At this level, they fuse to form the superficial and deep **palmar arches** that supply blood to the hand, as well as the **digital arteries** that supply blood to the digits.
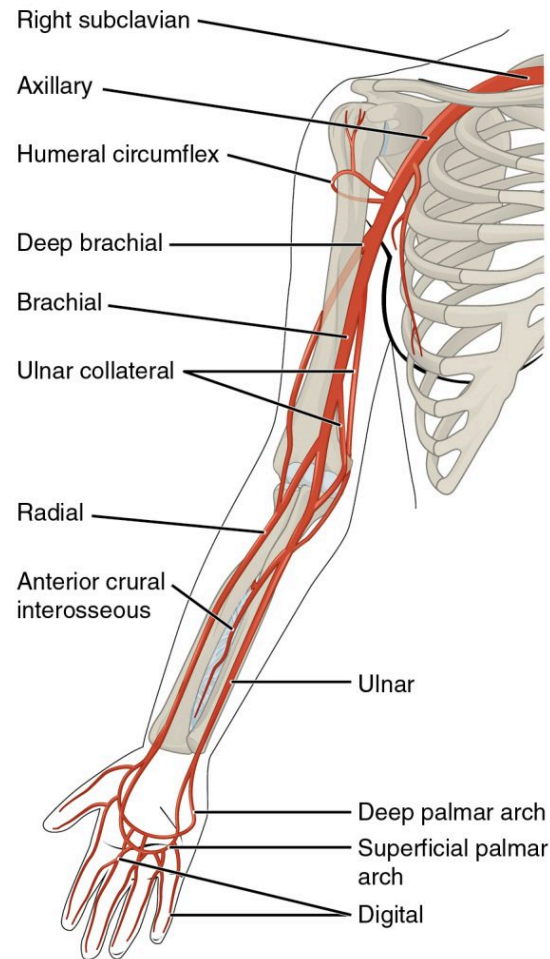
Figure 11.9 Major Arteries Serving the Thorax and Upper Limb The arteries that supply blood to the arms and hands are extensions of the subclavian arteries.

Arteries of the abdomen

After crossing through the diaphragm at the aortic hiatus, the thoracic aorta is called the **abdominal aorta** (see **Figure 11.10**), which gives rise to several important branches. A single **celiac trunk** (artery) emerges and divides into the **left gastric artery** to supply blood to the stomach and esophagus, the **splenic artery** to supply blood to the spleen, and the **common hepatic artery**, which in turn gives rise to the **hepatic artery proper** to supply blood to the liver, the **right gastric artery** to supply blood to the stomach, the **cystic artery** to supply blood to the gall bladder, and several branches, one to supply blood to the duodenum and another to supply blood to the pancreas. Two additional single vessels arise from the abdominal aorta. These are the superior and inferior mesenteric arteries. The **superior mesenteric artery** arises approximately 2.5 cm after the celiac trunk and branches into several major vessels that supply blood to the small intestine (duodenum, jejunum, and ileum), the pancreas, and a majority of the large intestine. The **inferior mesenteric artery** supplies blood to the distal segment of the large intestine, including the rectum. It arises approximately 5 cm superior to the common iliac arteries.
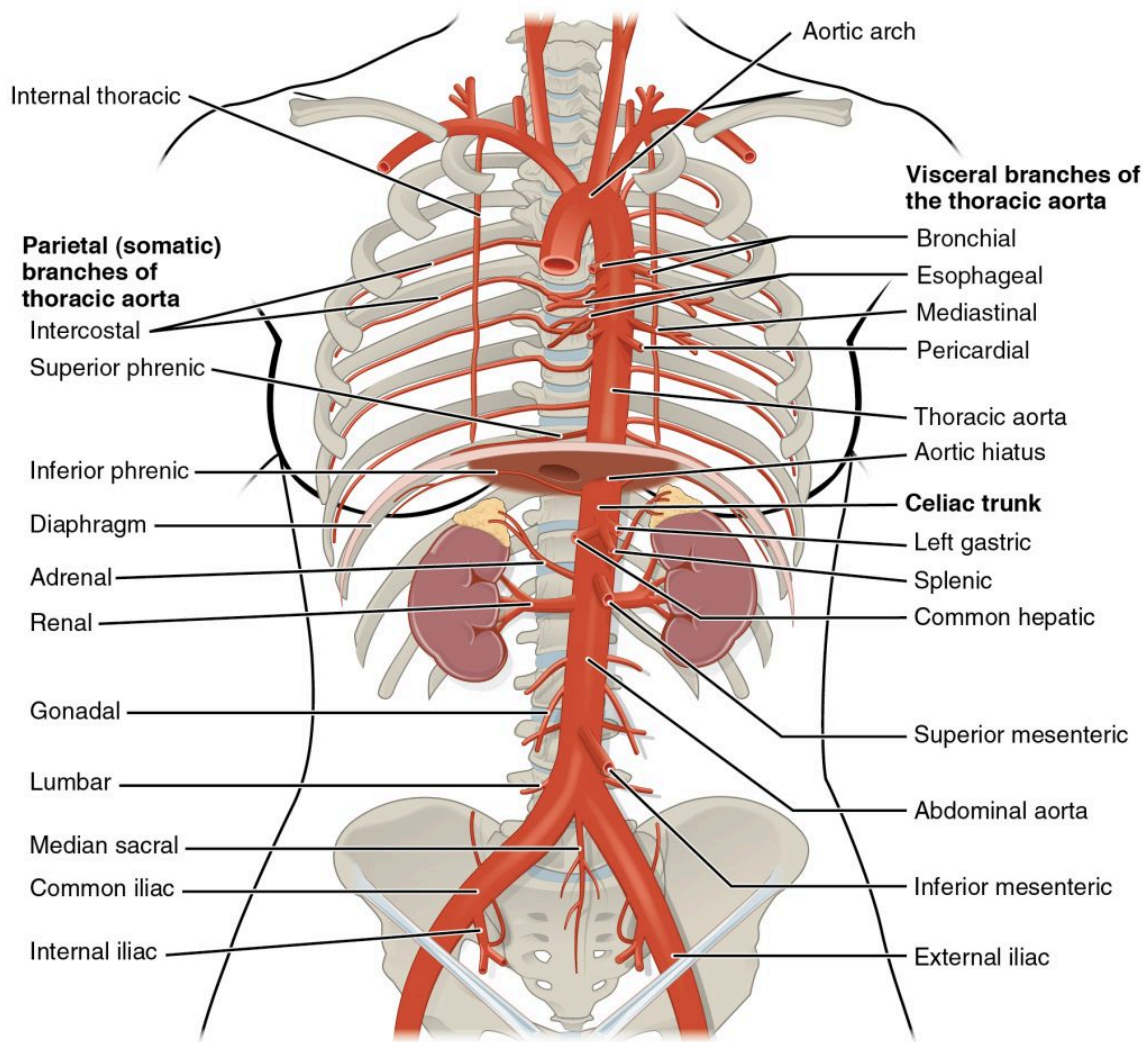
Figure 11.10 Arteries of the Thoracic and Abdominal Regions The thoracic aorta gives rise to the arteries of the visceral and parietal branches.

In addition to these single branches, the abdominal aorta gives rise to several significant paired arteries along the way. These include the inferior phrenic arteries, the adrenal arteries, the renal arteries, the gonadal arteries, and the lumbar arteries. Each **inferior phrenic artery** is supplies blood to the inferior surface of the diaphragm. The **adrenal artery** supplies blood to the adrenal (suprarenal) glands and arises near the superior mesenteric artery. Each **renal artery** branches approximately 2.5 cm inferior to the superior mesenteric arteries and supplies a kidney. The right renal artery is longer than the left since the aorta lies to the left of the vertebral column and the vessel must travel a greater distance to reach its target. Each **gonadal artery** supplies blood to the gonads, or reproductive organs, and is also described as either an ovarian artery or a testicular artery (internal spermatic), depending upon the sex of the individual. An **ovarian artery** supplies blood to an ovary, uterine (Fallopian) tube, and the uterus, and is located within the suspensory ligament of the uterus. It is considerably shorter than a **testicular artery**, which ultimately travels outside the body cavity to the testes, forming one component of the spermatic cord.The aorta divides at approximately the level of vertebra L4 into a left and a right **common iliac artery**. The common iliac arteries provide blood to the pelvic region and ultimately to the lower limbs. They split

into external and internal iliac arteries approximately at the level of the lumbar-sacral articulation. Each **internal iliac artery** sends branches to organs within the pelvic cavity. The much larger **external iliac artery** supplies blood to each of the lower limbs.

Arteries serving the lower limbs

The external iliac artery exits the body cavity and enters the femoral region of the lower leg (**Figure 11.11**). As it passes through the body wall, it is renamed the **femoral artery**. It has several smaller branches to supply thigh. As the femoral artery passes posterior to the knee near the popliteal fossa, it is called the popliteal artery. The **popliteal artery** branches into the anterior and posterior tibial arteries. The **anterior tibial artery** is located between the tibia and fibula, and supplies blood to the muscles and skin of the anterior tibial region. Upon reaching the tarsal region, it becomes the **dorsalis pedis artery**, which branches repeatedly and provides blood to the tarsal and dorsal regions of the foot. The **posterior tibial artery** provides blood to the muscles and skin on the posterior surface of the tibial region. The **fibular artery** (peroneal artery) branches from the posterior tibial artery.
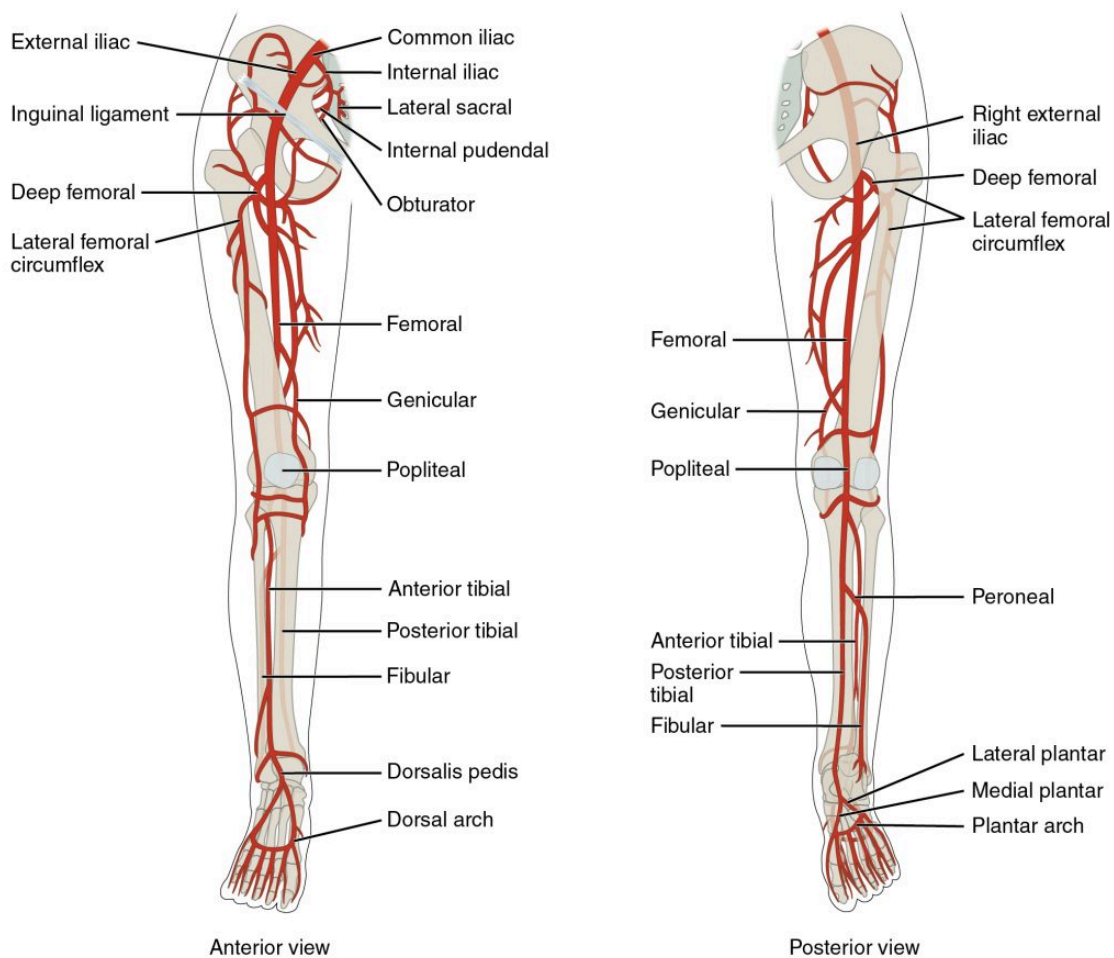

Figure 11.11 Major Arteries Serving the Lower Limb Major arteries serving the lower limb are shown in anterior and posterior views.

Overview of Systemic Veins

Systemic veins return blood to the right atrium. Since the blood has already passed through the systemic capillaries, it will be relatively low in oxygen concentration. In many cases, there will be veins draining organs and regions of the body with the same name as the arteries that supplied these regions and the two often parallel one another. This is often described as a "complementary" pattern. However, there is a great deal more variability in the venous circulation than normally occurs in the arteries.

In both the neck and limb regions, there are often both superficial and deeper levels of veins. The deeper veins generally correspond to the complementary arteries. The superficial veins do not normally have direct arterial counterparts, but in addition to returning blood, they also make contributions to the maintenance of body temperature. When the ambient temperature is warm, more blood is diverted to the superficial veins where heat can be more easily dissipated to the environment. In colder weather, there is more constriction of the superficial veins and blood is diverted deeper where the body can retain more of the heat.

Tracing blood flow through arteries follows the current in the direction of blood flow, so that we move from the heart through the large arteries and into the smaller arteries to the capillaries. From the capillaries, we move into the smallest veins and follow the direction of blood flow into larger veins and back to the heart. **Figure 11.12** below outlines the path of the major systemic veins.
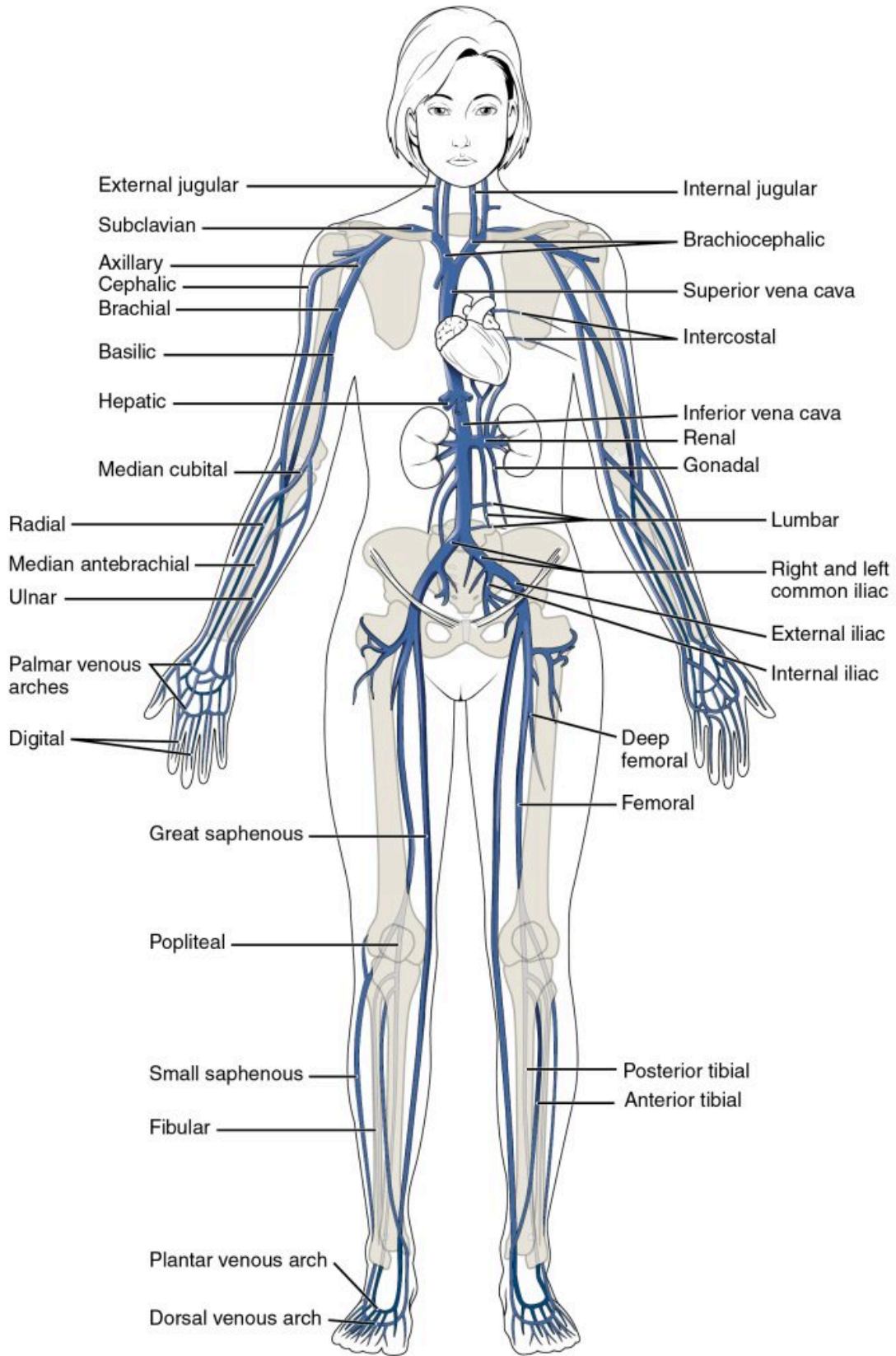
Figure 11.12 Major Systemic Veins of the Body The major systemic veins of the body are shown

The superior vena cava and veins of the head and neck

The right atrium receives all of the systemic venous return. Most of the blood flows into either the superior vena cava or inferior vena cava. If you draw an imaginary line at the level of the diaphragm, systemic venous circulation from above that line will generally flow into the **superior vena cava**; this includes blood from the head, neck, chest, shoulders, and upper limbs. The exception to this is that most venous blood flow from the coronary veins flows directly into the **coronary sinus** and from there directly into the right atrium. Beneath the diaphragm, systemic venous flow enters the **inferior vena cava**, that is, blood from the abdominal and pelvic regions and the lower limbs.

The **superior vena cava** drains most of the body superior to the diaphragm (**Figure 11.13**). On both the left and right sides, the **subclavian vein** forms when the axillary vein passes through the body wall from the axillary region. It fuses with the external and internal jugular veins from the head and neck to form the **brachiocephalic vein**.
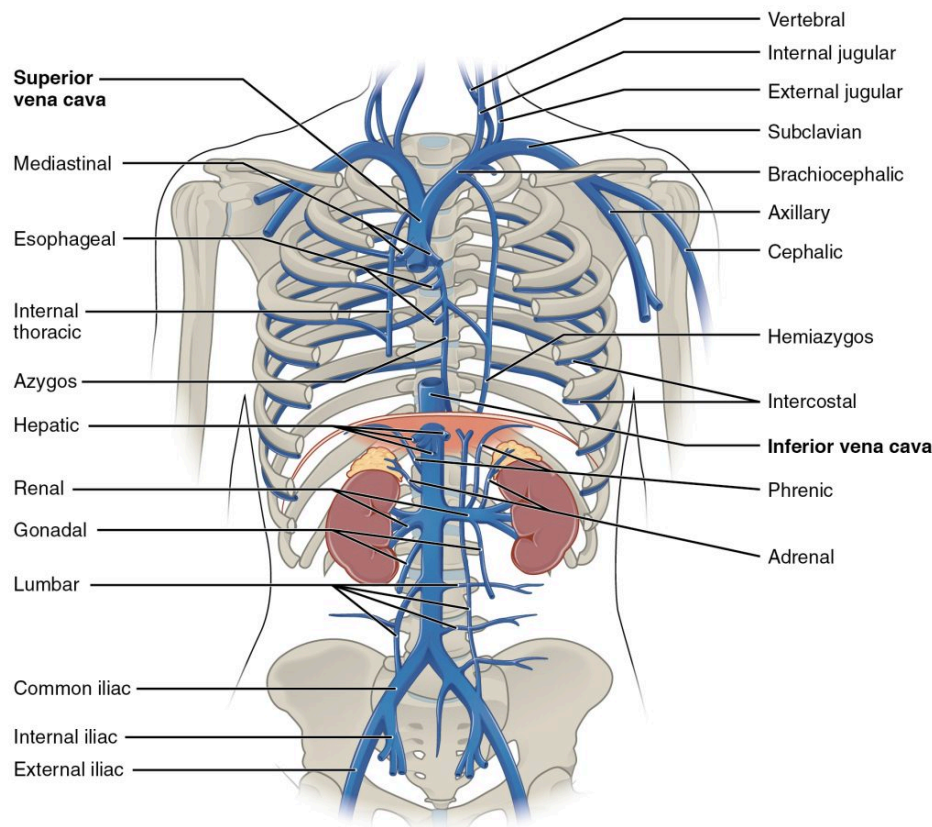

Figure 11.13 Veins of the Thoracic and Abdominal Regions Veins of the thoracic and abdominal regions drain blood from the area above the diaphragm, returning it to the right atrium via the superior vena cava.

Blood from the brain and the superficial facial vein flow into each **internal jugular vein** (**Figure 11.14**). Blood from the more superficial portions of the head, scalp, and cranial regions flow into each **external jugular vein**. Although

the external and internal jugular veins are separate vessels, there are anastomoses between them close to the thoracic region. Blood from the external jugular vein empties into the subclavian vein.
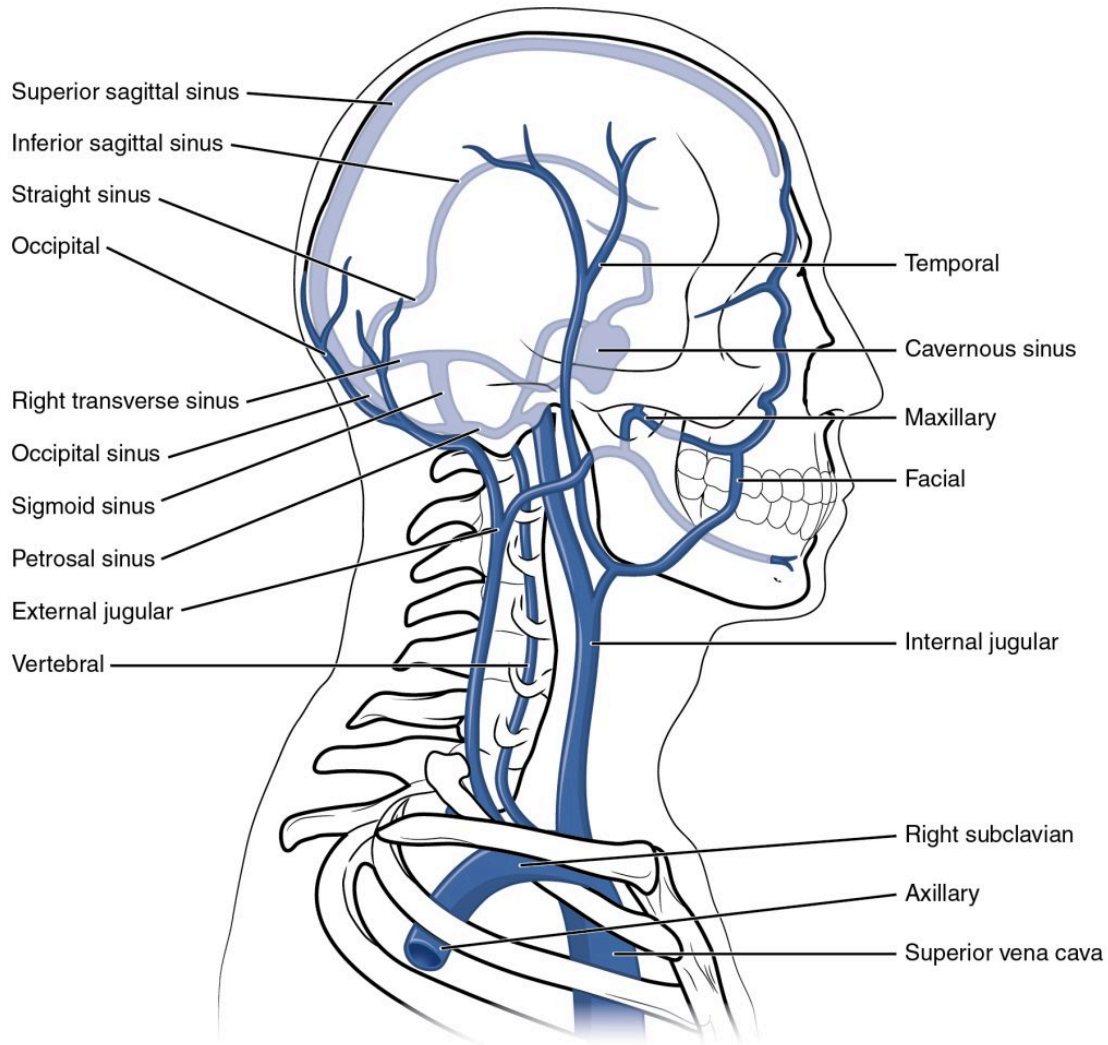

Figure 11.14 Veins of the Head and Neck This left lateral view shows the veins of the head and neck, including the intercranial sinuses.

Circulation to the brain is both critical and complex. Many smaller veins of the brain stem and the superficial veins of the cerebrum lead to larger vessels referred to as **dural venous sinuses**, located between layers of dura mater. These include the superior and inferior sagittal sinuses, straight sinus, cavernous sinuses, left and right sinuses, the petrosal sinuses, and the occipital sinuses. Ultimately, most of these sinuses will lead back to the inferior jugular vein.

Veins Draining the Upper Limbs

The **digital veins** in the fingers come together in the hand to form the **palmar venous arches** (**Figure 11.15**). From here, the veins come together to form the radial vein, the ulnar vein, and the median antebrachial vein.

The **radial vein** and the **ulnar vein** parallel the bones of the forearm and join together at the antebrachium to form the **brachial vein**, a deep vein that flows into the axillary vein in the brachium.
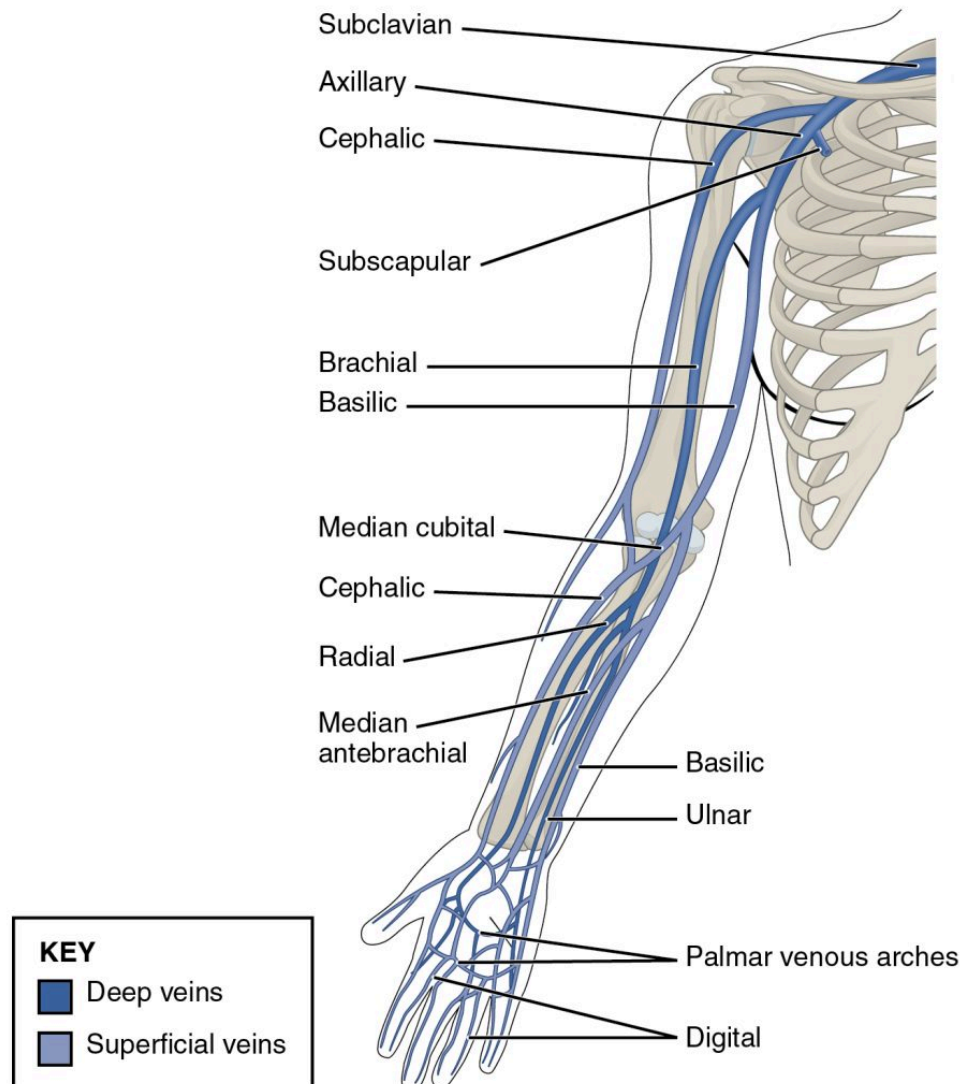

Figure 11.15 Veins of the Upper Limb This anterior view shows the veins that drain the upper limb.

The **median antebrachial vein** parallels the ulnar vein, is more medial in location, and joins the **basilic vein** in the forearm. As the basilic vein reaches the antecubital region, it gives off a branch called the **median cubital vein** that crosses at an angle to join the cephalic vein. The median cubital vein is the most common site for drawing venous blood in humans. The basilic vein continues through the arm medially and superficially to the axillary vein.

The **cephalic vein** begins in the antebrachium and drains blood from the superficial surface of the arm into the **axillary vein**. It is extremely superficial and easily seen along the surface of the biceps brachii muscle in individuals with good muscle tone and in those without excessive subcutaneous adipose tissue in the arms. As the **axillary vein** passes through the body wall and enters the thorax, it becomes the **subclavian vein**.

The inferior vena cava

Most of the blood inferior to the diaphragm drains into the inferior vena cava before it is returned to the heart. Lying just beneath the parietal peritoneum in the abdominal cavity, the **inferior vena cava** parallels the abdominal aorta, where it can receive blood from abdominal veins.

Blood supply from the kidneys flows into each **renal vein**, normally the largest veins entering the inferior vena cava. A number of other, smaller veins empty into the left renal vein. Each **adrenal vein** drains the adrenal or suprarenal glands located immediately superior to the kidneys. The right adrenal vein enters the inferior vena cava directly, whereas the left adrenal vein enters the left renal vein.

From the male reproductive organs, each **testicular vein** flows from the scrotum, forming a portion of the spermatic cord. Each **ovarian vein** drains an ovary in females. Each of these veins is generically called a **gonadal vein**. The right gonadal vein empties directly into the inferior vena cava, and the left gonadal vein empties into the left renal vein.

Each side of the diaphragm drains into a **phrenic vein**; the right phrenic vein empties directly into the inferior vena cava, whereas the left phrenic vein empties into the left renal vein. Blood supply from the liver drains into each **hepatic vein** and directly into the inferior vena cava. Since the inferior vena cava lies primarily to the right of the vertebral column and aorta, the left renal vein is longer, as are the left phrenic, adrenal, and gonadal veins. The longer length of the left renal vein makes the left kidney the primary target of surgeons removing this organ for donation.

Veins draining the lower limbs

From the smaller veins in the foot, blood supply drains into the anterior and posterior tibial veins. The **anterior tibial vein** drains the area near the tibialis anterior muscle and combines with the posterior tibial vein and the fibular vein to form the popliteal vein. The **posterior tibial vein** drains the posterior surface of the tibia and joins the popliteal vein. The **fibular vein** drains the muscles and skin in proximity to the fibula and also joins the **popliteal vein**. As the popliteal vein passes behind the knee in the popliteal region, it becomes the **femoral vein (Figure 11.16)**.
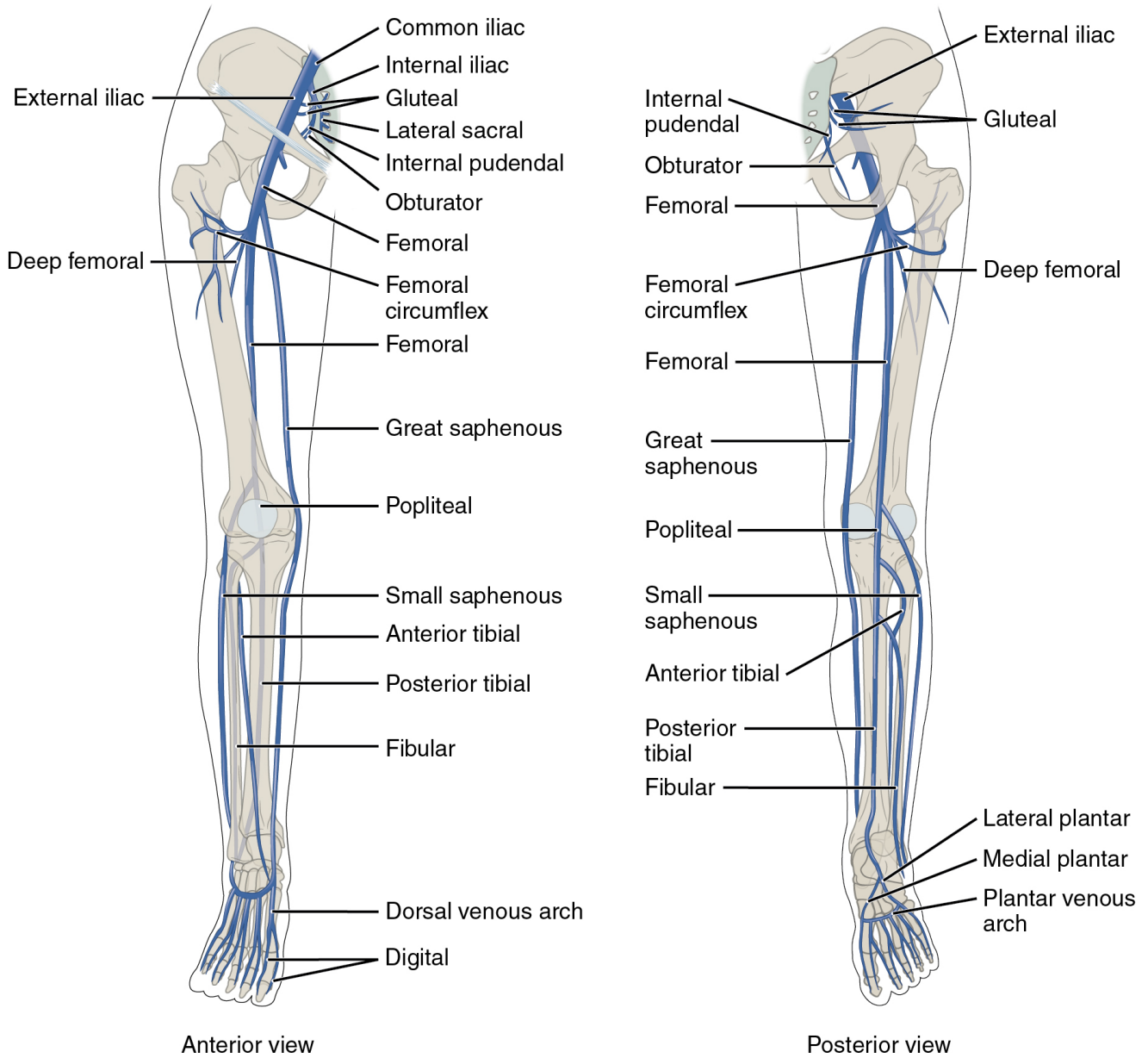
Figure 11.16 Major Veins Serving the Lower Limbs Anterior and posterior views show the major veins that drain the lower limb into the inferior vena cava.

The great saphenous vein and the deep femoral vein also drain into the femoral vein. The **great saphenous vein** is a prominent surface vessel located on the medial surface of the leg and thigh that collects blood from the superficial portions of these areas. The **deep femoral vein**, as the name suggests, drains blood from the deeper portions of the thigh.

As the **femoral vein** penetrates the body wall from the femoral portion of the upper limb, it becomes the **external iliac vein**, a large vein that drains blood from the leg to the common iliac vein. Smaller veins from the pelvic organs and skin drain into the **internal iliac vein**. The external and internal iliac veins combine near the inferior portion of

the sacroiliac joint to form the **common iliac vein**. Similar to the common iliac arteries, the common iliac veins come together at the level of L5 to form the **inferior vena cava**.

Hepatic portal system

The liver is a complex biochemical processing plant. It packages nutrients absorbed by the digestive system; produces plasma proteins, clotting factors, and bile; and disposes of worn-out cell components and waste products. Instead of entering the circulation directly, absorbed nutrients and certain wastes (for example, materials produced by the spleen) travel to the liver for processing. They do so via the **hepatic portal system** (**Figure 11.17**). Portal systems begin and end in capillaries. In this case, the initial capillaries from the stomach, small intestine, large intestine, and spleen lead to the hepatic portal vein and end in specialized capillaries within the liver, the hepatic sinusoids.
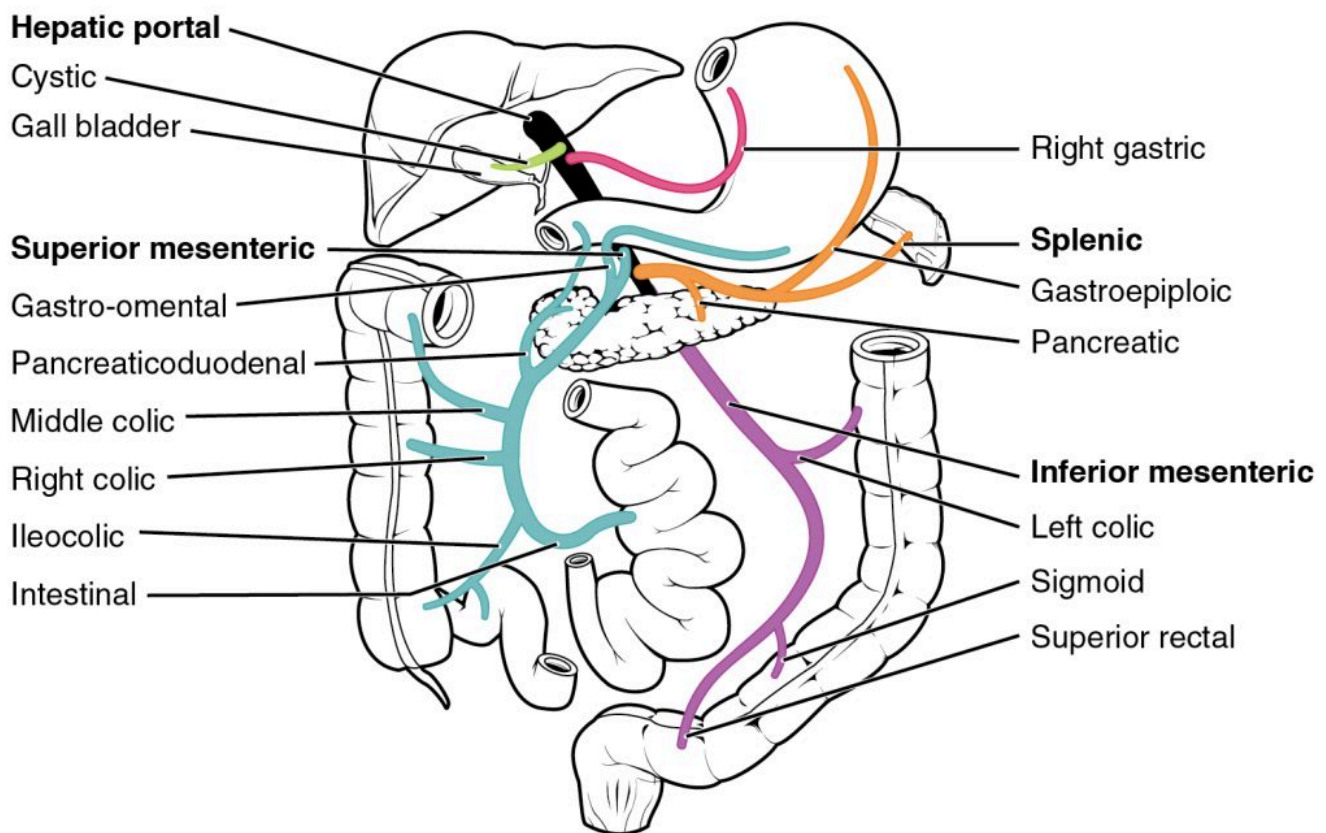

Figure 11.17 Hepatic Portal System The liver receives blood from the normal systemic circulation via the hepatic artery. It also receives and processes blood from other organs, delivered via the veins of the hepatic portal system. All blood exits the liver via the hepatic vein, which delivers the blood to the inferior vena cava. (Different colors are used to help distinguish among the different vessels in the system.)

The hepatic portal system consists of the hepatic portal vein and the veins that drain into it. The **hepatic portal vein** itself is relatively short, beginning at the level of L2 with the confluence of the superior mesenteric vein and splenic vein. It also receives blood from the inferior mesenteric vein. The **superior mesenteric vein** receives blood from the small intestine, two-thirds of the large intestine, and the stomach. The **inferior mesenteric vein** drains the distal third of the large intestine, including the descending colon, the sigmoid colon, and the rectum. The **splenic**

vein is formed from branches from the spleen, pancreas, and portions of the stomach, and the inferior mesenteric vein. After its formation, the hepatic portal vein also receives branches from the gastric veins of the stomach and cystic veins from the gall bladder. The **hepatic portal vein** delivers materials from these digestive and circulatory organs directly to the liver for processing.Because of the hepatic portal system, the liver receives its blood supply from two different sources: from normal systemic circulation via the hepatic artery and from the hepatic portal vein. The liver processes the blood from the portal system to remove certain wastes and excess nutrients, which are stored for later use. This processed blood, as well as the systemic blood that came from the hepatic artery, exits the liver via the **right, left, and middle hepatic veins**, and flows into the **inferior vena cava**.

Lab 12: Lymphatic & Respiratory systems

In Week 12, we will study two organ systems, the lymphatic and respiratory systems, that both work closely with the cardiovascular system to carry out important functions in the body.

The Lymphatic System

The **lymphatic system** includes organs and vessels dispersed throughout the body that assist in two major functions: returning excess fluid from tissues to the bloodstream and monitoring body fluids for pathogens in order to mount an immune response. Lymphatic vessels absorb and return interstitial fluid to the vessels of the circulatory system. They also transport lymphocytes, the main cells of the immune system. Lymphocytes come from the hematopoietic system of the bone marrow. Primary lymphoid organs, the bone marrow and thymus gland, are the locations where lymphocytes proliferate and mature. Secondary lymphoid organs are the site in which mature lymphocytes congregate to mount immune responses. Many immune system cells use the lymphatic and circulatory systems for transport throughout the body to search for and then protect against pathogens.

Functions of the Lymphatic System

A major function of the lymphatic system is to drain body fluids and return them to the bloodstream. Blood pressure causes leakage of fluid from the capillaries, resulting in the accumulation of fluid in the interstitial space—that is, spaces between individual cells in the tissues. In humans, 20 liters of plasma is released into the interstitial space of the tissues each day due to capillary filtration. Once this filtrate is out of the bloodstream

and in the tissue spaces, it is referred to as interstitial fluid. Of this, 17 liters is reabsorbed directly by the blood vessels. But what happens to the remaining three liters? This is where the lymphatic system comes into play. It drains the excess fluid and empties it back into the bloodstream via a series of vessels, trunks, and ducts. **Lymph** is the term used to describe interstitial fluid once it has entered the lymphatic system. When the lymphatic system is damaged in some way, such as by being blocked by cancer cells or destroyed by injury, protein-rich interstitial fluid accumulates (sometimes "backs up" from the lymph vessels) in the tissue spaces. This inappropriate accumulation of fluid referred to as lymphedema may lead to serious medical consequences.

As the vertebrate immune system evolved, the network of lymphatic vessels became convenient avenues for transporting the cells of the immune system. Additionally, the transport of dietary lipids and fat-soluble vitamins absorbed in the gut uses this system.

Cells of the immune system not only use lymphatic vessels to make their way from interstitial spaces back into the circulation, but they also use lymph nodes as major staging areas for the development of critical immune responses. A **lymph node** is one of the small, bean-shaped organs located throughout the lymphatic system.

Structure of the Lymphatic System

The lymphatic vessels begin as a blind ending, or closed at one end, capillaries, which feed into larger and larger lymphatic vessels, and eventually empty into the bloodstream by a series of ducts. Along the way, the lymph travels through the lymph nodes, which are commonly found near the groin, armpits, neck, chest, and abdomen. Humans have about 500−600 lymph nodes throughout the body (**Figure 12.1**).
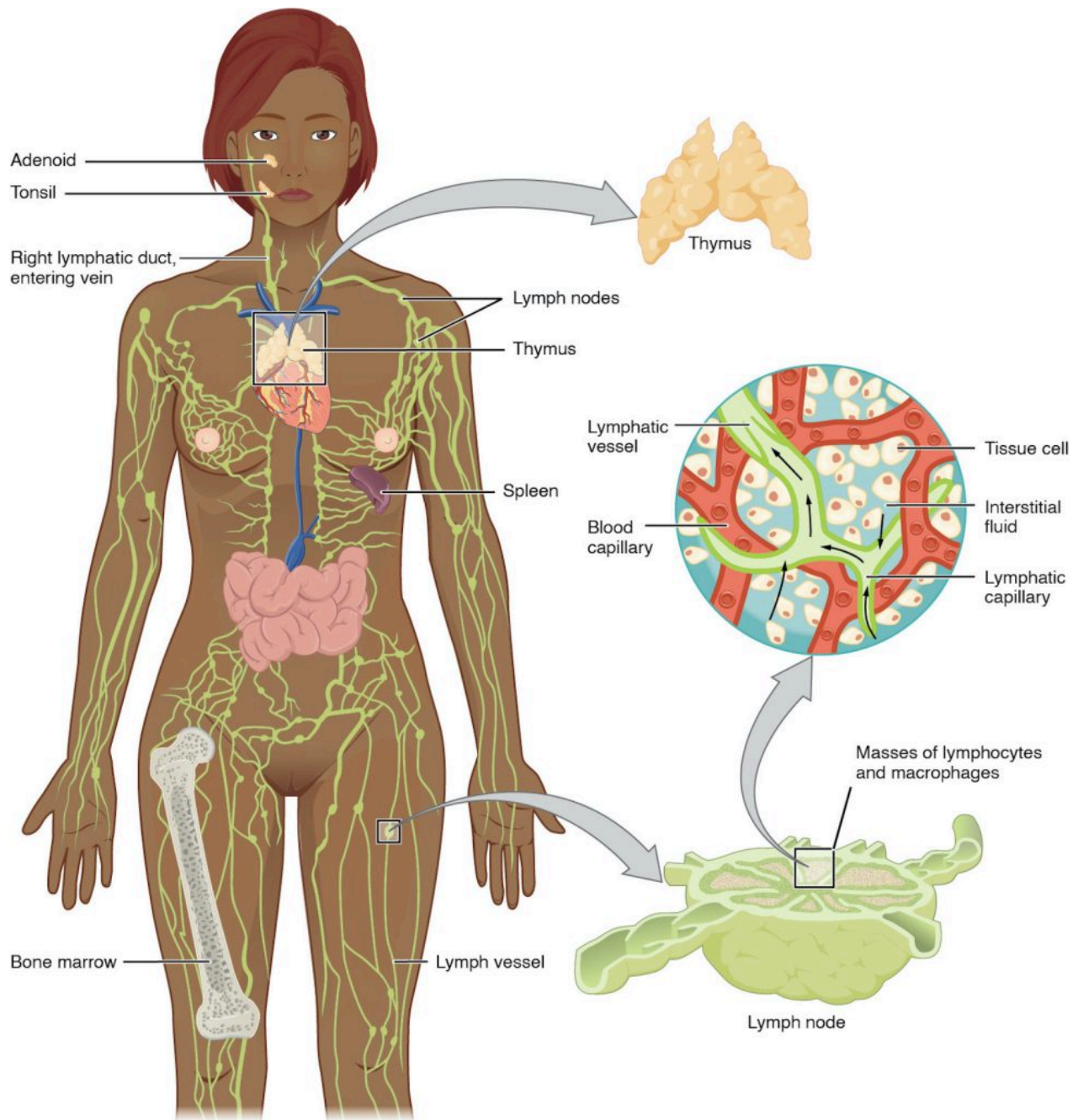
Figure 12.1 Anatomy of the Lymphatic System Lymphatic vessels in the arms and legs convey lymph to the larger lymphatic vessels in the torso.

A major distinction between the lymphatic and cardiovascular systems in humans is that lymph is not actively pumped by the heart, but is forced through the vessels by the movements of the body, the contraction of skeletal muscles during body movements, and breathing. One-way valves (semi-lunar valves) in lymphatic vessels keep the lymph moving toward the heart. Lymph flows from the lymphatic capillaries, through lymphatic vessels, and then is dumped into the circulatory system via the lymphatic ducts located at the junction of the jugular and subclavian veins in the neck.

Lymphatic Capillaries

Lymphatic capillaries, also called the terminal lymphatics, are vessels where interstitial fluid enters the lymphatic system to become lymph fluid. Located in almost every tissue in the body, these vessels are interlaced among the arterioles and venules of the circulatory system in the soft connective tissues of the body (**Figure 12.2**). Exceptions are the central nervous system, bone marrow, bones, teeth, and the cornea of the eye, which do not contain lymph vessels.
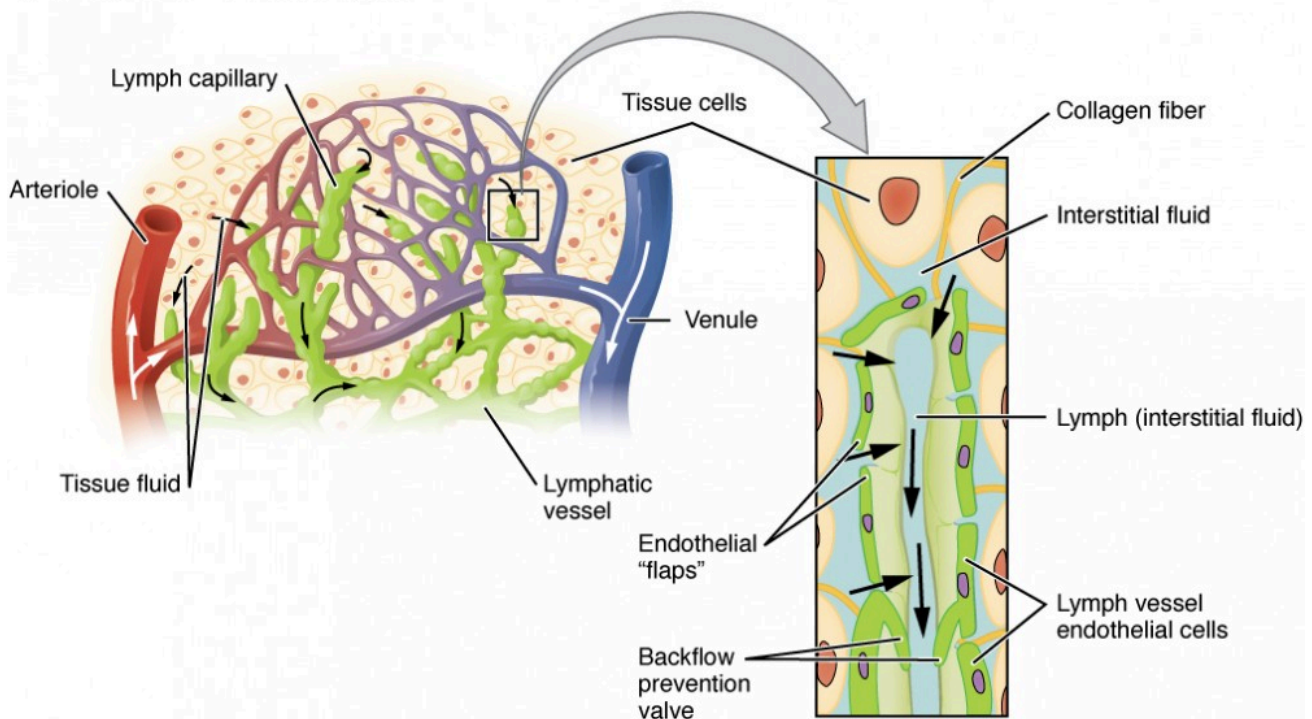

Figure 12.2 Lymphatic Capillaries Lymphatic capillaries are interlaced with the arterioles and venules of the cardiovascular system. Collagen fibers anchor a lymphatic capillary in the tissue (inset). Interstitial fluid slips through spaces between the overlapping endothelial cells that compose the lymphatic capillary.

Lymphatic capillaries are formed by a one cell-thick layer of endothelial cells and represent the open end of the system, allowing interstitial fluid to flow into them via overlapping cells (**see Figure 12.2**). When interstitial pressure is low, the endothelial flaps close to prevent "backflow." As interstitial pressure increases, the spaces between the cells open up, allowing the fluid to enter. Entry of fluid into lymphatic capillaries is also enabled by the collagen filaments that anchor the capillaries to surrounding structures. As interstitial pressure increases, the filaments pull on the endothelial cell flaps, opening up them even further to allow easy entry of fluid.

In the small intestine, lymphatic capillaries called **lacteals** are critical for the transport of dietary lipids and lipid-soluble vitamins to the bloodstream. In the small intestine, dietary triglycerides combine with other lipids and proteins, and enter the lacteals to form a milky fluid called **chyle**. The chyle then travels through the lymphatic system, eventually entering the bloodstream.

Larger Lymphatic Vessels, Trunks, and Ducts

The lymphatic capillaries empty into larger lymphatic vessels, which are similar to veins in terms of their three-tunic structure and the presence of valves. These one-way valves are located fairly close to one another, and each one causes a bulge in the lymphatic vessel, giving the vessels a beaded appearance.

The superficial and deep lymphatics eventually merge to form larger lymphatic vessels known as **lymphatic trunks**. On the right side of the body, the right sides of the head, thorax, and right upper limb drain lymph fluid into the right subclavian vein via the **right lymphatic duct**. On the left side of the body, the remaining portions of the body drain into the larger **thoracic duct**, which drains into the left subclavian vein. The thoracic duct itself begins just beneath the diaphragm in the **cisterna chyli**, a sac-like chamber that receives lymph from the lower abdomen, pelvis, and lower limbs by way of the left and right lumbar trunks and the intestinal trunk (**Figure 12.3**)
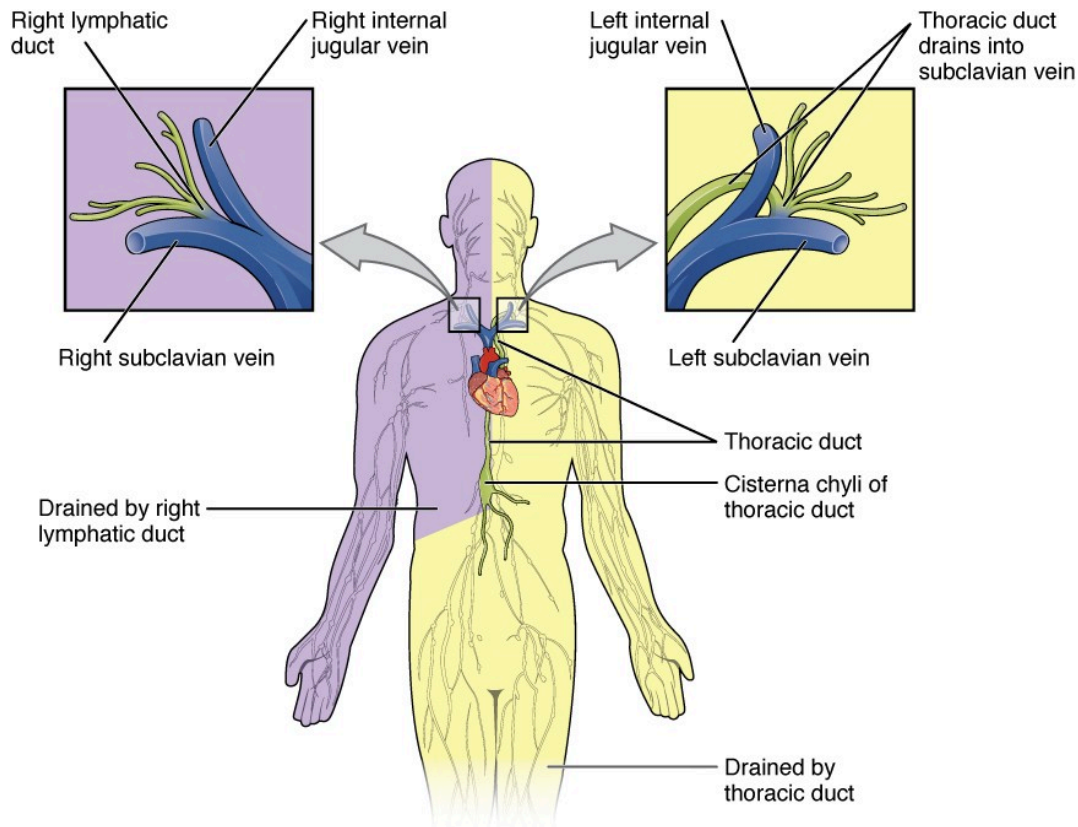

Figure 12.3 Major Trunks and Ducts of the Lymphatic System The thoracic duct drains a much larger portion of the body than does the right lymphatic duct.

The overall drainage system of the body is asymmetrical. The **right lymphatic duct** receives lymph from only the upper right side of the body. The lymph from the rest of the body enters the bloodstream through the **thoracic duct** via all the remaining lymphatic trunks. In general, lymphatic vessels of the subcutaneous tissues of the skin, that is, the superficial lymphatics, follow the same routes as veins, whereas the deep lymphatic vessels of the viscera generally follow the paths of arteries.

Primary Lymphoid Organs and Lymphocyte Development

Understanding the differentiation and development of B and T cells is critical to the understanding of the adaptive immune response. It is through this process that the body (ideally) learns to destroy only pathogens and leaves the body's own cells relatively intact. The **primary lymphoid organs** are the bone marrow and thymus gland. The primary lymphoid organs are where lymphocytes mature, proliferate, and are selected, which enables them to attack pathogens without harming the cells of the body.

Bone Marrow

In the embryo, blood cells are made in the yolk sac. As development proceeds, this function is taken over by the spleen, lymph nodes, and liver. Later, the bone marrow takes over most hematopoietic functions, although the final stages of the differentiation of some cells may take place in other organs. The **red bone marrow** is a loose collection of cells where hematopoiesis occurs (review Chapters 4 and 10 for the location of red bone marrow and a discussion on hematopoiesis, respectively). The B cell undergoes nearly all of its development in the red bone marrow, whereas the immature T cell, called a thymocyte, leaves the bone marrow and matures largely in the thymus gland.

Thymus

The **thymus** gland is a bilobed organ found in the space between the sternum and the aorta of the heart (**Figure 12.4**). It is larger and more active during infancy and early childhood, and begins to atrophy as we age.

Connective tissue holds the lobes closely together but also separates them and forms a capsule. The connective tissue capsule further divides the thymus into lobules via extensions called trabeculae. The outer region of the organ is known as the cortex and contains large numbers of thymocytes with some epithelial cells, macrophages, and dendritic cells (two types of phagocytic cells that are derived from monocytes). The cortex is densely packed so it stains more intensely than the rest of the thymus. The medulla, where thymocytes migrate before leaving the thymus, contains a less dense collection of thymocytes, epithelial cells, and dendritic cells.
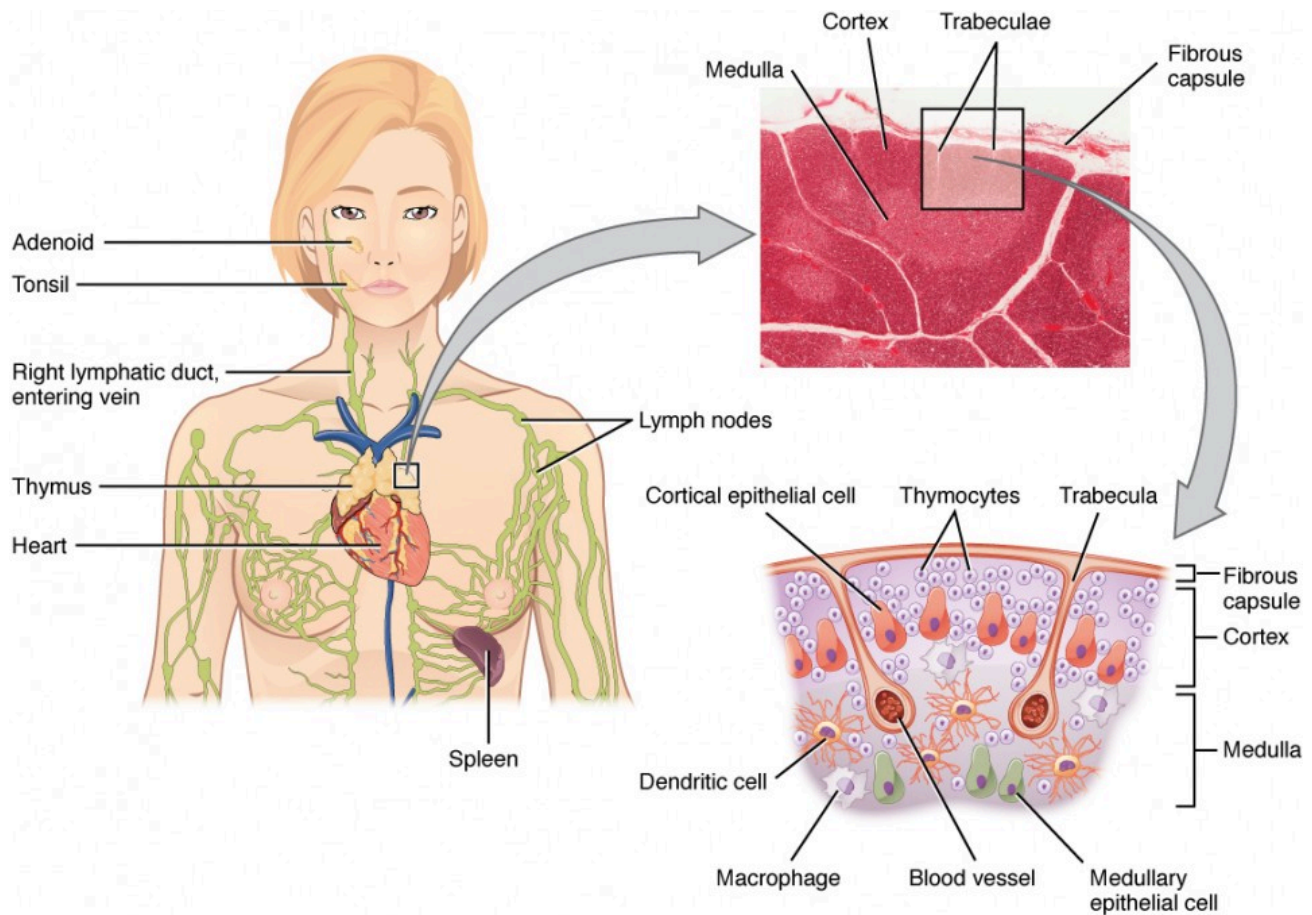
Figure 12.4 Location, Structure, and Histology of the Thymus The thymus lies above the heart. The trabeculae and lobules, including the darkly staining cortex and the lighter staining medulla of each lobule, are clearly visible in the light micrograph of the thymus of a newborn. LM × 100. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Secondary Lymphoid Organs and their Roles in Active Immune Responses

Lymphocytes develop and mature in the primary lymphoid organs, but they mount immune responses from the **secondary lymphoid organs**. A **naïve lymphocyte** is one that has left the primary organ and entered a secondary lymphoid organ. Naïve lymphocytes are fully functional immunologically, but have yet to encounter an antigen to respond to. In addition to circulating in the blood and lymph, lymphocytes concentrate in secondary lymphoid organs, which include the lymph nodes, spleen, and lymphoid nodules. All of these tissues have many features in common, including the following:

- The presence of lymphoid follicles, the sites of the formation of lymphocytes, with specific B cell-rich and T cell-rich areas
- An internal structure of reticular fibers with associated fixed macrophages
- **Germinal centers**, which are the sites of rapidly dividing B lymphocytes and plasma cells, with the exception of the spleen
- Specialized post-capillary vessels known as **high endothelial venules**; the cells lining these venules are

thicker and more columnar than normal endothelial cells, which allow cells from the blood to directly enter these tissues

Lymph Nodes

Lymph nodes are found in many areas of the body and are often located in clusters that lymph vessels connect to and flow through. **Figure 12.5** shows the locations of lymph nodes throughout the body.
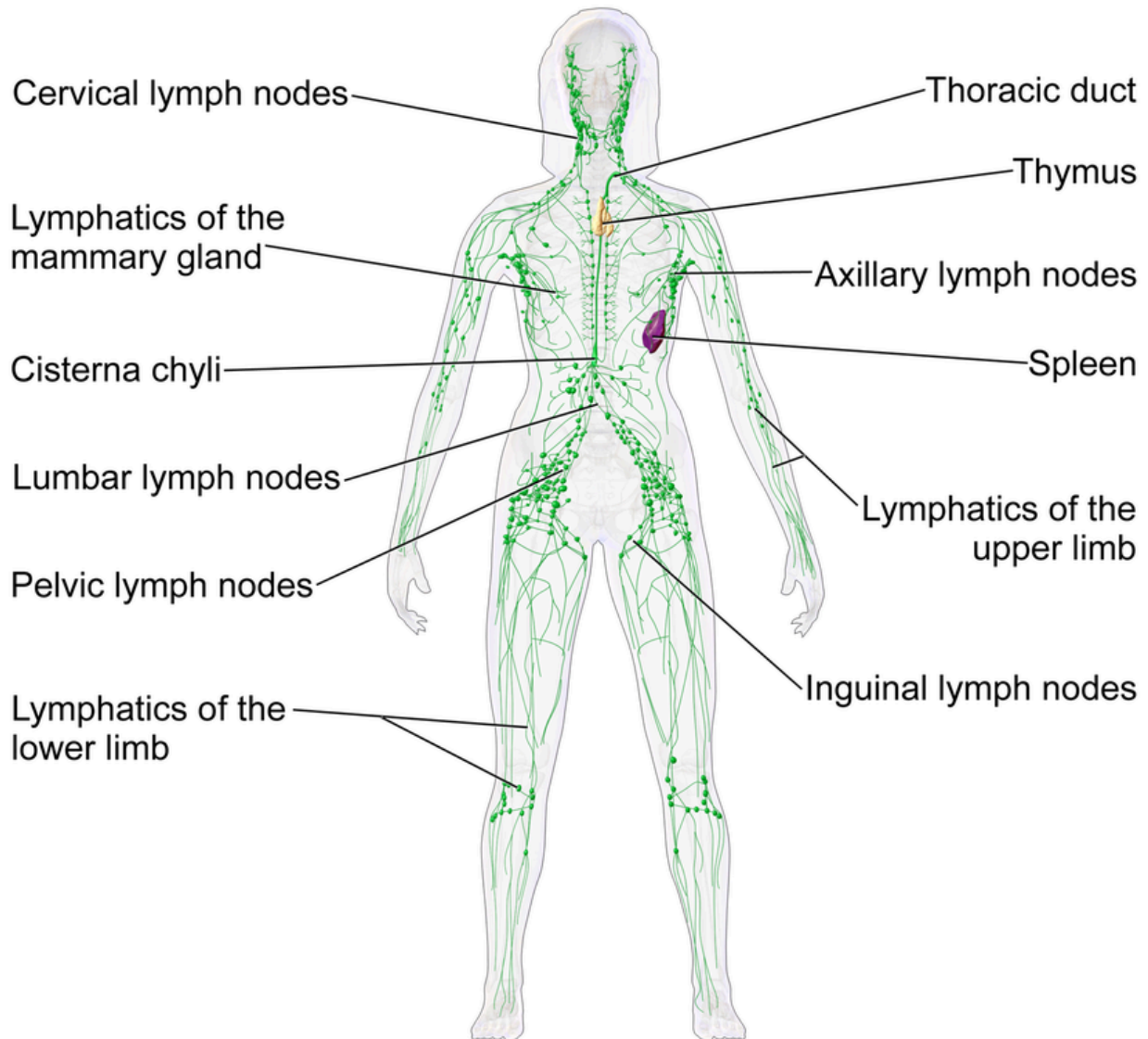

Figure 12.5 Lymphatic System. Image Source: Blausen Medical via Wikimedia Commons, CC BY 3.0.

Lymph nodes function to remove debris and pathogens from the lymph, and are thus sometimes referred to as the "filters of the lymph" (**Figure 12.6**). Any bacteria that infect the interstitial fluid are taken up by the lymphatic capillaries and transported to a regional lymph node. Dendritic cells and macrophages within this organ internalize and kill many of the pathogens that pass through, thereby removing them from the body. The lymph node is also the site of adaptive immune responses mediated by T cells, B cells, and accessory cells of the

adaptive immune system. Like the thymus, the bean-shaped lymph nodes are surrounded by a tough capsule of connective tissue and are separated into compartments by trabeculae, the extensions of the capsule. In addition to the structure provided by the capsule and trabeculae, the structural support of the lymph node is provided by a series of reticular fibers laid down by fibroblasts.
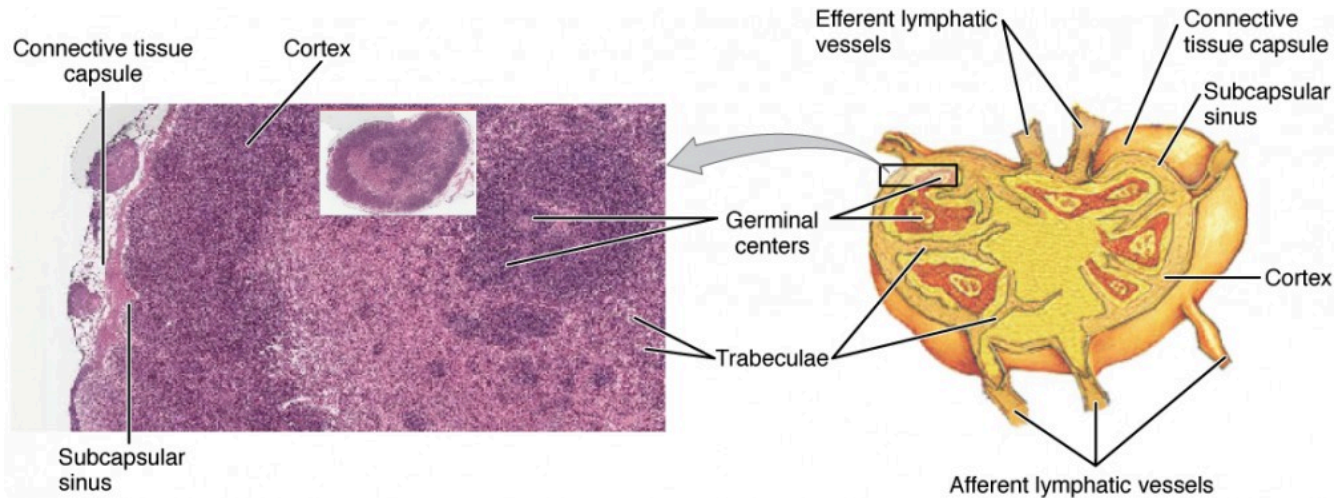

Figure 12.6 Structure and Histology of a Lymph Node Lymph nodes are masses of lymphatic tissue located along the larger lymph vessels. The micrograph of the lymph nodes shows a germinal center, which consists of rapidly dividing B cells surrounded by a layer of T cells and other accessory cells. LM × 128. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

The major routes into the lymph node are via **afferent lymphatic vessels** (**Figure 12.6**). Cells and lymph fluid that leave the lymph node may do so by another set of vessels known as the **efferent lymphatic vessels**. Lymph enters the lymph node via the subcapsular sinus, which is occupied by dendritic cells, macrophages, and reticular fibers. Within the cortex of the lymph node are lymphoid follicles, which consist of **germinal centers** of rapidly dividing B cells surrounded by a layer of T cells and other accessory cells. As the lymph continues to flow through the node, it enters the medulla, which consists of medullary cords of B cells and plasma cells, and the medullary sinuses where the lymph collects before leaving the node via the efferent lymphatic vessels.

Spleen

In addition to the lymph nodes, the **spleen** is a major secondary lymphoid organ (**Figure 12.7**). It is about 12 cm (5 in) long and is attached to the lateral border of the stomach via the gastrosplenic ligament. The spleen is a fragile organ without a strong capsule, and is dark red due to its extensive vascularization. The spleen is sometimes called the "filter of the blood" because of its extensive vascularization and the presence of macrophages and dendritic cells that remove microbes and other materials from the blood, including dying red blood cells. The spleen also functions as the location of immune responses to blood-borne pathogens.
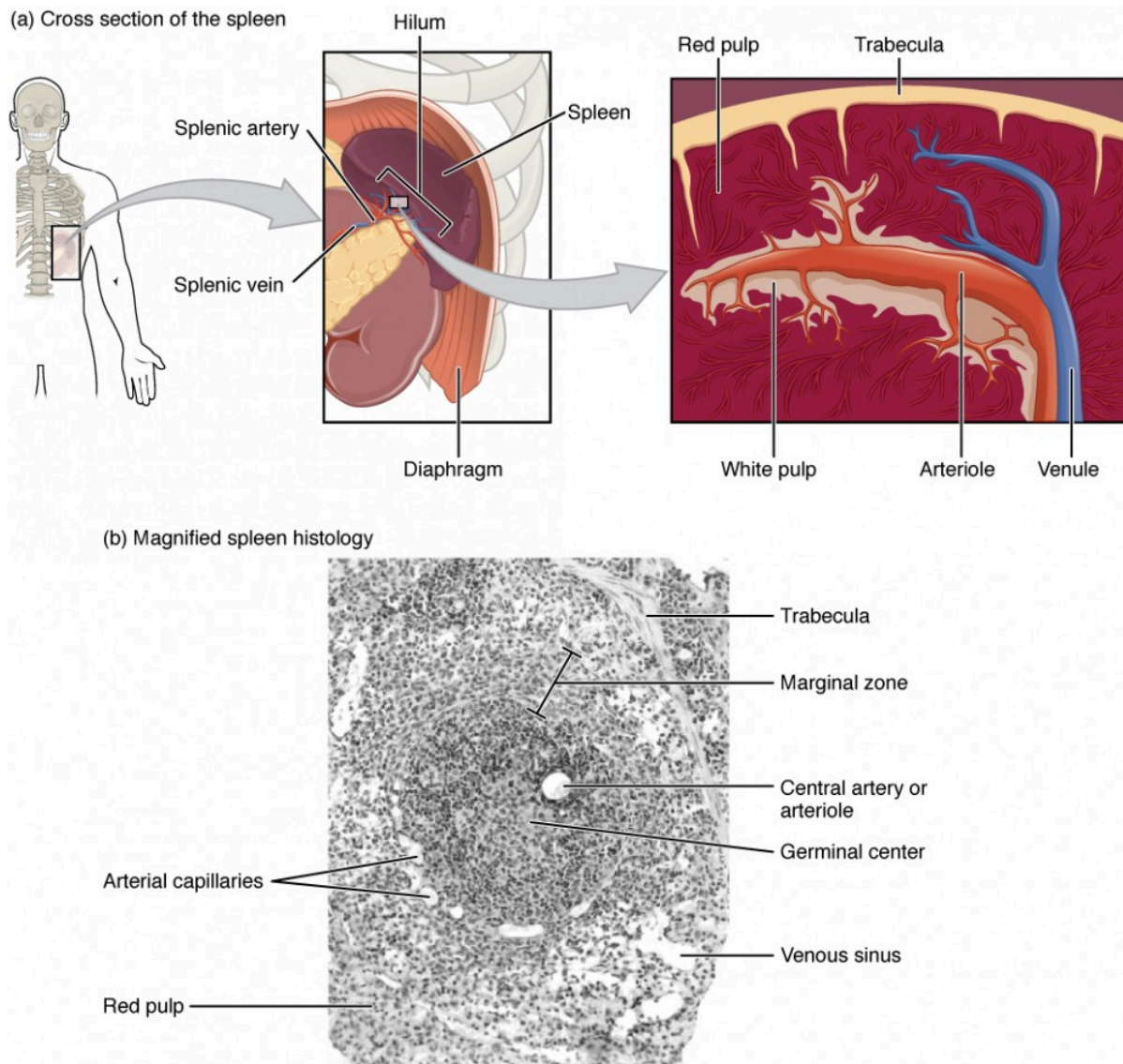
(a) Cross section of the spleen

Hilum

Splenic artery

Spleen

Splenic vein

Diaphragm

Red pulp

Trabecula

White pulp

Arteriole

Venule

(b) Magnified spleen histology

Trabecula

Marginal zone

Central artery or arteriole

Germinal center

Arterial capillaries

Venous sinus

Red pulp

Figure 12.7 Spleen (a) The spleen is attached to the stomach. (b) A micrograph of spleen tissue shows the germinal center. The marginal zone is the region between the red pulp and white pulp, which sequesters particulate antigens from the circulation and presents these antigens to lymphocytes in the white pulp. EM × 660. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

The spleen is also divided by trabeculae of connective tissue, and within each splenic nodule is an area of red pulp, consisting of mostly red blood cells, and white pulp, which resembles the lymphoid follicles of the lymph nodes. Upon entering the spleen, the splenic artery splits into several arterioles (surrounded by white pulp) and eventually into sinusoids. Blood from the capillaries subsequently collects in the venous sinuses and leaves via the splenic vein. The red pulp consists of reticular fibers with fixed macrophages attached, free macrophages, and all of the other cells typical of the blood, including some lymphocytes. The white pulp surrounds a central arteriole and consists of germinal centers of dividing B cells surrounded by T cells and accessory cells, including macrophages and dendritic cells. Thus, the red pulp primarily functions as a filtration system of the blood, using cells of the relatively nonspecific immune response, and white pulp is where adaptive T and B cell responses are mounted.

Lymphoid Nodules

The other lymphoid tissues, the **lymphoid nodules**, have a simpler architecture than the spleen and lymph nodes in that they consist of a dense cluster of lymphocytes without a surrounding fibrous capsule. These nodules are located in the respiratory and digestive tracts, areas routinely exposed to environmental pathogens.

Tonsils are lymphoid nodules located along the inner surface of the pharynx and are important in developing immunity to oral pathogens (**Figure 12.8**). The tonsil located at the back of the throat, the pharyngeal tonsil, is sometimes referred to as the adenoid when swollen. Such swelling is an indication of an active immune response to infection. Histologically, tonsils do not contain a complete capsule, and the epithelial layer invaginates deeply into the interior of the tonsil to form tonsillar crypts. These structures, which accumulate all sorts of materials taken into the body through eating and breathing, actually "encourage" pathogens to penetrate deep into the tonsillar tissues where they are acted upon by numerous lymphoid follicles and eliminated. This seems to be the major function of tonsils—to help children's bodies recognize, destroy, and develop immunity to common environmental pathogens so that they will be protected in their later lives. Tonsils are often removed in those children who have recurring throat infections, especially those involving the palatine tonsils on either side of the throat, whose swelling may interfere with their breathing and/or swallowing.

(a) Locations of the tonsils
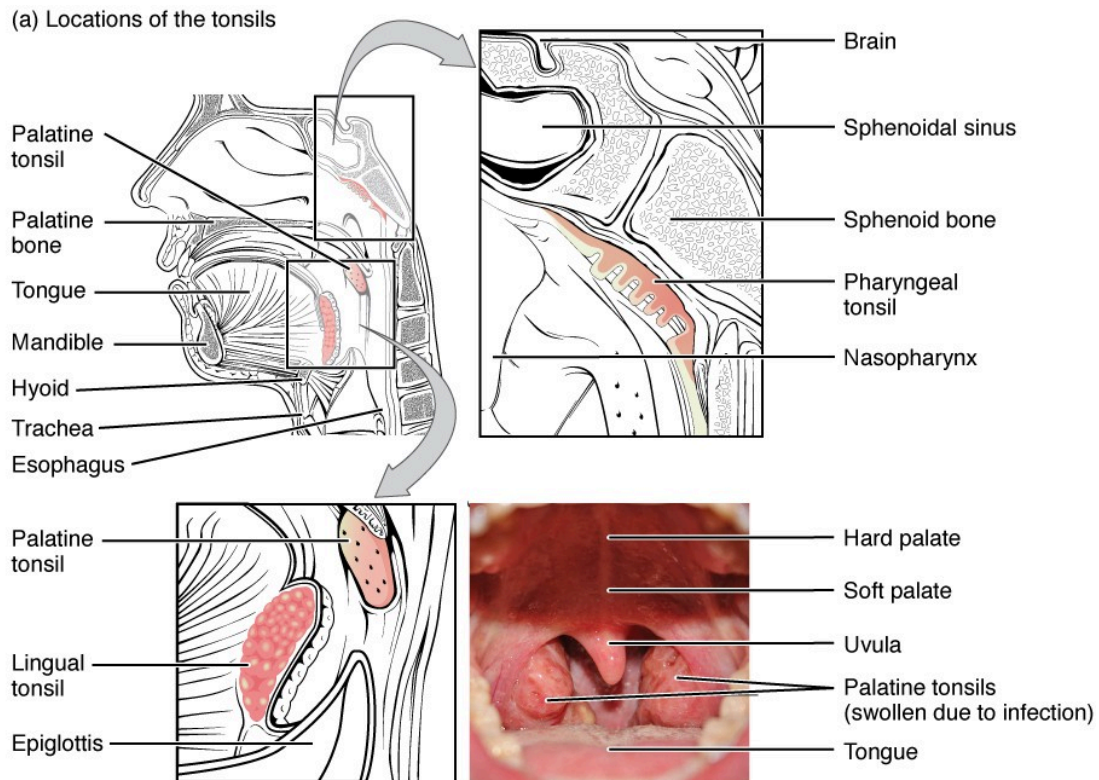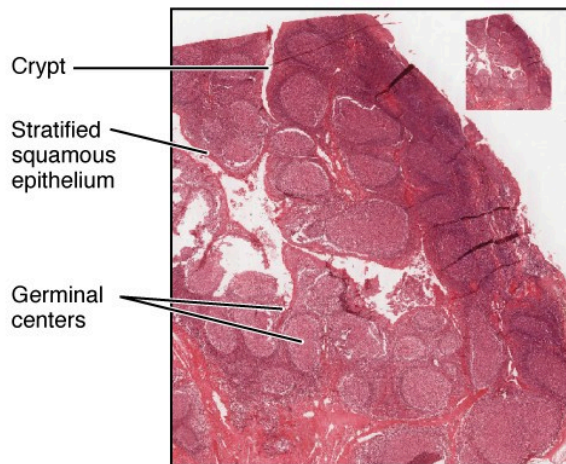
(b) Histology of palatine tonsil

Figure 12.8 Locations and Histology of the Tonsils (a) The pharyngeal tonsil is located on the roof of the posterior superior wall of the nasopharynx. The palatine tonsils lay on each side of the pharynx. (b) A micrograph shows the palatine tonsil tissue. LM × 40. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Mucosa-associated lymphoid tissue (MALT) consists of an aggregate of lymphoid follicles directly associated with the mucous membrane epithelia. MALT makes up dome-shaped structures found underlying the mucosa of

the gastrointestinal tract, breast tissue, lungs, and eyes. Peyer's patches, a type of MALT in the small intestine, are especially important for immune responses against ingested substances (**Figure 12.9**). Peyer's patches contain specialized endothelial cells called M (or microfold) cells that sample material from the intestinal lumen and transport it to nearby follicles so that adaptive immune responses to potential pathogens can be mounted.
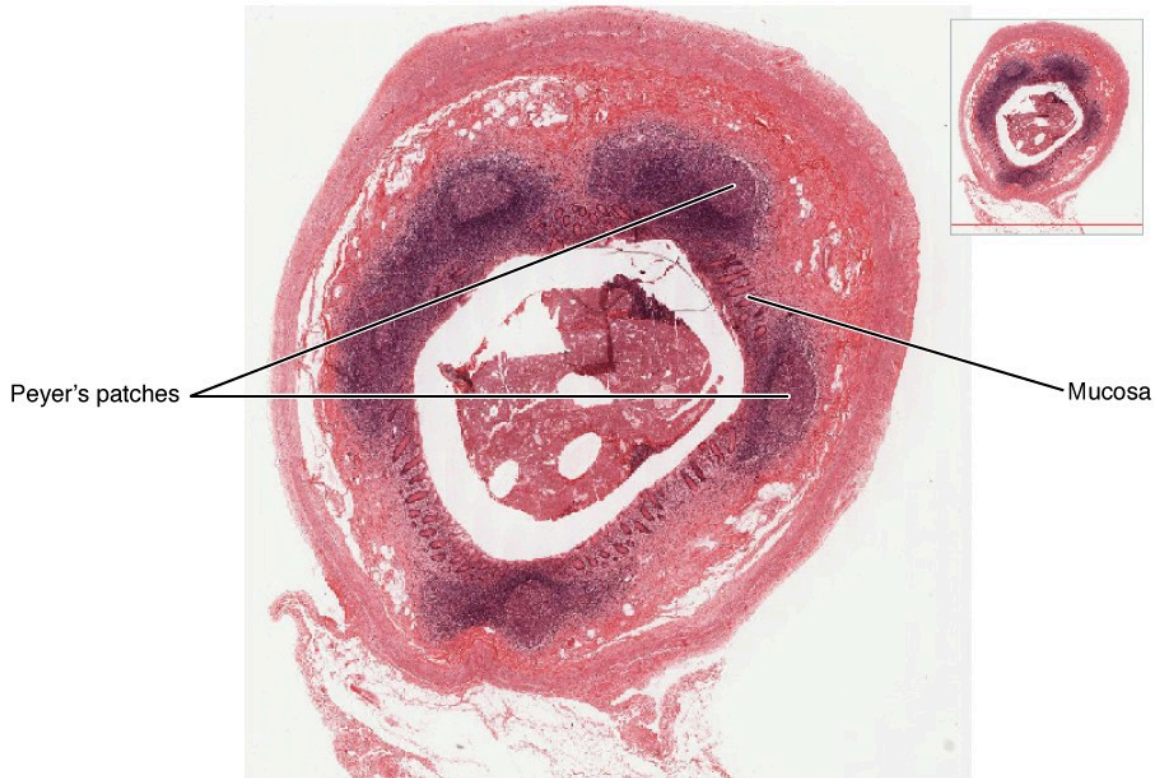

Figure 12.9 Mucosa-associated Lymphoid Tissue (MALT) Nodule LM LM × 40. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Bronchus-associated lymphoid tissue (BALT) consists of lymphoid follicular structures with an overlying epithelial layer found along the bifurcations of the bronchi, and between bronchi and arteries. They also have the typically less-organized structure of other lymphoid nodules. These tissues, in addition to the tonsils, are effective against inhaled pathogens.

The Respiratory System

Hold your breath. Really! See how long you can hold your breath as you continue reading…How long can you do it? Chances are you are feeling uncomfortable already. A typical human cannot survive without breathing for more than 3 minutes, and even if you wanted to hold your breath longer, your autonomic nervous system would take control. This is because every cell in the body needs to run the oxidative stages of cellular respiration, the process by which energy is produced in the form of adenosine triphosphate (ATP). For oxidative phosphorylation to occur, oxygen is used as a reactant and carbon dioxide is released as a waste product. Carbon dioxide is exhaled and oxygen is inhaled through the respiratory system, which includes muscles to move air into and out of

the lungs, passageways through which air moves, and microscopic gas exchange surfaces covered by capillaries. The circulatory system transports gases from the lungs to tissues throughout the body and vice versa.

Organs and Structures of the Respiratory system

The major organs of the respiratory system function primarily to provide oxygen to body tissues for cellular respiration, remove the waste product carbon dioxide, and help to maintain acid-base balance (**Figure 12.10**). Portions of the respiratory system are also used for non-vital functions, such as sensing odors, speech production, and for straining, such as during childbirth or coughing.
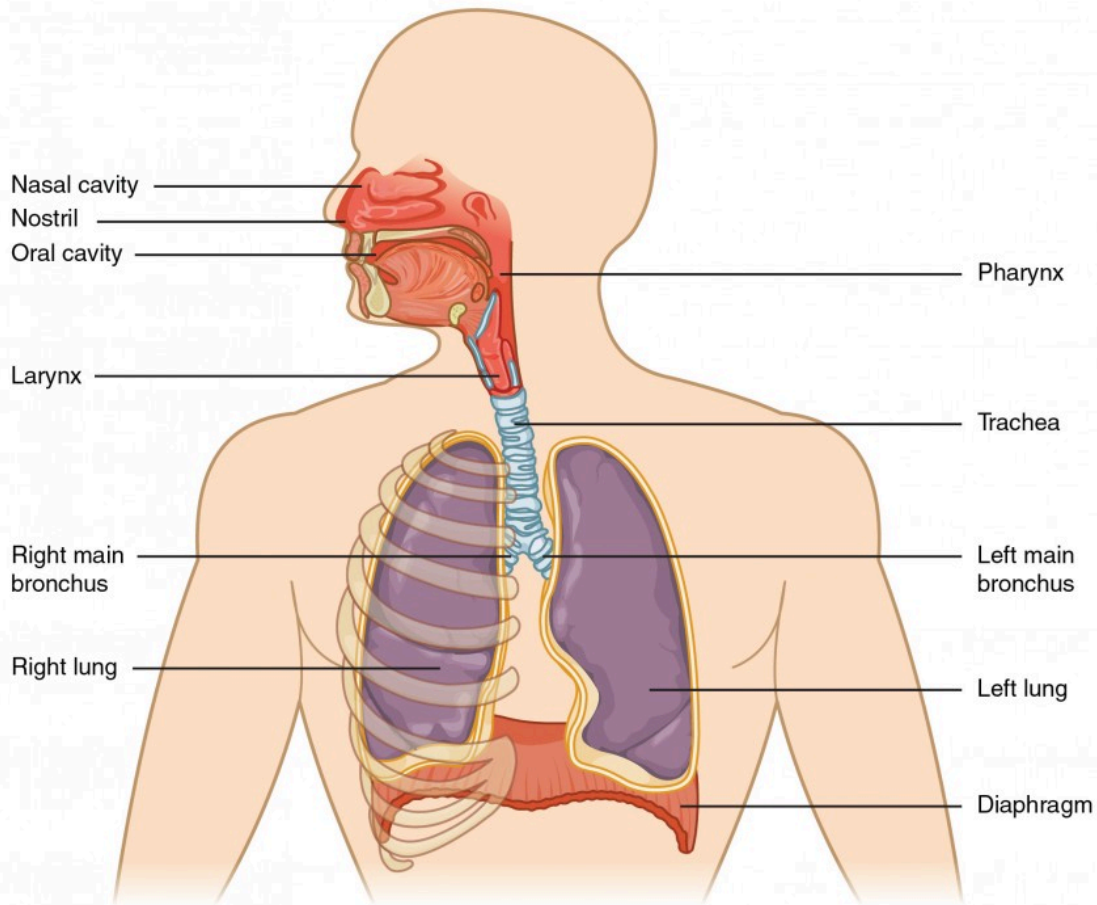

Figure 12.10. Major Respiratory Structures The major respiratory structures span the nasal cavity to the diaphragm.

Functionally, the respiratory system can be divided into a conducting zone and a respiratory zone. The **conducting zone** of the respiratory system includes the organs and structures not directly involved in gas exchange. The gas exchange occurs in the **respiratory zone**.

Conducting Zone

The major functions of the conducting zone are to provide a route for incoming and outgoing air, remove debris and pathogens from the incoming air, and warm and humidify the incoming air. Several structures within the

conducting zone perform other functions as well. The epithelium of the nasal passages, for example, is essential to sensing odors, and the bronchial epithelium that lines the lungs can metabolize some airborne carcinogens.

The Nose and its Adjacent Structures

The major entrance and exit for the respiratory system is through the nose. Underneath the thin skin of the nose are its skeletal features. While the root and bridge of the nose consist of bone, the protruding portion of the nose is composed of cartilage. As a result, when looking at a skull, the nose is missing. The nasal bone is one of a pair of bones that lies under the root and bridge of the nose. The nasal bone articulates superiorly with the frontal bone and laterally with the maxillary bones. Septal cartilage is flexible hyaline cartilage connected to the nasal bone, forming the dorsum nasi. The alar cartilage consists of the apex of the nose; it surrounds the naris.

The nares open into the nasal cavity, which is separated into left and right sections by the nasal septum. The **nasal septum** is formed anteriorly by a portion of the septal cartilage (the flexible portion you can touch with your fingers) and posteriorly by the perpendicular plate of the ethmoid bone (a cranial bone located just posterior to the nasal bones) and the thin vomer bone (whose name refers to its plough shape). Each lateral wall of the nasal cavity has three bony projections, called the **superior, middle, and inferior nasal conchae**. The inferior conchae are separate bones, whereas the superior and middle conchae are portions of the ethmoid bone. Conchae serve to increase the surface area of the nasal cavity and to disrupt the flow of air as it enters the nose, causing air to bounce along the epithelium, where it is cleaned and warmed. The conchae and **meatuses** also conserve water and prevent dehydration of the nasal epithelium by trapping water during exhalation. The floor of the nasal cavity is composed of the palate. The **hard palate** at the anterior region of the nasal cavity is composed of bone. The **soft palate** at the posterior portion of the nasal cavity consists of muscle tissue. Air exits the nasal cavities via the internal nares and moves into the pharynx (**Figure 12.11**).
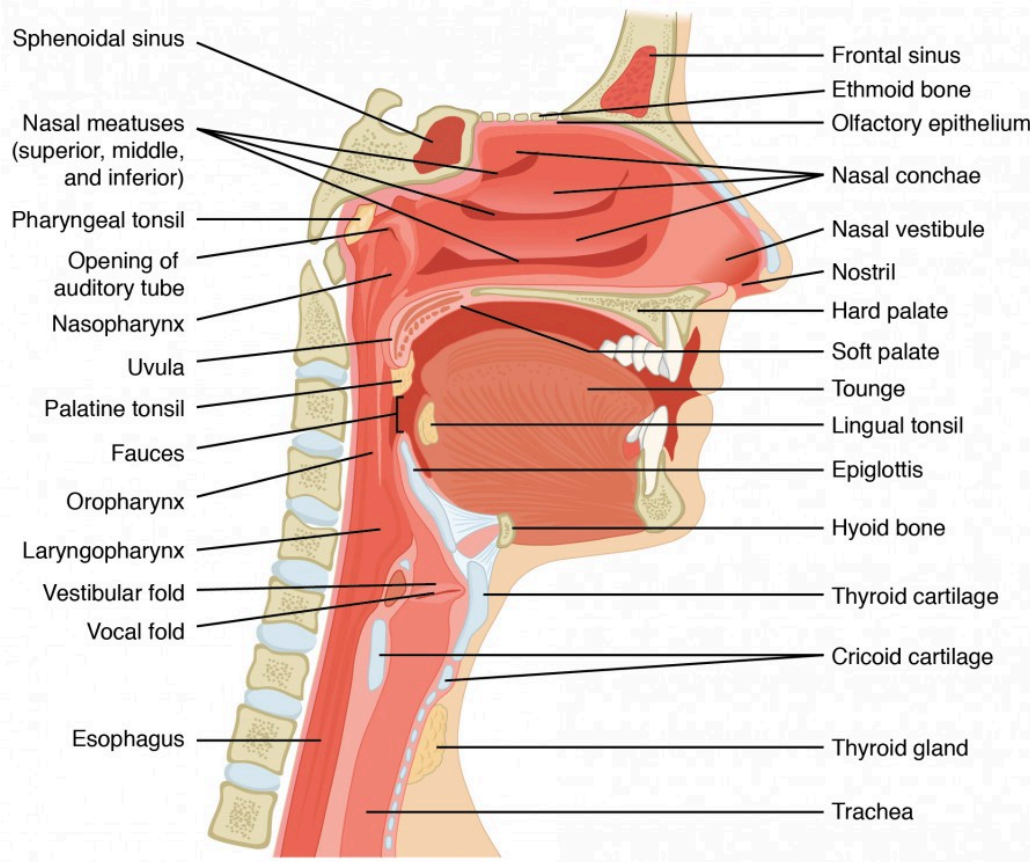
Figure 12.11. Upper Airway

Several bones that help form the walls of the nasal cavity have air-containing spaces called the paranasal sinuses, which serve to warm and humidify incoming air. Sinuses are lined with a mucosa. Each **paranasal sinus** is named for its associated bone: **frontal sinus**, **maxillary sinus**, **sphenoidal sinus**, and **ethmoidal sinus**. The sinuses produce mucus and lighten the weight of the skull.

The nares and anterior portion of the nasal cavities are lined with mucous membranes, containing sebaceous glands and hair follicles that serve to prevent the passage of large debris, such as dirt, through the nasal cavity. An olfactory epithelium used to detect odors is found deeper in the nasal cavity.

The conchae, meatuses, and paranasal sinuses are lined by **respiratory epithelium** composed of pseudostratified ciliated columnar epithelium (**Figure 12.12**). The epithelium contains goblet cells, one of the specialized, columnar epithelial cells that produce mucus to trap debris. The cilia of the respiratory epithelium help remove the mucus and debris from the nasal cavity with a constant beating motion, sweeping materials towards the throat to be swallowed. Interestingly, cold air slows the movement of the cilia, resulting in accumulation of mucus that may in turn lead to a runny nose during cold weather. This moist epithelium functions to warm and humidify incoming air. Capillaries located just beneath the nasal epithelium warm the air by convection. Serous and mucus-producing cells also secrete the lysozyme enzyme and proteins called defensins, which have antibacterial properties. Immune cells that patrol the connective tissue deep to the respiratory epithelium provide additional protection.
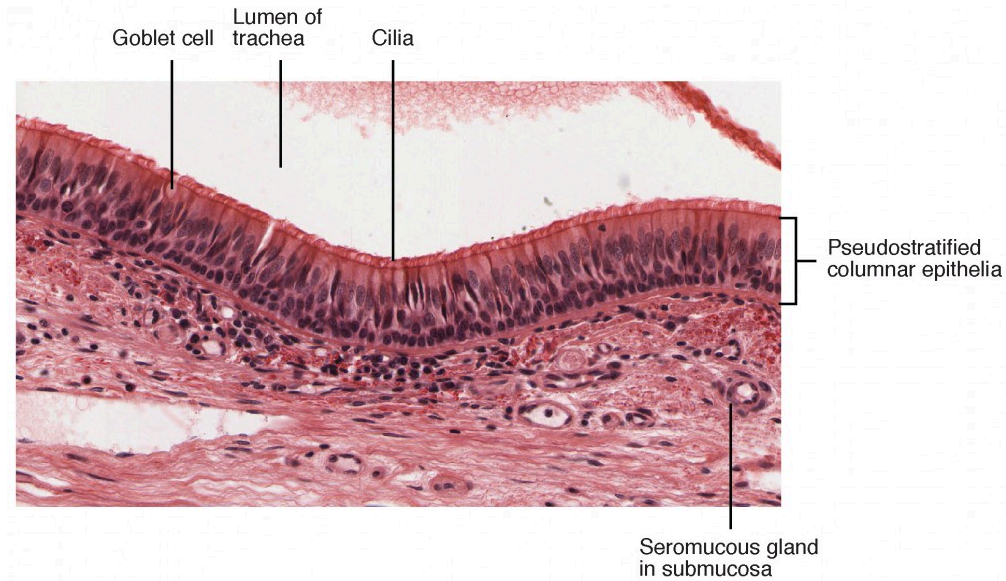
Figure 12.12 Pseudostratified Ciliated Columnar Epithelium Respiratory epithelium is pseudostratified ciliated columnar epithelium. Seromucous glands provide lubricating mucus. LM × 680. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Pharynx

The **pharynx** is a tube formed by skeletal muscle and lined by mucous membrane that is continuous with that of the nasal cavities (Figure #). The pharynx is divided into three major regions: the nasopharynx, the oropharynx, and the laryngopharynx (**Figure 12.13**).
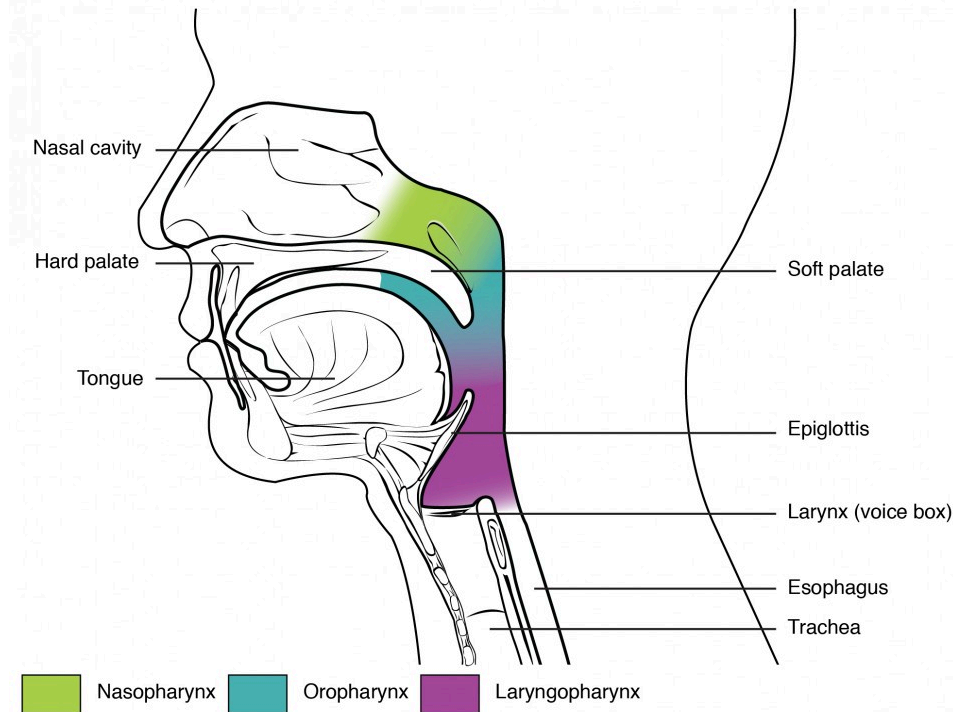
Figure 12.13. Pharynx The pharynx is divided into three regions: the nasopharynx, the oropharynx, and the laryngopharynx.

The **nasopharynx** is flanked by the conchae of the nasal cavity, and it serves only as an airway. At the top of the nasopharynx are the pharyngeal tonsils. A **pharyngeal tonsil**, also called an adenoid, is an aggregate of lymphoid reticular tissue similar to a lymph node that lies at the superior portion of the nasopharynx. The function of the pharyngeal tonsil is not well understood, but it contains a rich supply of lymphocytes and is covered with ciliated epithelium that traps and destroys invading pathogens that enter during inhalation. The pharyngeal tonsils are large in children, but interestingly, tend to regress with age and may even disappear. The uvula is a small bulbous, teardrop-shaped structure located at the apex of the soft palate. Both the uvula and soft palate move like a pendulum during swallowing, swinging upward to close off the nasopharynx to prevent ingested materials from entering the nasal cavity. In addition, **auditory (Eustachian) tubes** that connect to each middle ear cavity open into the nasopharynx. This connection is why colds often lead to ear infections.

The **oropharynx** is a passageway for both air and food. The oropharynx is bordered superiorly by the nasopharynx and anteriorly by the oral cavity. The **fauces** is the opening at the connection between the oral cavity and the oropharynx. As the nasopharynx becomes the oropharynx, the epithelium changes from pseudostratified ciliated columnar epithelium to stratified squamous epithelium. The oropharynx contains two distinct sets of tonsils, the palatine and lingual tonsils. A **palatine tonsil** is one of a pair of structures located laterally in the oropharynx in the area of the fauces. The **lingual tonsil** is located at the base of the tongue. Similar to the pharyngeal tonsil, the palatine and lingual tonsils are composed of lymphoid tissue, and trap and destroy pathogens entering the body through the oral or nasal cavities.

The **laryngopharynx** is inferior to the oropharynx and posterior to the larynx. It continues the route for ingested material and air until its inferior end, where the digestive and respiratory systems diverge. The stratified squamous

epithelium of the oropharynx is continuous with the laryngopharynx. Anteriorly, the laryngopharynx opens into the larynx, whereas posteriorly, it enters the esophagus.

Larynx

The **larynx** is a cartilaginous structure inferior to the laryngopharynx that connects the pharynx to the trachea and helps regulate the volume of air that enters and leaves the lungs (**Figure 12.14**). The structure of the larynx is formed by several pieces of cartilage. Three large cartilage pieces—the thyroid cartilage (anterior), epiglottis (superior), and cricoid cartilage (inferior)—form the major structure of the larynx. The **thyroid cartilage** is the largest piece of cartilage that makes up the larynx. The thyroid cartilage consists of the **laryngeal prominence**, or "Adam's apple," which tends to be more prominent in males. The thick **cricoid cartilage** forms a ring, with a wide posterior region and a thinner anterior region. Three smaller, paired cartilages—the arytenoids, corniculates, and cuneiforms—attach to the epiglottis and the vocal cords and muscle that help move the vocal cords to produce speech.
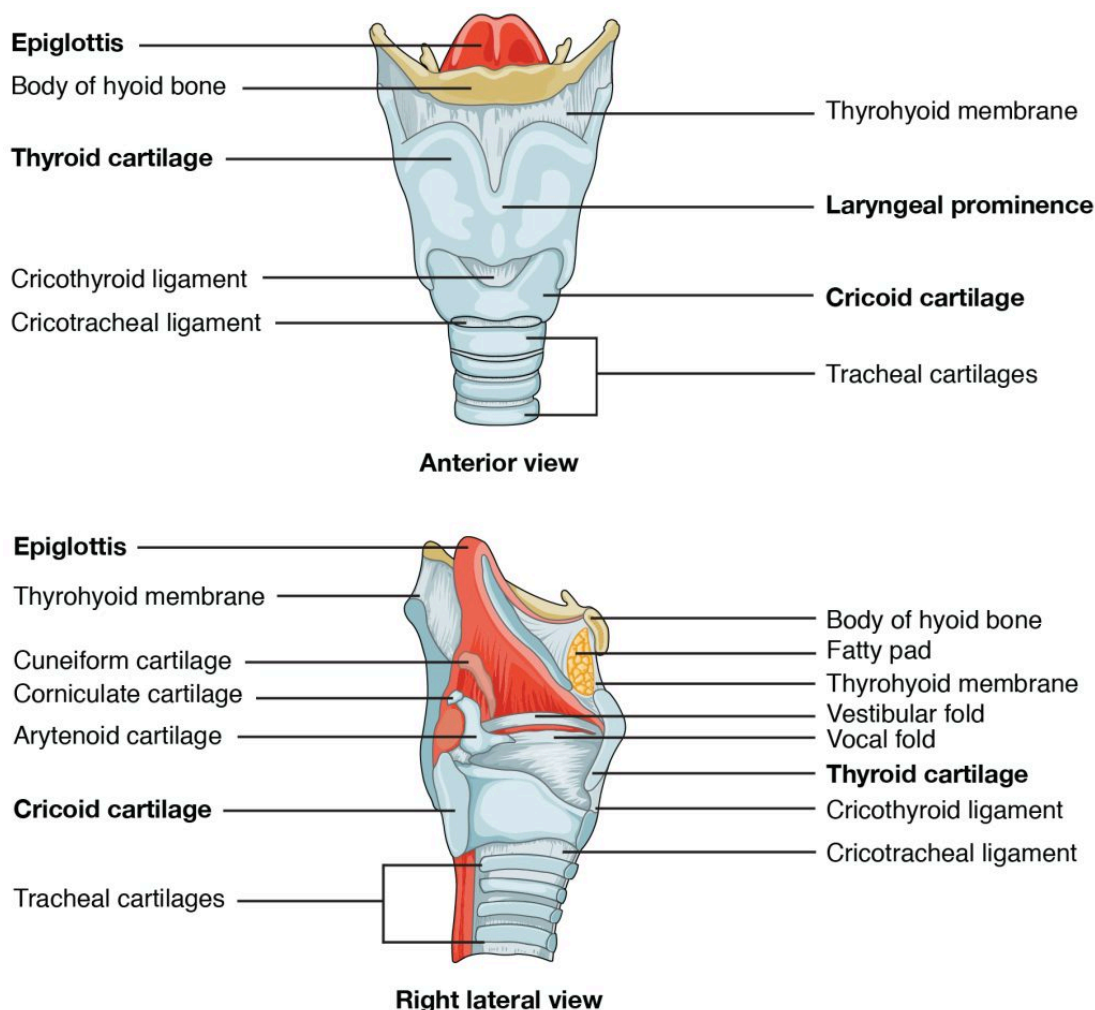

Figure 12.14 Larynx The larynx extends from the laryngopharynx and the hyoid bone to the trachea.

The **epiglottis,** attached to the thyroid cartilage, is a very flexible piece of elastic cartilage that covers the opening

of the trachea. When in the "closed" position, the unattached end of the epiglottis rests on the glottis. The **glottis** is composed of the vestibular folds, the true vocal cords, and the space between these folds (**Figure 12.15**). A **vestibular fold**, or false vocal cord, is one of a pair of folded sections of mucous membrane. A **true vocal cord** is one of the white, membranous folds attached by muscle to the thyroid and arytenoid cartilages of the larynx on their outer edges. The inner edges of the true vocal cords are free, allowing oscillation to produce sound. The size of the membranous folds of the true vocal cords differs between individuals, producing voices with different pitch ranges. Folds in males tend to be larger than those in females, which create a deeper voice. The act of swallowing causes the pharynx and larynx to lift upward, allowing the pharynx to expand and the epiglottis of the larynx to swing downward, closing the opening to the trachea. These movements produce a larger area for food to pass through, while preventing food and beverages from entering the trachea.
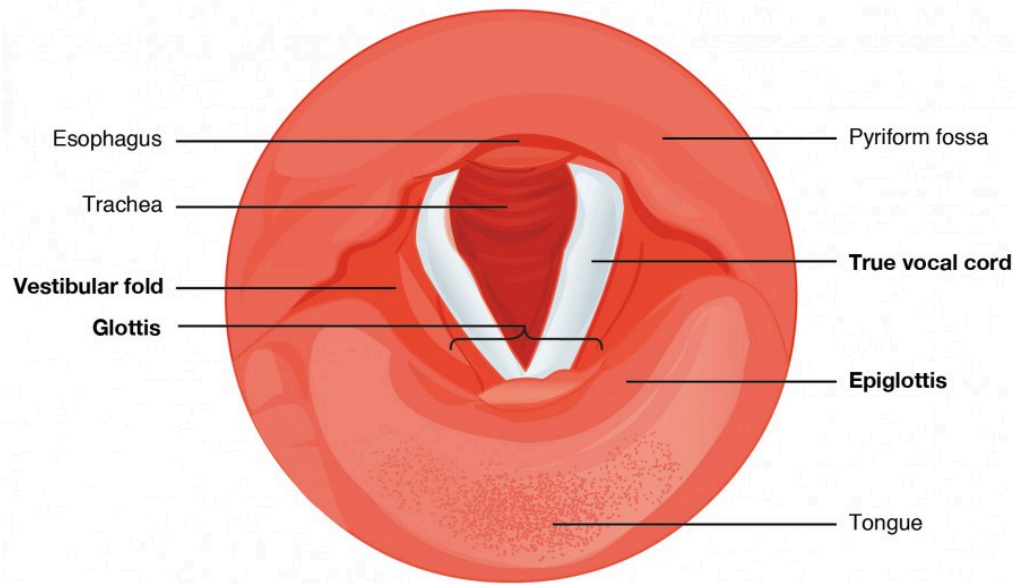

Figure 12.15 Vocal Cords. The true vocal cords and vestibular folds of the larynx are viewed inferiorly from the laryngopharynx.

Continuous with the laryngopharynx, the superior portion of the larynx is lined with stratified squamous epithelium, transitioning into pseudostratified ciliated columnar epithelium that contains goblet cells. Similar to the nasal cavity and nasopharynx, this specialized epithelium produces mucus to trap debris and pathogens as they enter the trachea. The cilia beat the mucus upward towards the laryngopharynx, where it can be swallowed down the esophagus.

Trachea

The trachea (windpipe) extends from the larynx toward the lungs (**Figure 12.16a**). The **trachea** is formed by 16 to 20 stacked, C-shaped pieces of hyaline cartilage that are connected by dense connective tissue. The trachealis muscle and elastic connective tissue together form the fibroelastic membrane, a flexible membrane that closes the posterior surface of the trachea, connecting the C-shaped cartilages. The fibroelastic membrane allows the trachea to stretch and expand slightly during inhalation and exhalation, whereas the rings of cartilage provide structural support and prevent the trachea from collapsing. In addition, the trachealis muscle can be contracted to force air through the trachea during exhalation. The trachea is lined with pseudostratified ciliated columnar epithelium, which is continuous with the larynx (**Figure 12.16b**). The esophagus borders the trachea posteriorly.
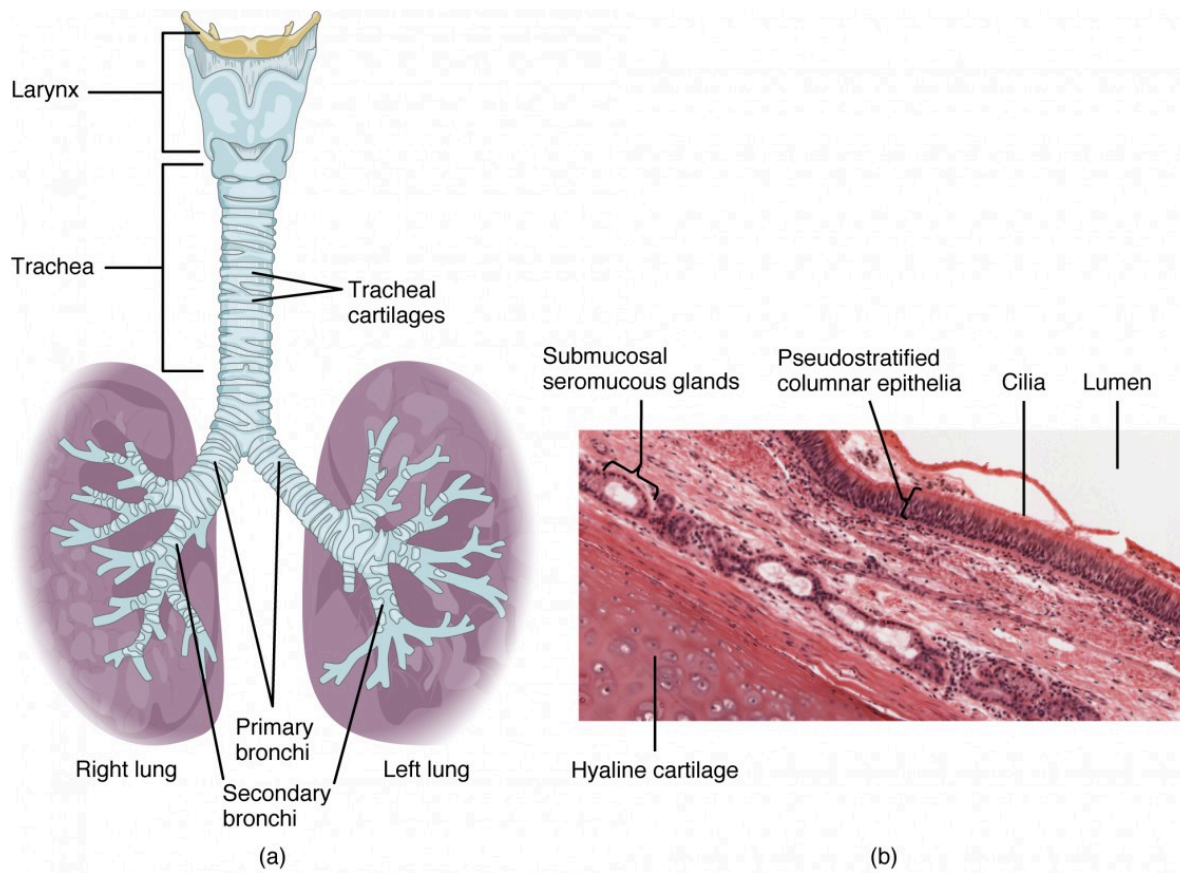
Figure 12.16 Trachea (a) The tracheal tube is formed by stacked, C-shaped pieces of hyaline cartilage. (b) The layer visible in this cross-section of tracheal wall tissue between the hyaline cartilage and the lumen of the trachea is the mucosa, which is composed of pseudostratified ciliated columnar epithelium that contains goblet cells. LM × 1220. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Bronchial Tree

The trachea branches into the **right and left primary bronchi** at the carina. These bronchi are also lined by pseudostratified ciliated columnar epithelium containing mucus-producing goblet cells. The **carina** is a raised structure that contains specialized nervous tissue that induces violent coughing if a foreign body, such as food, is present. Rings of cartilage, similar to those of the trachea, support the structure of the bronchi and prevent their collapse. The primary bronchi enter the lungs at the hilum, a concave region where blood vessels, lymphatic vessels, and nerves also enter the lungs. The bronchi continue to branch into bronchial a tree. A **bronchial tree** (or respiratory tree) is the collective term used for these multiple-branched bronchi. The main function of the bronchi, like other conducting zone structures, is to provide a passageway for air to move into and out of each lung. In addition, the mucous membrane traps debris and pathogens.

A **bronchiole** branches from the tertiary bronchi. Bronchioles, which are about 1 mm in diameter, further branch until they become the tiny terminal bronchioles, which lead to the structures of gas exchange. There are more than 1000 terminal bronchioles in each lung. The muscular walls of the bronchioles do not contain cartilage like those of the bronchi. This muscular wall can change the size of the tubing to increase or decrease airflow through the tube.

Respiratory Zone

In contrast to the conducting zone, the respiratory zone includes structures that are directly involved in gas exchange. The respiratory zone begins where the terminal bronchioles join a **respiratory bronchiole**, the smallest type of bronchiole (**Figure 12.17**), which then leads to an alveolar duct, opening into a cluster of alveoli.
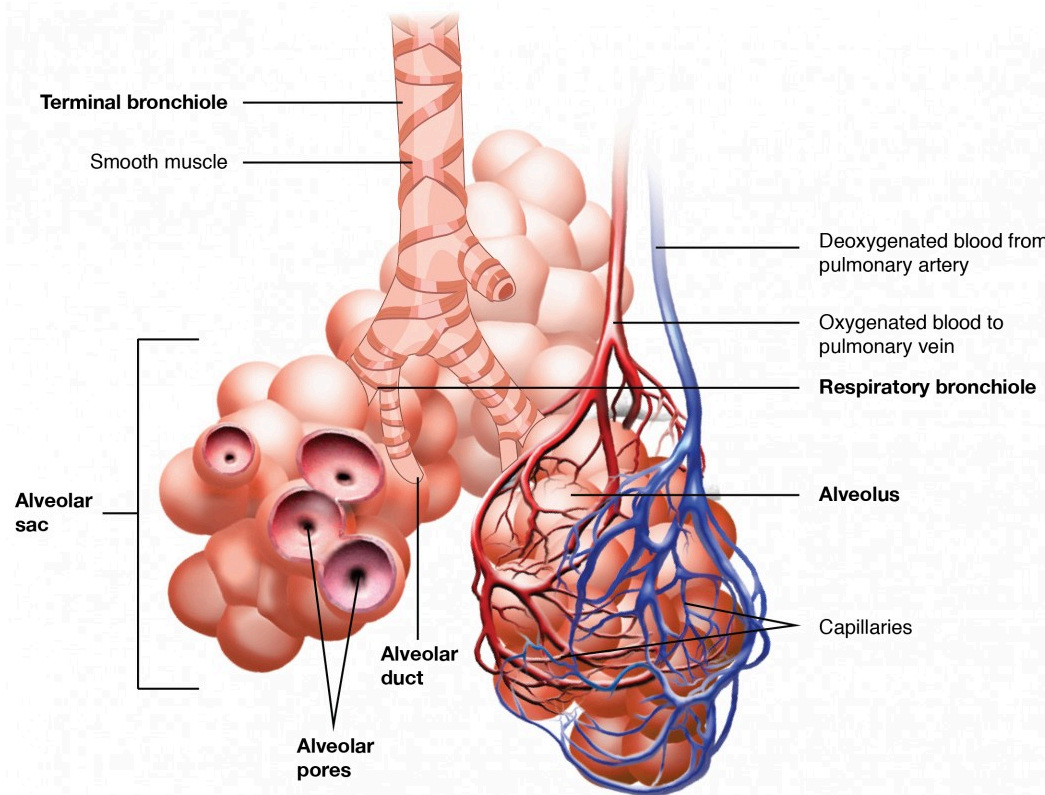

Figure 12.17 Respiratory Zone Bronchioles lead to alveolar sacs in the respiratory zone, where gas exchange occurs.

Alveoli

An **alveolar duct** is a tube composed of smooth muscle and connective tissue, which opens into a cluster of alveoli. An **alveolus** is one of the many small, grape-like sacs that are attached to the alveolar ducts.

An **alveolar sac** is a cluster of many individual alveoli that are responsible for gas exchange. An alveolus is approximately 200 mm in diameter with elastic walls that allow the alveolus to stretch during air intake, which greatly increases the surface area available for gas exchange. Alveoli are connected to their neighbors by **alveolar pores**, which help maintain equal air pressure throughout the alveoli and lung (**Figure 12.18**).
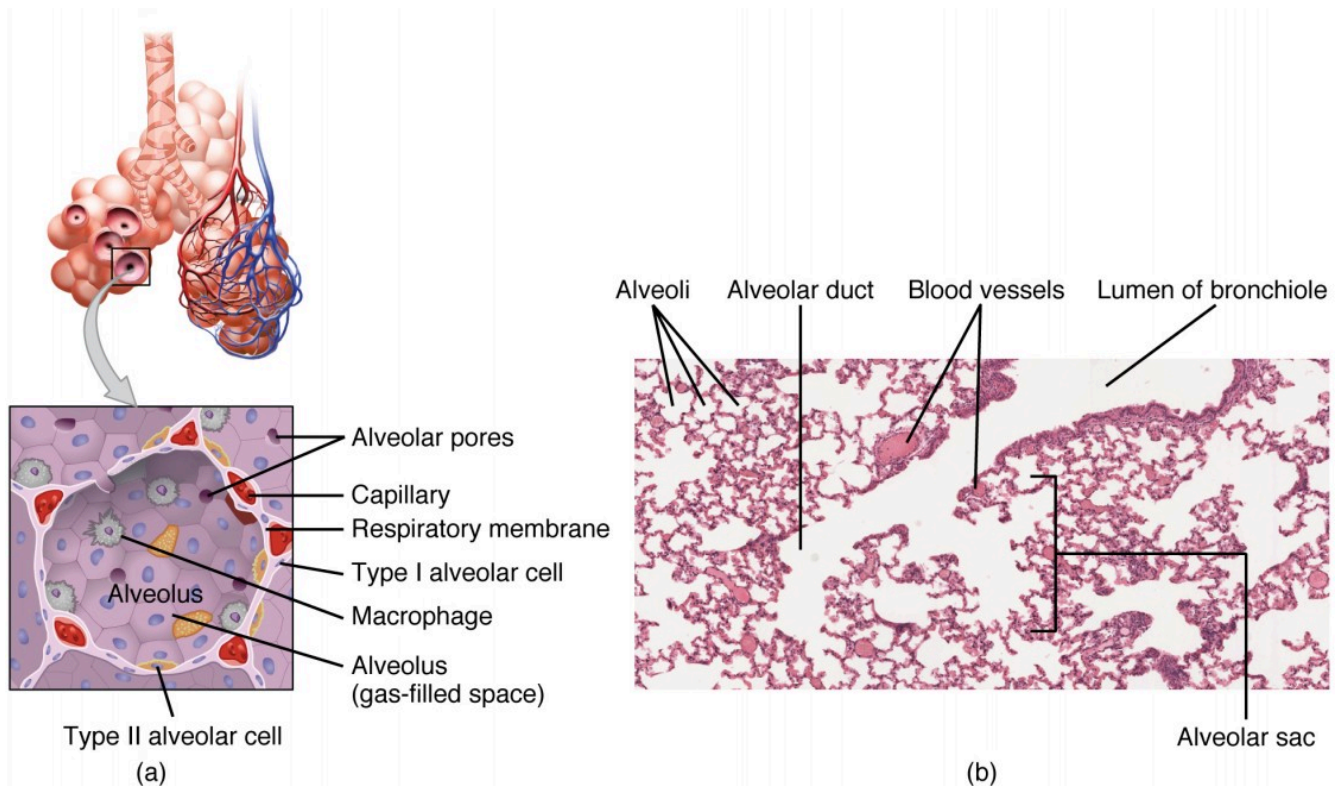
Figure 12.18 Structures of the Respiratory Zone (a) The alveolus is responsible for gas exchange. (b) A micrograph shows the alveolar structures within lung tissue. LM × 178. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The Lungs

A major organ of the respiratory system, each **lung** houses structures of both the conducting and respiratory zones. The main function of the lungs is to perform the exchange of oxygen and carbon dioxide with air from the atmosphere. To this end, the lungs exchange respiratory gases across a very large epithelial surface area—about 70 square meters—that is highly permeable to gases.

Gross Anatomy of the Lungs

The lungs are pyramid-shaped, paired organs that are connected to the trachea by the right and left bronchi; on the inferior surface, the lungs are bordered by the diaphragm. The **diaphragm** is the flat, dome-shaped muscle located at the base of the lungs and thoracic cavity. The lungs are enclosed by the pleurae, which are attached to the mediastinum. The right lung is shorter and wider than the left lung, and the left lung occupies a smaller volume than the right. The **cardiac notch** is an indentation on the surface of the left lung, and it allows space for the heart (**Figure 12.19**). The apex of the lung is the superior region, whereas the base is the opposite region near the diaphragm. The costal surface of the lung borders the ribs. The mediastinal surface faces the midline.
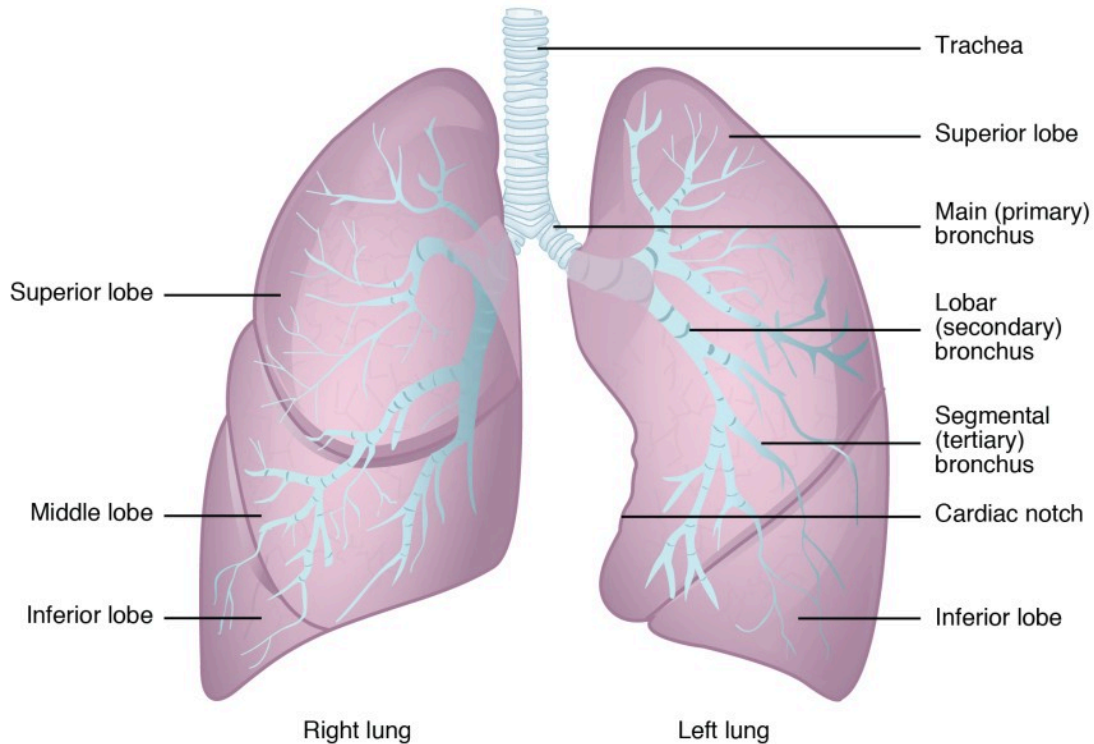
Figure 12.19. Gross Anatomy of the Lungs

Each lung is composed of smaller units called **lobes**. **Fissures** separate these lobes from each other. The right lung consists of three lobes: the superior, middle, and inferior lobes. The left lung consists of two lobes: the superior and inferior lobes. A bronchopulmonary segment is a division of a lobe, and each lobe houses multiple bronchopulmonary segments. Each segment receives air from its own tertiary bronchus and is supplied with blood by its own artery. Some diseases of the lungs typically affect one or more bronchopulmonary segments, and in some cases, the diseased segments can be surgically removed with little influence on neighboring segments. A pulmonary lobule is a subdivision formed as the bronchi branch into bronchioles. Each lobule receives its own large bronchiole that has multiple branches. An interlobular septum is a wall, composed of connective tissue, which separates lobules from one another.

Blood Supply of the Lungs

The blood supply of the lungs plays an important role in gas exchange and serves as a transport system for gases throughout the body. The major function of the lungs is to perform gas exchange, which requires blood from the pulmonary circulation. This blood supply contains deoxygenated blood and travels to the lungs where erythrocytes, also known as red blood cells, pick up oxygen to be transported to tissues throughout the body. The **pulmonary artery** is an artery that arises from the pulmonary trunk and carries deoxygenated, arterial blood to the alveoli. The pulmonary artery branches multiple times as it follows the bronchi, and each branch becomes progressively smaller in diameter. One arteriole and an accompanying venule supply and drain one pulmonary lobule. As they near the alveoli, the pulmonary arteries become the pulmonary capillary network. The pulmonary capillary network consists of tiny vessels with very thin walls that lack smooth muscle fibers. The capillaries branch and follow the bronchioles and structure of the alveoli. It is at this point that the capillary wall meets the

alveolar wall, creating the respiratory membrane. Once the blood is oxygenated, it drains from the alveoli by way of multiple **pulmonary veins**, which exit the lungs through the **hilum**.

Pleura of the Lungs

Each lung is enclosed within a cavity that is surrounded by the pleura. The pleura (plural = pleurae) is a serous membrane that surrounds the lung. The right and left pleurae, which enclose the right and left lungs, respectively, are separated by the mediastinum. The pleurae consist of two layers. The **visceral pleura** is the layer that is superficial to the lungs, and extends into and lines the lung fissures (**Figure 12.20**). In contrast, the **parietal pleura** is the outer layer that connects to the thoracic wall, the mediastinum, and the diaphragm. The visceral and parietal pleurae connect to each other at the hilum. The **pleural cavity** is the space between the visceral and parietal layers.
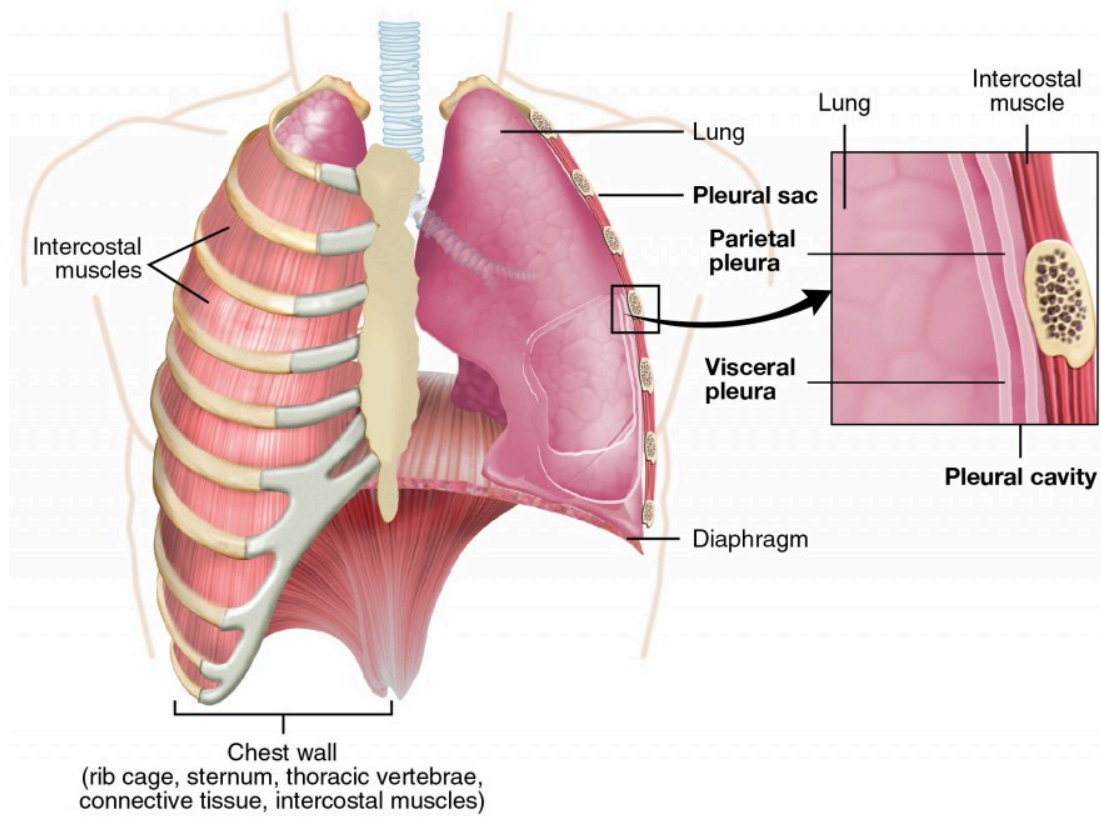

Figure 12.20. Parietal and Visceral Pleurae of the Lungs

The pleurae perform two major functions: They produce pleural fluid and create cavities that separate the major organs. **Pleural fluid** is secreted by mesothelial cells from both pleural layers and acts to lubricate their surfaces. This lubrication reduces friction between the two layers to prevent trauma during breathing, and creates surface tension that helps maintain the position of the lungs against the thoracic wall. This adhesive characteristic of the pleural fluid causes the lungs to enlarge when the thoracic wall expands during ventilation, allowing the lungs to fill with air. The pleurae also create a division between major organs that prevents interference due to the movement of the organs, while preventing the spread of infection.

Lab 13: Endocrine system & Digestive system

Learning Objectives

When you are prepared for the Test on Week 13Learning Objectives in Week 14, you will be able to:

1. Identify endocrine glands and describe their basic functions.
2. Identify major structures and organs of the digestive system and their functions.
3. Identify structures of teeth and classify teeth as incisors, canines, premolars, and molars.
4. Identify absorptive structures of the small intestine.
5. Identify mesentery structures and peritoneal attachments of abdominal organs.
6. Describe the pathway that food takes through the primary organs of the digestive system.
7. Describe the pathways of bile and pancreatic enzymes to the small intestine.

The Endocrine System

Communication is a process in which a sender transmits signals to one or more receivers to control and coordinate actions. In the human body, two major organ systems participate in relatively "long distance" communication: the nervous system and the endocrine system. Together, these two systems are primarily responsible for maintaining homeostasis in the body.

The nervous system uses two types of intercellular communication, electrical signaling (action potentials) and chemical signaling (neurotransmitters) that results in rapid signaling through the body. The target cell of the nervous system responds within milliseconds of receiving the chemical "message"; this response then ceases very quickly once the neural signaling ends. In this way, neural communication enables body functions that involve quick, brief actions, such as movement, sensation, and cognition. In contrast, the **endocrine system** uses just one method of communication: chemical signaling. These signals are sent by the endocrine organs, which secrete chemicals—the **hormone**—into the extracellular fluid. Hormones are transported primarily via the bloodstream throughout the body, where they bind to receptors on target cells, inducing a characteristic response. As a result, endocrine signaling requires more time than neural signaling to prompt a response in target cells, though the precise amount of time varies with different hormones. For example, the hormones released when you are confronted with a dangerous or frightening situation, called the fight-or-flight response, occur by the release of adrenal hormones—epinephrine and norepinephrine—within seconds. In contrast, it may take up to 48 hours for target cells to respond to certain reproductive hormones.

Although a given hormone may travel throughout the body in the bloodstream, it will affect the activity only of its

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target cells; that is, cells with receptors for that particular hormone. Once the hormone binds to the receptor, a chain of events is initiated that leads to the target cell's response. Hormones play a critical role in the regulation of physiological processes because of the target cell responses they regulate. These responses contribute to human reproduction, growth and development of body tissues, metabolism, fluid, and electrolyte balance, sleep, and many other body functions. The major hormones of the human body and their effects are identified in **Table 13.1**.

Table 13.1 Major organs and hormones of the Endocrine system

Endocrine gland	Associated hormones	Effect
Pituitary (anterior)	Growth hormone (GH)	Promotes growth of body tissues
Pituitary (anterior)	Prolactin (PRL)	Promotes milk production
Pituitary (anterior)	Thyroid-stimulating hormone (TSH)	Stimulates thyroid hormone release
Pituitary (anterior)	Adrenocorticotropic hormone (ACTH)	Stimulates hormone release by adrenal cortex
Pituitary (anterior)	Follicle-stimulating hormone (FSH)	Stimulates gamete production
Pituitary (anterior)	Luteinizing hormone (LH)	Stimulates androgen production by gonads
Pituitary (posterior)	Antidiuretic hormone (ADH)	Stimulates water reabsorption by kidneys
Pituitary (posterior)	Oxytocin	Stimulates uterine contractions during childbirth
Thyroid	Thyroxine (T_4), triiodothyronine (T_3)	Stimulate basal metabolic rate
Thyroid	Calcitonin	Reduces blood Ca^{2+} levels
Parathyroid	Parathyroid hormone (PTH)	Increases blood Ca^{2+} levels
Adrenal (cortex)	Aldosterone	Increases blood Na^+ levels
Adrenal (cortex)	Cortisol, corticosterone, cortisone	Increase blood glucose levels
Adrenal (medulla)	Epinephrine, norepinephrine	Stimulate fight-or-flight response
Pineal	Melatonin	Regulates sleep cycles
Pancreas	Insulin	Reduces blood glucose levels
Pancreas	Glucagon	Increases blood glucose levels
Testes	Testosterone	Stimulates development of male secondary sex characteristics and sperm production
Ovaries	Estrogens and progesterone	Stimulate development of female secondary sex characteristics and prepare the body for childbirth

Structures of the Endocrine System

The endocrine system consists of cells, tissues, and organs that secrete hormones as a primary or secondary function (**Figure 13.1**). The **endocrine gland** is the major player in this system. The primary function of these ductless glands is to secrete their hormones directly into the surrounding fluid. The interstitial fluid and the blood vessels then transport the hormones throughout the body. The endocrine system includes the pituitary, thyroid, parathyroid, adrenal, and pineal glands. Some of these glands have both endocrine and non-endocrine functions. For example, the pancreas contains cells that function in digestion as well as cells that secrete the hormones insulin and glucagon, which regulate blood glucose levels. The hypothalamus, thymus, heart, kidneys, stomach, small intestine, liver, skin, female ovaries, and male testes are other organs that contain cells with endocrine function. Moreover, adipose tissue has long been known to produce hormones, and recent research has revealed that even bone tissue has endocrine functions.
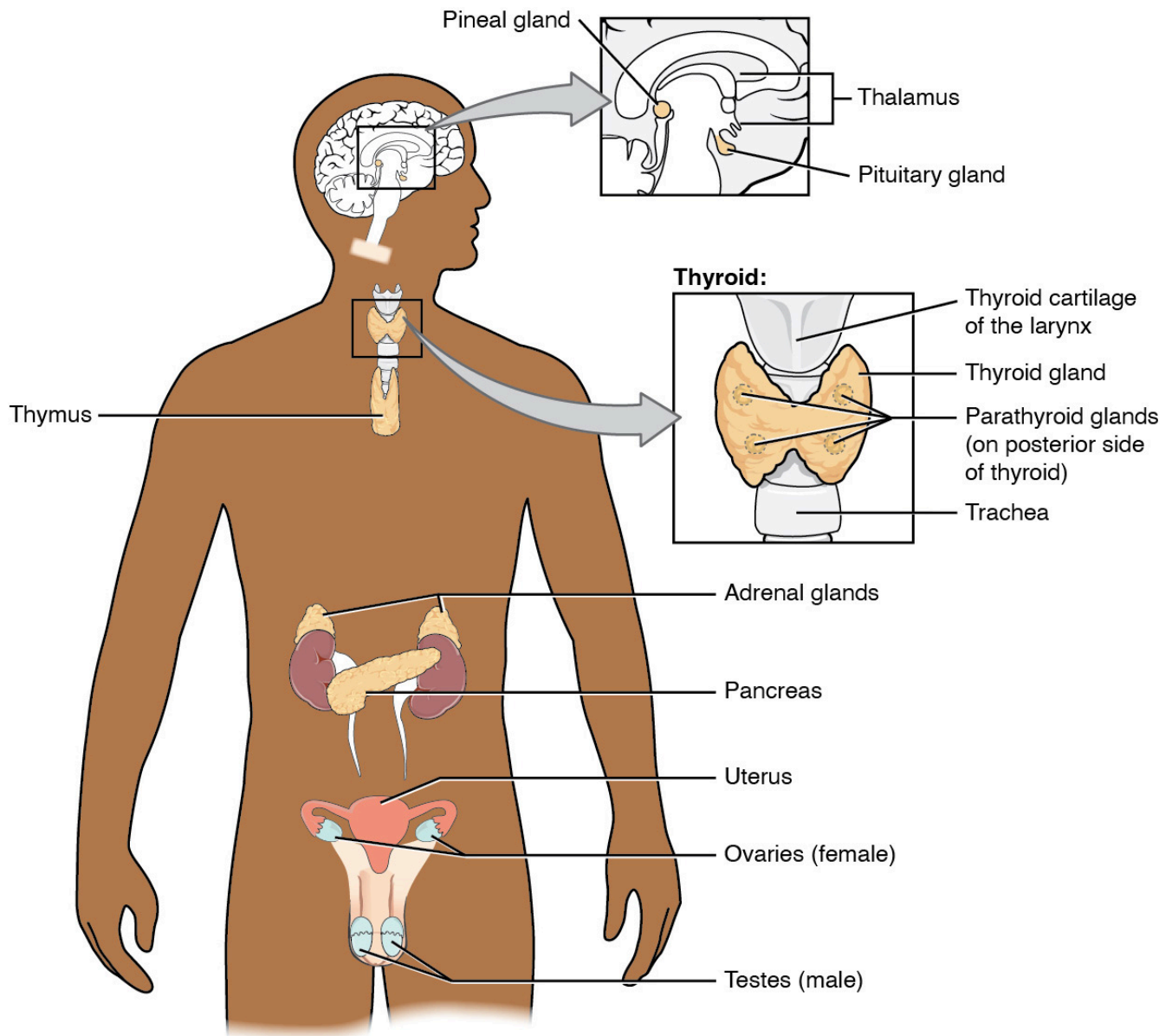
Figure 13.1 Endocrine System Endocrine glands and cells are located throughout the body and play an important role in homeostasis.

The ductless endocrine glands are not to be confused with the body's **exocrine system**, whose glands release their secretions through ducts. Examples of exocrine glands include the sebaceous and sweat glands of the skin. As just noted, the pancreas also has an exocrine function: most of its cells secrete pancreatic juice through the pancreatic and accessory ducts to the lumen of the small intestine.

The pituitary gland and hypothalamus

The hypothalamus–pituitary complex can be thought of as the "command center" of the endocrine system. This complex secretes several hormones that directly produce responses in target tissues, as well as hormones that regulate the synthesis and secretion of hormones of other glands. In addition, the hypothalamus–pituitary

complex coordinates the messages of the endocrine and nervous systems. In many cases, a stimulus received by the nervous system must pass through the hypothalamus–pituitary complex to be translated into hormones that can initiate a response.

The **hypothalamus** is a structure of the diencephalon of the brain located anterior and inferior to the thalamus (**Figure 13.2**). It has both neural and endocrine functions, producing and secreting many hormones. In addition, the hypothalamus is anatomically and functionally related to the **pituitary gland** (or hypophysis), a bean-sized organ suspended from it by a stem called the **infundibulum** (or pituitary stalk). The pituitary gland is cradled within the sella turcica of the sphenoid bone of the skull. It consists of two lobes that arise from distinct parts of embryonic tissue: the posterior pituitary (neurohypophysis) is neural tissue, whereas the anterior pituitary (also known as the adenohypophysis) is glandular tissue that develops from the primitive digestive tract.
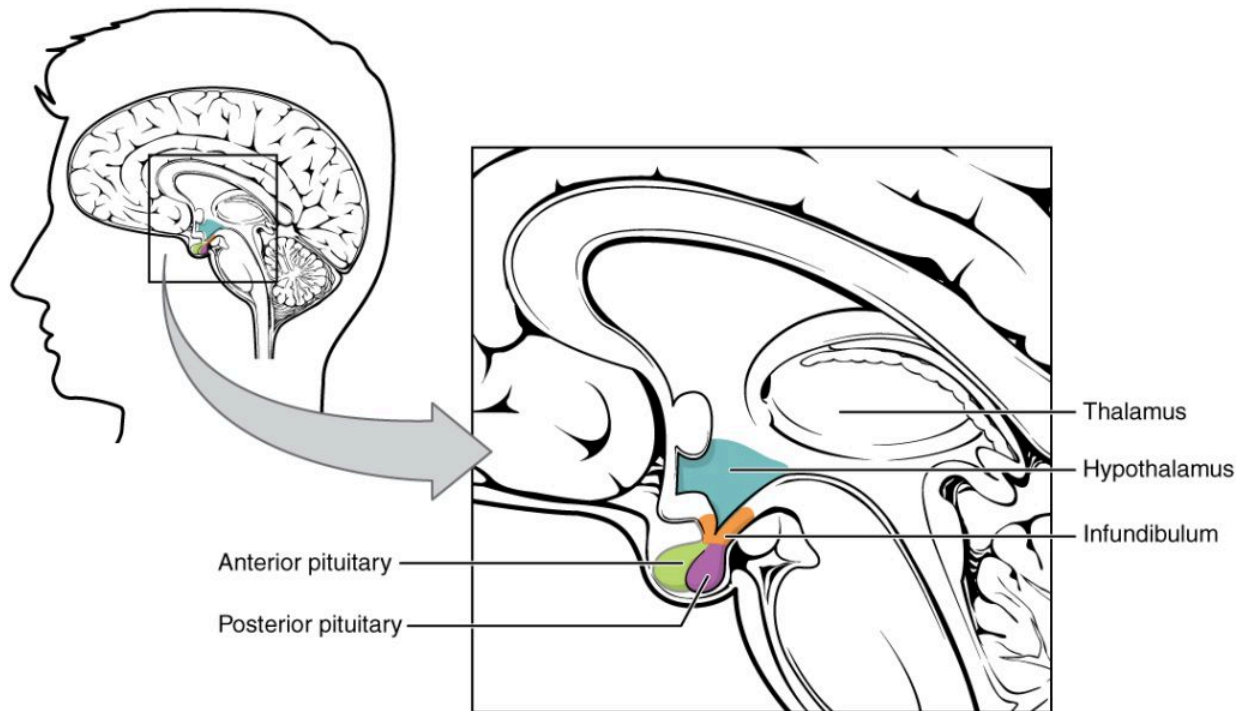

Figure 13.2 Hypothalamus–Pituitary Complex The hypothalamus region lies inferior and anterior to the thalamus. It connects to the pituitary gland by the stalk-like infundibulum. The pituitary gland consists of an anterior and posterior lobe, with each lobe secreting different hormones in response to signals from the hypothalamus.

The **posterior pituitary** is actually an extension of the neurons in the hypothalamus. The cell bodies of these neurons rest in the hypothalamus, but their axons descend as the hypothalamic–hypophyseal tract within the infundibulum, and end in axon terminals that comprise the posterior pituitary. The posterior pituitary gland does not produce hormones, but rather stores and secretes hormones produced by the hypothalamus, including oxytocin and ADH (**Figure 13.3**).

In contrast to the posterior pituitary, the **anterior pituitary** does manufacture hormones. However, the secretion of hormones from the anterior pituitary is regulated by two classes of hormones secreted by the hypothalamus, the releasing hormones that stimulate the secretion, and the inhibiting hormones that inhibit secretion.

Hypothalamic releasing and inhibiting hormones are secreted by neurons, but enter the anterior pituitary through

blood vessels. Within the infundibulum is a bridge of capillaries that connects the hypothalamus to the anterior pituitary. This network, called the **hypophyseal portal system**, allows hypothalamic hormones to be transported to the anterior pituitary without first entering the systemic circulation. Hormones produced by the anterior pituitary (in response to releasing hormones) enter a secondary capillary plexus, and from there drain into the circulation.
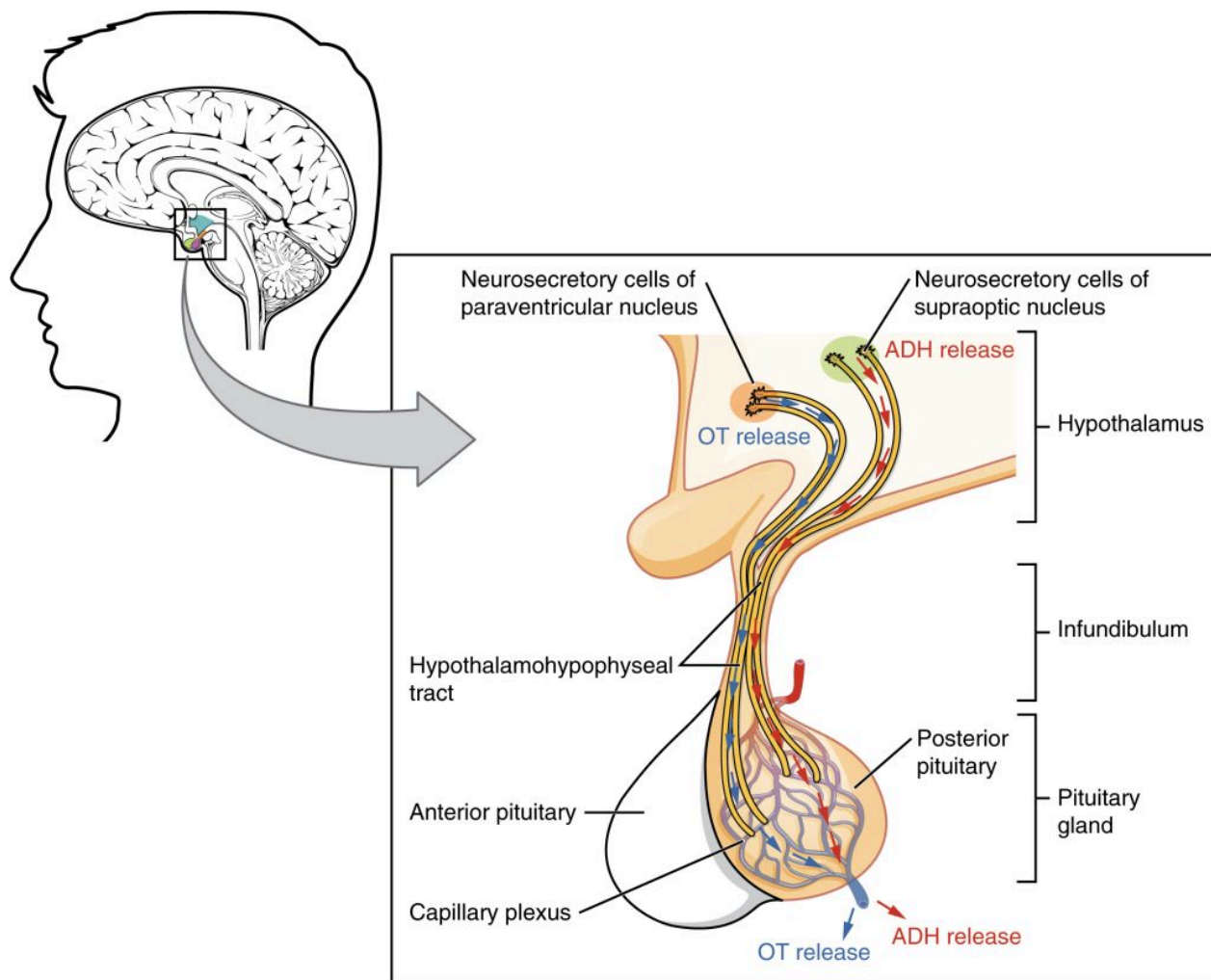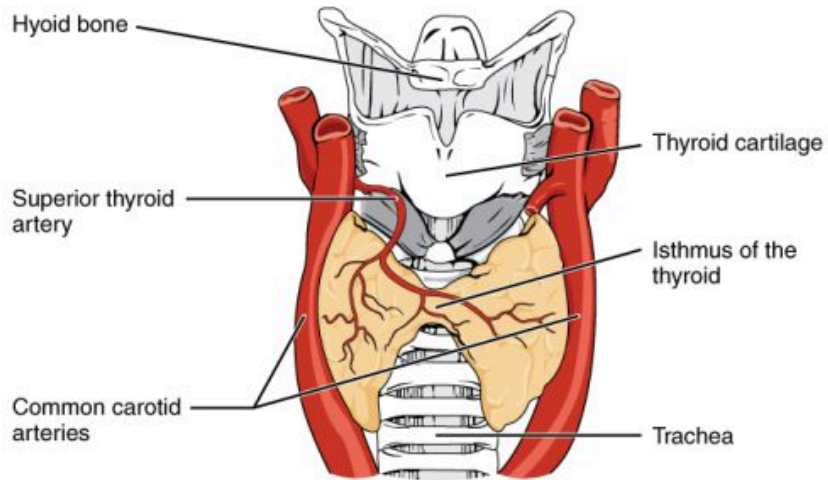

Figure 13.3 Posterior Pituitary Neurosecretory cells in the hypothalamus release oxytocin (OT) or ADH into the posterior lobe of the pituitary gland. These hormones are stored or released into the blood via the capillary plexus.

The anterior pituitary produces seven hormones. These are the growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), beta endorphin, and prolactin. Of the hormones of the anterior pituitary, TSH, ACTH, FSH, and LH are collectively referred to as tropic hormones (trope- = "turning") because they turn on or off the function of other endocrine glands. The hormones secreted by the pituitary gland are summarized in **Table 13.1**.
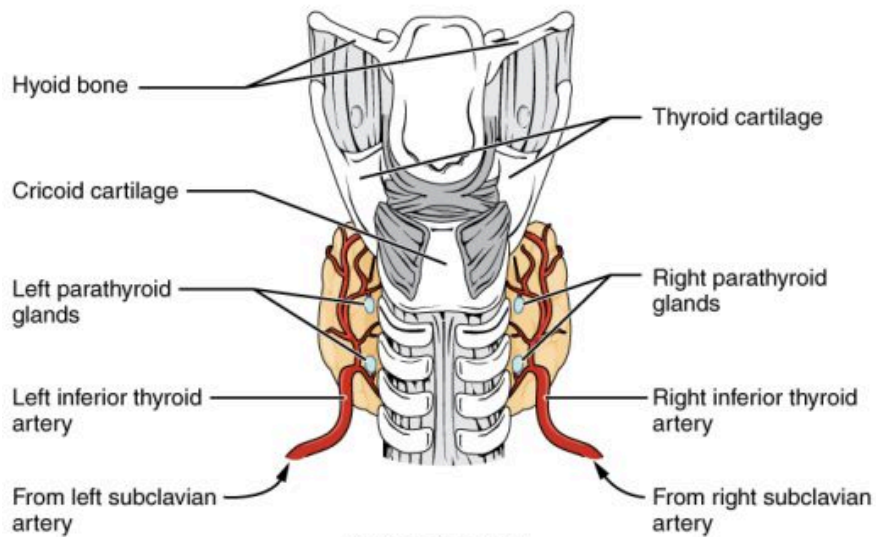
The thyroid and parathyroid glands

A butterfly-shaped organ, the **thyroid gland** is located anterior to the trachea, just inferior to the larynx (**Figure 13.4**). The medial region, called the isthmus, is flanked by wing-shaped left and right lobes. Each of the thyroid
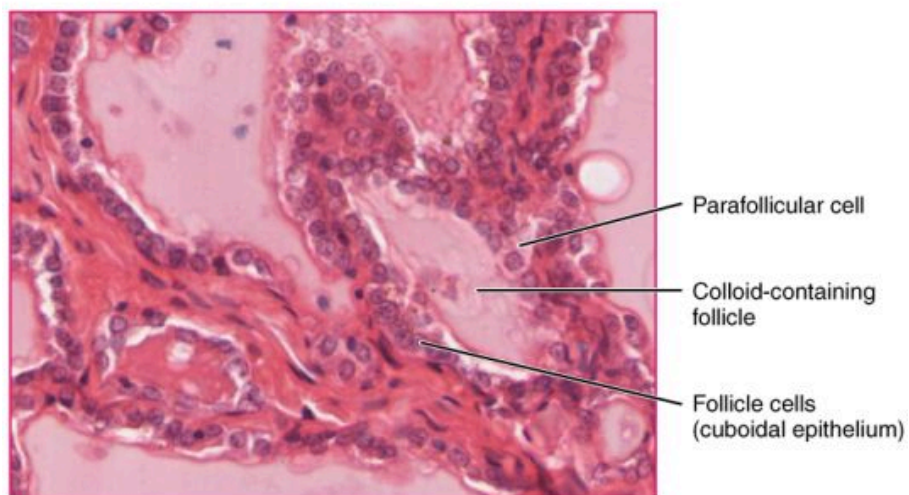
lobes are embedded with parathyroid glands, primarily on their posterior surfaces. The tissue of the thyroid gland is composed mostly of thyroid follicles, where thyroid hormones are produced. There are two types of **thyroid hormone**, triiodothyronine (T_3) and thyroxine (T_4), which both influence the body's basal metabolic rate. The thyroid gland also secretes a hormone called **calcitonin**, which helps regulate calcium concentrations in the blood along with parathyroid hormone.

Hyoid bone

Superior thyroid artery

Common carotid arteries

Thyroid cartilage

Isthmus of the thyroid

Trachea

a) Anterior view

Hyoid bone

Cricoid cartilage

Left parathyroid glands

Left inferior thyroid artery

From left subclavian artery

Thyroid cartilage

Right parathyroid glands

Right inferior thyroid artery

From right subclavian artery

b) Posterior view

Parafollicular cell

Colloid-containing follicle

Follicle cells (cuboidal epithelium)

c) Thyroid follicle cells

The **parathyroid glands** are tiny, round structures usually found embedded in the posterior surface of the thyroid gland (**Figure 13.4**). A thick connective tissue capsule separates the glands from the thyroid tissue. Most people have four parathyroid glands, but occasionally there are more in tissues of the neck or chest. The parathyroid glands produce and secrete the **parathyroid hormone (PTH)**, the major hormone involved in the regulation of blood calcium levels.

The adrenal glands

The **adrenal glands** are wedges of glandular and neuroendocrine tissue adhering to the top of the kidneys by a fibrous capsule (**Figure 13.5**). The adrenal gland consists of an outer cortex of glandular tissue and an inner medulla of nervous tissue. The adrenal glands have a rich blood supply and experience one of the highest rates of blood flow in the body. They are served by several arteries branching off the aorta, including the suprarenal and renal arteries. Adrenal hormones are released into the circulation via the left and right suprarenal veins.
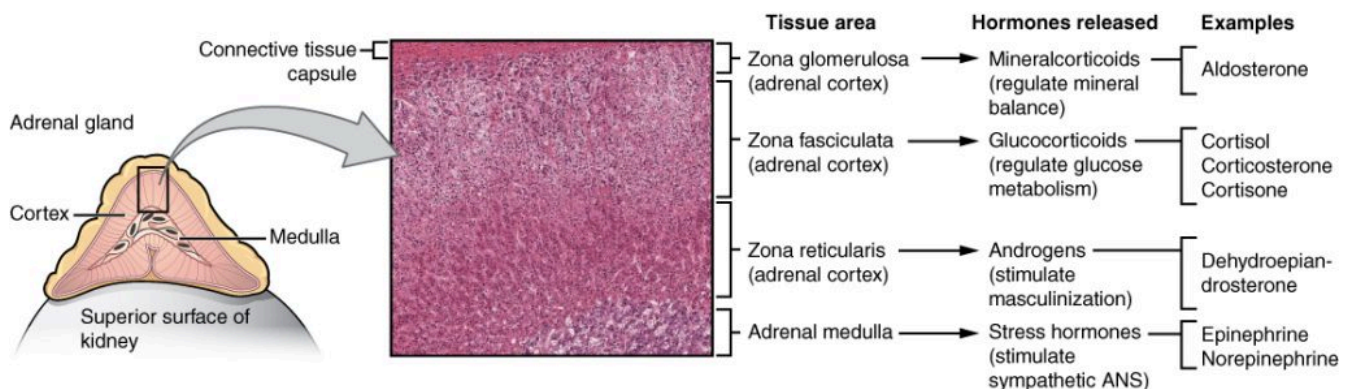

Figure 13.5 Adrenal Glands Both adrenal glands sit atop the kidneys and are composed of an outer cortex and an inner medulla, all surrounded by a connective tissue capsule. The cortex can be subdivided into additional zones, all of which produce different types of hormones. LM × 204. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

The **adrenal cortex** is divided into three zones: the zona glomerulosa, the zona fasciculata, and the zona reticularis. Each region secretes its own set of hormones, involved in functions such as the regulation of the long-term stress response, blood pressure and blood volume, nutrient uptake and storage, fluid and electrolyte balance, and inflammation.

The **adrenal medulla** is neuroendocrine tissue composed of postganglionic sympathetic nervous system neurons. It is really an extension of the autonomic nervous system, which regulates homeostasis in the body. The medulla is stimulated to secrete the hormones epinephrine and norepinephrine.

The endocrine functions of the pancreas

The **pancreas** is a long, slender organ, most of which is located posterior to the bottom half of the stomach (**Figure 13.6**). Although it is primarily an exocrine gland, secreting a variety of digestive enzymes, the pancreas has an endocrine function. Its **pancreatic islets**—clusters of cells formerly known as the islets of Langerhans—secrete the hormones glucagon, insulin, somatostatin, and pancreatic polypeptide (PP). Most of these hormones are involved in the regulation of blood glucose levels.
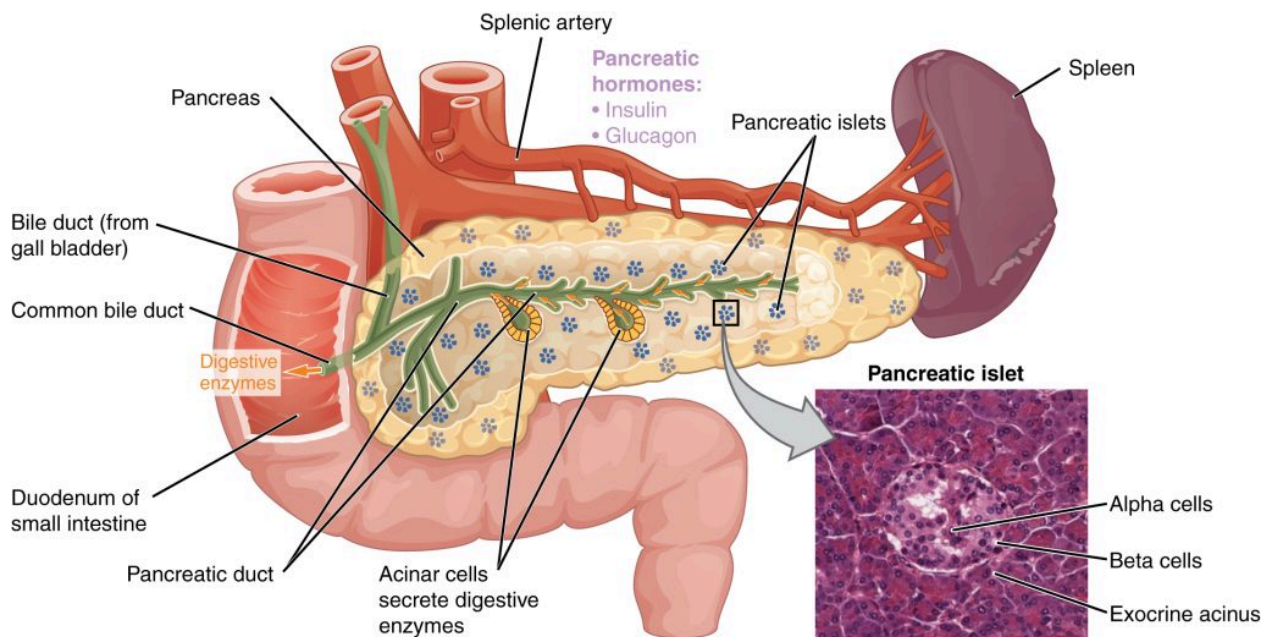

Figure 13.6 Pancreas The pancreatic exocrine function involves the acinar cells secreting digestive enzymes that are transported into the small intestine by the pancreatic duct. Its endocrine function involves the secretion of insulin (produced by beta cells) and glucagon (produced by alpha cells) within the pancreatic islets. These two hormones regulate the rate of glucose metabolism in the body. The micrograph reveals pancreatic islets. LM × 760. (Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Glucose is required for cellular respiration and is the preferred fuel for all body cells. The body derives glucose from the breakdown of the carbohydrate-containing foods and drinks we consume. Glucose not immediately taken up by cells for fuel can be stored by the liver and muscles as glycogen, or converted to triglycerides and stored in the adipose tissue. Hormones regulate both the storage and the utilization of glucose as required. Receptors located in the pancreas sense blood glucose levels, and subsequently the pancreatic cells secrete **glucagon** or **insulin** to maintain normal levels.

Other organs involved with the endocrine system

The **pineal gland** is located in the diencephalon of the brain, along the inferoposterior edge. It is a tiny endocrine gland that produces and secretes the hormone **melatonin**, which is involved in the sleep-wake cycle of the body.

The gonads, the male **testes** and female **ovaries**, produce the sex cells (sperm and ova) and secrete the gonadal hormones. The primary hormone produced by the male testes is **testosterone**, a steroid hormone important in the development of the male reproductive system, the maturation of sperm cells, and the development of male secondary sex characteristics. The primary hormones produced by the ovaries are **estrogens**, which play

an important role in the development of the female reproductive system, regulation of the menstrual cycle, the development of female secondary sex characteristics, and the maintenance of pregnancy. Another significant ovarian hormone is **progesterone**, which contributes to regulation of the menstrual cycle and is important in preparing the body for pregnancy as well as maintaining pregnancy.

During the initial stages of pregnancy, an organ called the **placenta** develops within the uterus. The placenta supplies oxygen and nutrients to the fetus, excretes waste products, and produces and secretes estrogens and progesterone. The placenta also produces human chorionic gonadotropin (hCG), which helps maintain pregnancy.

The heart, gastrointestinal tract, kidneys, skeleton, adipose tissue, skin, and thymus all have secondary endocrine functions, meaning they produce hormones apart from their primary function. The major hormones of these organs are summarized in **Table 13.2**.

Table 13.2 Organs with secondary endocrine functions

Organ	Major hormones	Effects
Heart	Atrial natriuretic peptide (ANP)	Reduces blood volume, blood pressure, and Na^+ concentration
Gastrointestinal tract	Gastrin, secretin, and cholecystokinin	Aid digestion of food and buffering of stomach acids
Gastrointestinal tract	Glucose-dependent insulinotropic peptide (GIP) and glucagon-like peptide 1 (GLP-1)	Stimulate beta cells of the pancreas to release insulin
Kidneys	Renin	Stimulates release of aldosterone
Kidneys	Calcitriol	Aids in the absorption of Ca^{2+}
Kidneys	Erythropoietin	Triggers the formation of red blood cells in the bone marrow
Skeleton	FGF23	Inhibits production of calcitriol and increases phosphate excretion
Skeleton	Osteocalcin	Increases insulin production
Adipose tissue	Leptin	Promotes satiety signals in the brain
Adipose tissue	Adiponectin	Reduces insulin resistance
Skin	Cholecalciferol	Modified to form vitamin D
Thymus (and other organs)	Thymosins	Among other things, aids in the development of T lymphocytes of the immune system
Liver	Insulin-like growth factor-1	Stimulates bodily growth
Liver	Angiotensinogen	Raises blood pressure
Liver	Thrombopoietin	Causes increase in platelets
Liver	Hepcidin	Blocks release of iron into body fluids

The Digestive System

The digestive system is continually at work, yet people seldom appreciate the complex tasks it performs in a choreographed biologic symphony. Consider what happens when you eat an apple. Of course, you enjoy the apple's taste as you chew it, but in the hours that follow, unless something goes amiss and you get a stomachache, you don't notice that your digestive system is working. You may be taking a walk or studying or sleeping, having forgotten all about the apple, but your stomach and intestines are busy digesting it and absorbing its vitamins and other nutrients. By the time any waste material is excreted, the body has appropriated all it can use from the apple. In short, whether you pay attention or not, the organs of the digestive system perform their specific functions, allowing you to use the food you eat to keep you going. This chapter examines the structure and functions of these organs, and explores the mechanics and chemistry of the digestive processes.

The function of the digestive system is to break down the foods you eat, release their nutrients, and absorb those nutrients into the body. Although the small intestine is the workhorse of the system, where the majority of digestion occurs, and where most of the released nutrients are absorbed into the blood or lymph, each of the digestive system organs makes a vital contribution to this process (**Figure 13.7**).
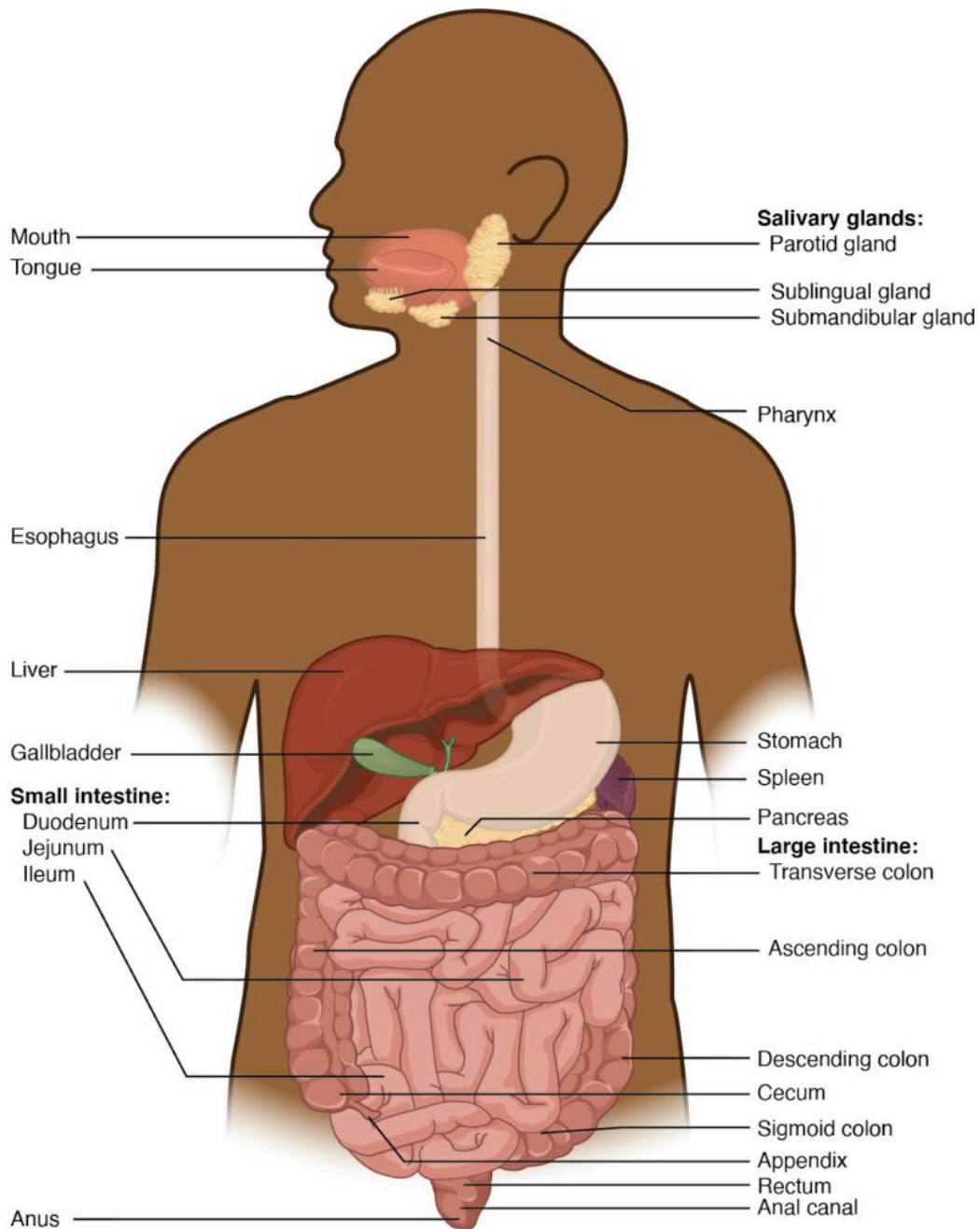
Figure 13.7 Components of the Digestive System All digestive organs play integral roles in the life-sustaining process of digestion.

The easiest way to understand the digestive system is to divide its organs into two main categories. The first group is the organs that make up the alimentary canal. Accessory digestive organs comprise the second group and are critical for orchestrating the breakdown of food and the assimilation of its nutrients into the body. Accessory digestive organs, despite their name, are critical to the function of the digestive system.

Alimentary Canal Organs

Also called the **gastrointestinal (GI) tract** or gut, the **alimentary canal** (aliment- = "to nourish") is a one-way tube about 7.62 meters (25 feet) in length during life and closer to 10.67 meters (35 feet) in length when measured after death, once smooth muscle tone is lost. The main function of the organs of the alimentary canal is to nourish the body. This tube begins at the mouth and terminates at the anus. Between those two points, the canal is modified as the pharynx, esophagus, stomach, and small and large intestines to fit the functional needs of the body. Both the mouth and anus are open to the external environment; thus, food and wastes within the alimentary canal are technically considered to be outside the body. Only through the process of absorption do the nutrients in food enter into and nourish the body's "inner space."

Accessory Structures

Each **accessory digestive organ** aids in the breakdown of food. Within the mouth, the teeth and tongue begin mechanical digestion, whereas the salivary glands begin chemical digestion. Once food products enter the small intestine, the gallbladder, liver, and pancreas release secretions—such as bile and enzymes—essential for digestion to continue. Together, these are called accessory organs because they sprout from the lining cells of the developing gut (mucosa) and augment its function; indeed, you could not live without their vital contributions, and many significant diseases result from their malfunction. Even after development is complete, they maintain a connection to the gut by way of ducts.

The Peritoneum

The digestive organs within the abdominal cavity are held in place by the **peritoneum**, a broad serous membranous sac made up of squamous epithelial tissue surrounded by connective tissue. It is composed of two different regions: the **parietal peritoneum**, which lines the abdominal wall, and the **visceral peritoneum**, which envelopes the abdominal organs (**Figure 13.8**). The peritoneal cavity is the space bounded by the visceral and parietal peritoneal surfaces. A few milliliters of watery fluid act as a lubricant to minimize friction between the serosal surfaces of the peritoneum.
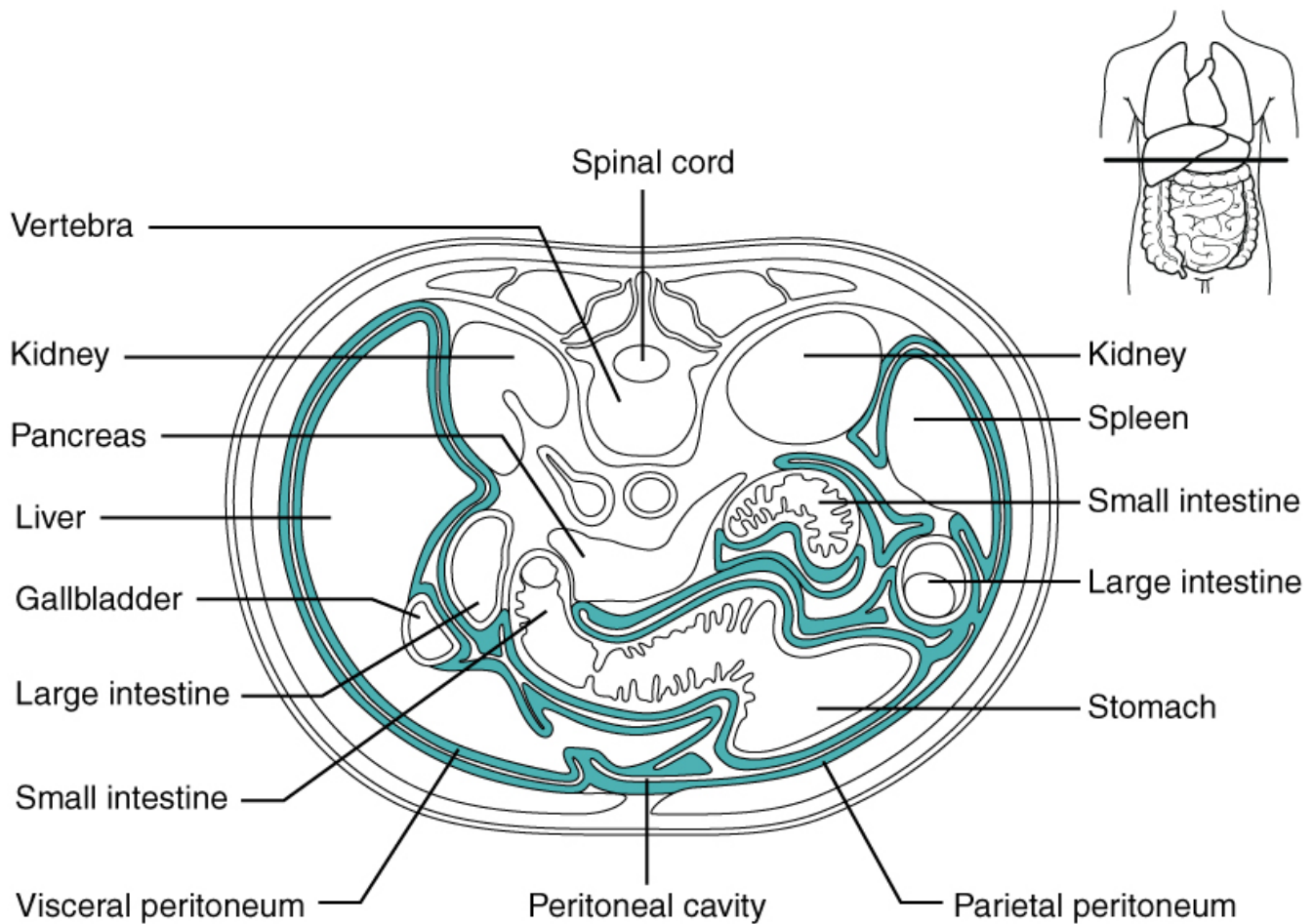
Figure 13.8 The Peritoneum A cross-section of the abdomen shows the relationship between abdominal organs and the peritoneum (darker lines).

The visceral peritoneum includes multiple large folds that envelope various abdominal organs, holding them to the dorsal surface of the body wall. Within these folds are blood vessels, lymphatic vessels, and nerves that innervate the organs with which they are in contact, supplying their adjacent organs. The five major peritoneal folds are described in **Table 13.3**. Note that during fetal development, certain digestive structures, including the first portion of the small intestine (called the duodenum), the pancreas, and portions of the large intestine (the ascending and descending colon, and the rectum) remain completely or partially posterior to the peritoneum. Thus, the location of these organs is described as **retroperitoneal.**

Table 13.3 The Five Major Peritoneal Folds

Fold	Description
Greater omentum	Apron-like structure that lies superficial to the small intestine and transverse colon; a site of fat deposition in people who are overweight
Falciform ligament	Anchors the liver to the anterior abdominal wall and inferior border of the diaphragm
Lesser omentum	Suspends the stomach from the inferior border of the liver; provides a pathway for structures connecting to the liver
Mesentery	Vertical band of tissue anterior to the lumbar vertebrae and anchoring all of the small intestine except the initial portion (the duodenum)
Mesocolon	Attaches two portions of the large intestine (the transverse and sigmoid colon) to the posterior abdominal wall

The Mouth

The cheeks, tongue, and palate frame the mouth, which is also called the **oral cavity** (or buccal cavity). The structures of the mouth are illustrated in **Figure 13.9**.
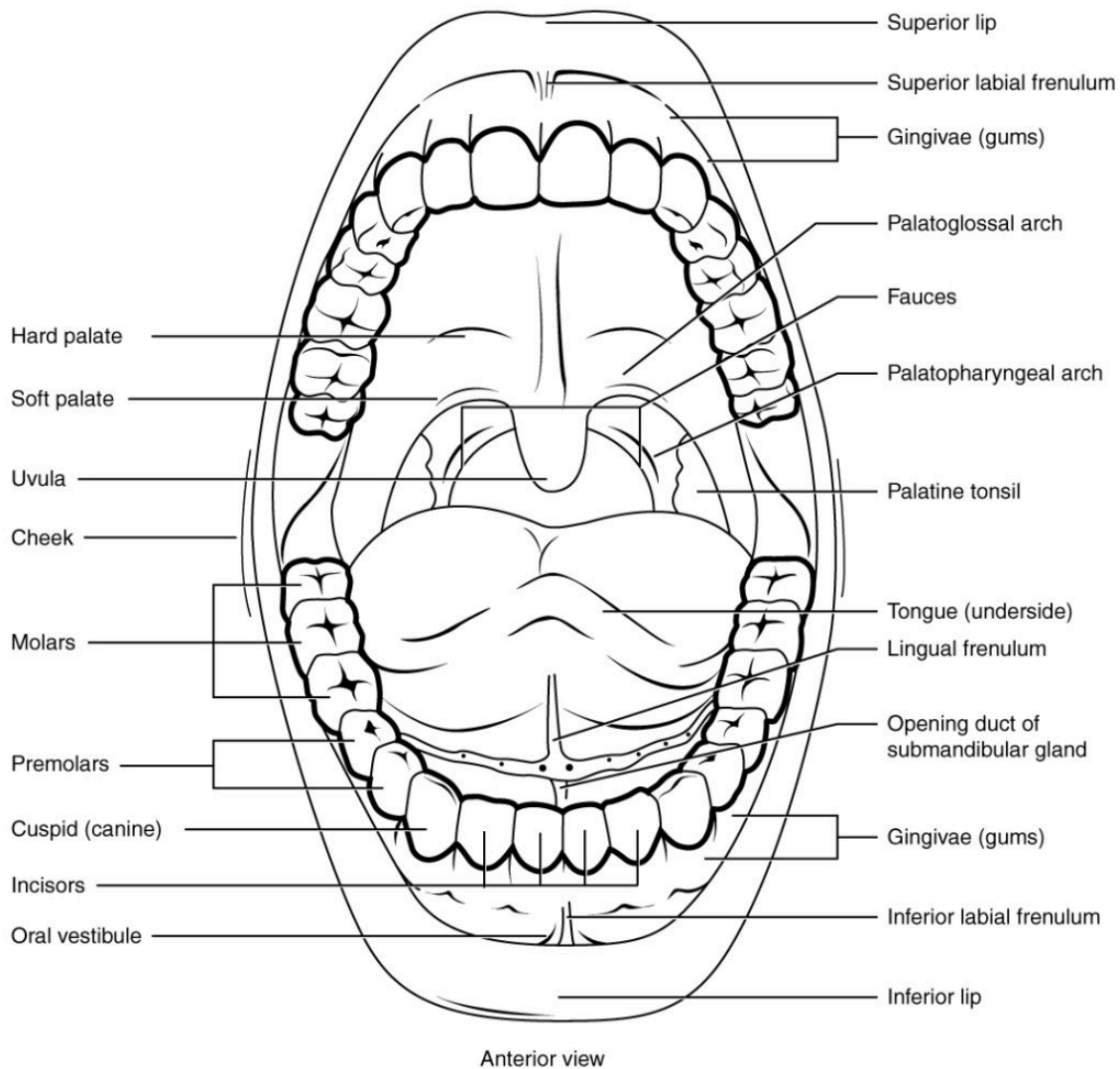
Figure 13.9 Mouth The mouth includes the lips, tongue, palate, gums, and teeth.

At the entrance to the mouth are the lips, or **labia** (singular = labium). Their outer covering is skin, which transitions to a mucous membrane in the mouth proper. Lips are very vascular with a thin layer of keratin; hence, the reason they are "red." The lips cover the orbicularis oris muscle, which regulates what comes in and goes out of the mouth. The **labial frenulum** is a midline fold of mucous membrane that attaches the inner surface of each lip to the gum. The cheeks make up the oral cavity's sidewalls. While their outer covering is skin, their inner covering is mucous membrane. This membrane is made up of non-keratinized, stratified squamous epithelium. Between the skin and mucous membranes are connective tissue and buccinator muscles. The next time you eat some food, notice how the buccinator muscles in your cheeks and the orbicularis oris muscle in your lips contract, helping you keep the food from falling out of your mouth. Additionally, notice how these muscles work when you are speaking.

The pocket-like part of the mouth that is framed on the inside by the gums and teeth, and on the outside by the cheeks and lips is called the **oral vestibule**. Moving farther into the mouth, the opening between the oral cavity and throat (oropharynx) is called the **fauces** (like the kitchen "faucet"). The main open area of the mouth, or oral cavity proper, runs from the gums and teeth to the fauces.

When you are chewing, you do not find it difficult to breathe simultaneously. The next time you have food in your mouth, notice how the arched shape of the roof of your mouth allows you to handle both digestion and respiration at the same time. This arch is called the palate. The anterior region of the palate serves as a wall (or septum) between the oral and nasal cavities as well as a rigid shelf against which the tongue can push food. It is created by the maxillary and palatine bones of the skull and, given its bony structure, is known as the hard palate. If you run your tongue along the roof of your mouth, you'll notice that the hard palate ends in the posterior oral cavity, and the tissue becomes fleshier. This part of the palate, known as the **soft palate**, is composed mainly of skeletal muscle. You can therefore manipulate, subconsciously, the soft palate—for instance, to yawn, swallow, or sing.

A fleshy bead of tissue called the uvula drops down from the center of the posterior edge of the soft palate. Although some have suggested that the uvula is a vestigial organ, it serves an important purpose. When you swallow, the soft palate and uvula move upward, helping to keep foods and liquid from entering the nasal cavity. Unfortunately, it can also contribute to the sound produced by snoring. Two muscular folds extend downward from the soft palate, on either side of the uvula. Toward the front, the **palatoglossal arch** lies next to the base of the tongue; behind it, the **palatopharyngeal arch** forms the superior and lateral margins of the fauces. Between these two arches are the palatine tonsils, clusters of lymphoid tissue that protect the pharynx. The lingual tonsils are located at the base of the tongue.

The Tongue

Perhaps you have heard it said that the tongue is the strongest muscle in the body. Those who stake this claim cite its strength proportionate to its size. Although it is difficult to quantify the relative strength of different muscles, it remains indisputable that the tongue is a workhorse, facilitating ingestion, mechanical digestion, chemical digestion (lingual lipase), sensation (of taste, texture, and temperature of food), swallowing, and vocalization.

The tongue is attached to the mandible, the styloid processes of the temporal bones, and the hyoid bone. The tongue is positioned over the floor of the oral cavity. A medial septum extends the entire length of the tongue, dividing it into symmetrical halves.

The Salivary Glands

Many small **salivary glands** are housed within the mucous membranes of the mouth and tongue. These minor exocrine glands are constantly secreting saliva, either directly into the oral cavity or indirectly through ducts, even while you sleep. In fact, an average of 1 to 1.5 liters of saliva is secreted each day. Usually just enough saliva is present to moisten the mouth and teeth. Secretion increases when you eat, because saliva is essential to moisten food and initiate the chemical breakdown of carbohydrates.

Outside the oral mucosa are three pairs of major salivary glands, which secrete the majority of saliva into ducts that open into the mouth (**Figure 13.10**):

- The **submandibular glands**, which are in the floor of the mouth, secrete saliva into the mouth through the submandibular ducts.
- The **sublingual glands**, which lie below the tongue, use the lesser sublingual ducts to secrete saliva into the oral cavity.
- The **parotid glands** lie between the skin and the masseter muscle, near the ears. They secrete saliva into the mouth through the parotid duct, which is located near the second upper molar tooth (Figure 13.10).
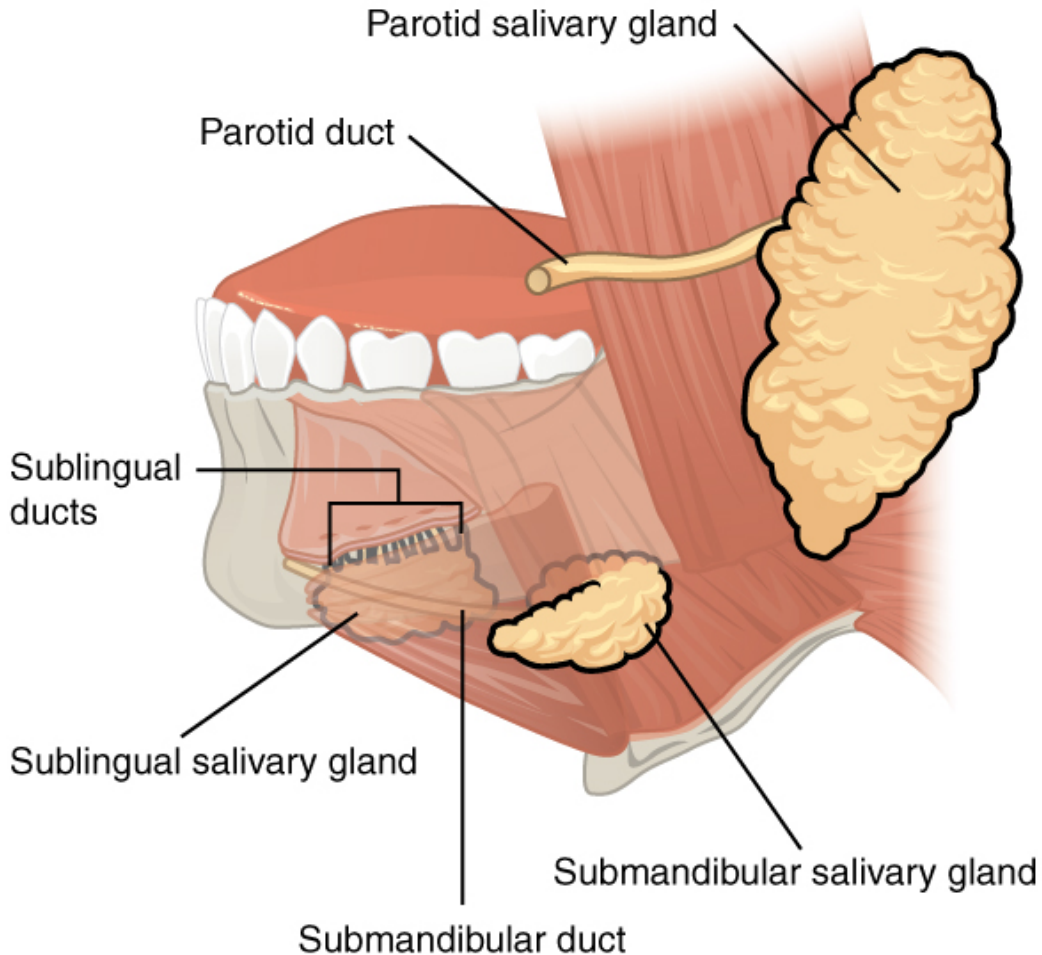
Figure 13.10 Salivary glands The major salivary glands are located outside the oral mucosa and deliver saliva into the mouth through ducts.

The Teeth

The teeth, or **dentes** (singular = dens), are organs similar to bones that you use to tear, grind, and otherwise mechanically break down food. During the course of your lifetime, you have two sets of teeth (one set of teeth is a **dentition**). Your 20 **deciduous teeth**, or baby teeth, first begin to appear at about 6 months of age. Between approximately age 6 and 12, these teeth are replaced by 32 **permanent teeth**. Moving from the center of the mouth toward the side, these are as follows (**Figure 13.11**):

- The eight **incisors**, four top and four bottom, are the sharp front teeth you use for biting into food.
- The four **canines** (or cuspids) flank the incisors and have a pointed edge (cusp) to tear up food. These fang-like teeth are superb for piercing tough or fleshy foods.
- Posterior to the cuspids are the eight **premolars** (or bicuspids), which have an overall flatter shape with two rounded cusps useful for mashing foods.
- The most posterior and largest are the 12 **molars**, which have several pointed cusps used to crush food so it is ready for swallowing. The third members of each set of three molars, top and bottom, are commonly referred to as the wisdom teeth, because their eruption is commonly delayed until early adulthood. It is not

uncommon for wisdom teeth to fail to erupt; that is, they remain impacted. In these cases, the teeth are typically removed by orthodontic surgery.
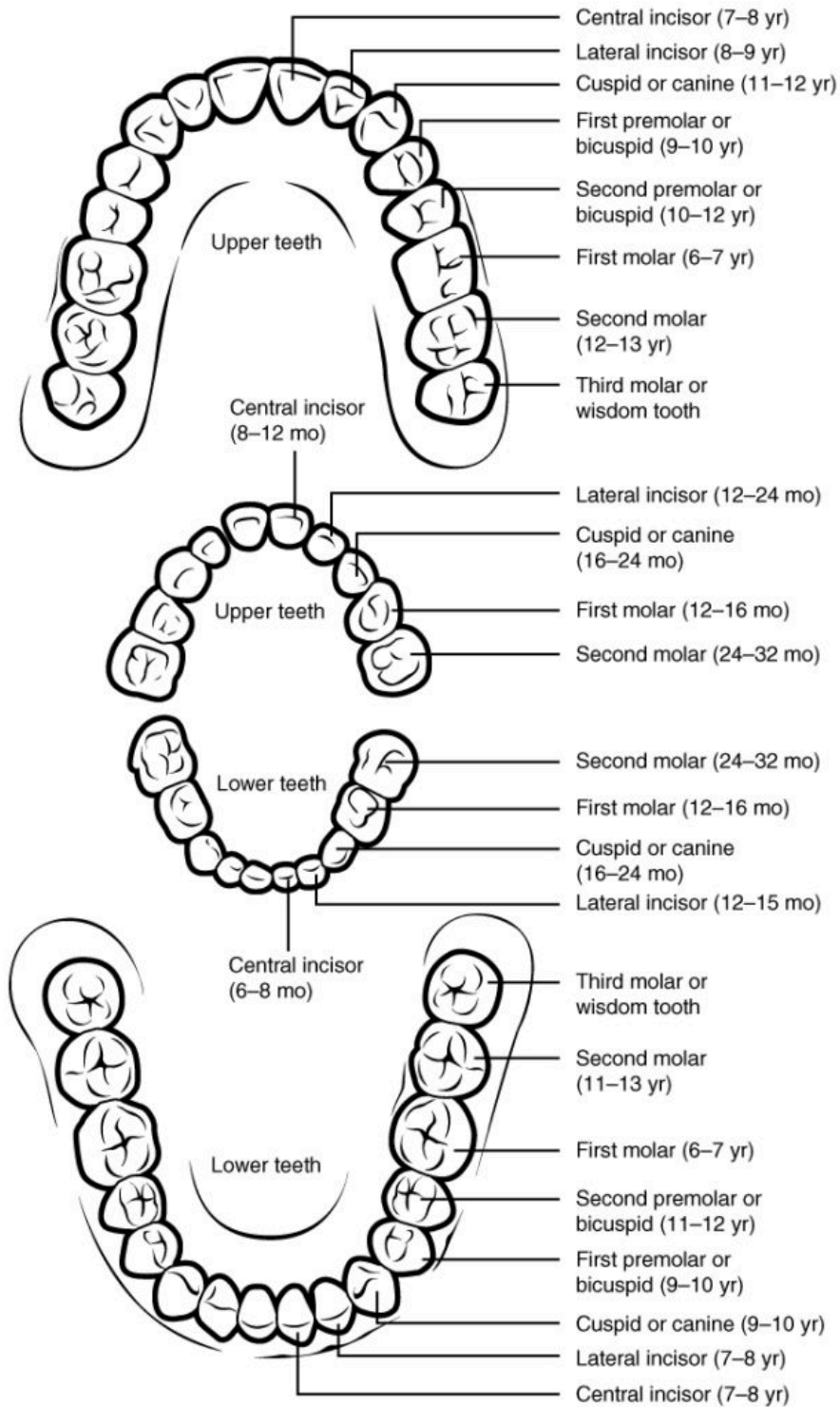

Figure 13.11 Permanent and Deciduous Teeth This figure of two human dentitions shows the arrangement of teeth in the maxilla and mandible, and the relationship between the deciduous and permanent teeth.

The teeth are secured in the alveolar processes (sockets) of the maxilla and the mandible. **Gingivae** (commonly called the gums) are soft tissues that line the alveolar processes and surround the necks of the teeth. Teeth are also held in their sockets by a connective tissue called the **periodontal ligament**.

The two main parts of a tooth are the **crown**, which is the portion projecting above the gum line, and the **root**, which is embedded within the maxilla and mandible. Both parts contain an inner **pulp cavity**, containing loose connective tissue through which run nerves and blood vessels. The region of the pulp cavity that runs through the root of the tooth is called the root canal. Surrounding the pulp cavity is **dentin**, a bone-like tissue. In the root of each tooth, the dentin is covered by an even harder bone-like layer called **cementum**. In the crown of each tooth, the dentin is covered by an outer layer of **enamel**, the hardest substance in the body (**Figure 13.12**).
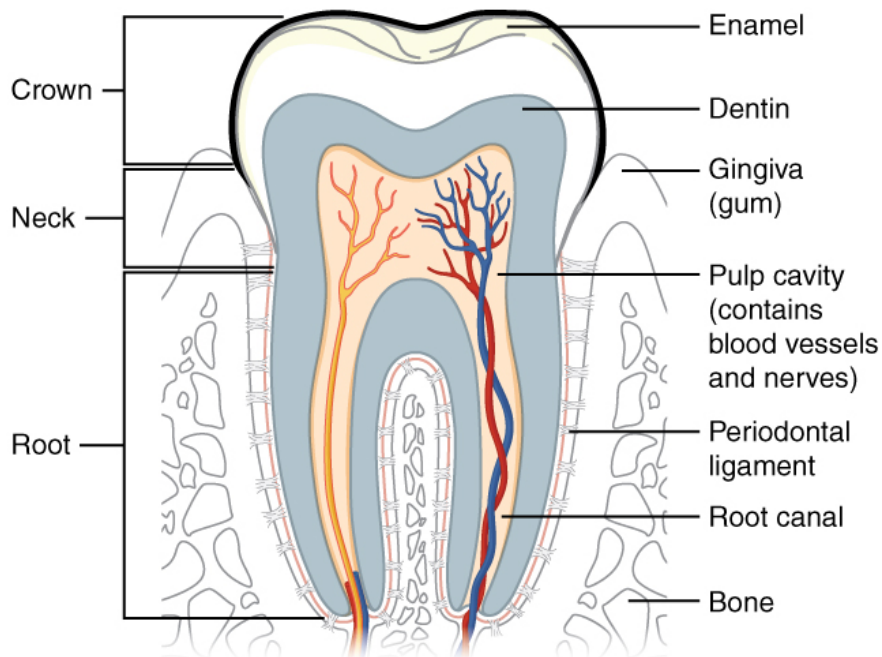

Figure 13.12 The Structure of the Tooth This longitudinal section through a molar in its alveolar socket shows the relationships between enamel, dentin, and pulp.

Although enamel protects the underlying dentin and pulp cavity, it is still nonetheless susceptible to mechanical and chemical erosion, or what is known as tooth decay. The most common form, dental caries (cavities) develops when colonies of bacteria feeding on sugars in the mouth release acids that cause soft tissue inflammation and degradation of the calcium crystals of the enamel. The digestive functions of the mouth are summarized in Table 13.4.

The Pharynx

The **pharynx** (throat) is involved in both digestion and respiration. It receives food and air from the mouth, and air from the nasal cavities. When food enters the pharynx, involuntary muscle contractions close off the air passageways.

A short tube of skeletal muscle lined with a mucous membrane, the pharynx runs from the posterior oral and

nasal cavities to the opening of the esophagus and larynx. It has three subdivisions. The most superior, the **nasopharynx**, is involved only in breathing and speech. The other two subdivisions, the **oropharynx** and the **laryngopharynx**, are used for both breathing and digestion. The oropharynx begins inferior to the nasopharynx and is continuous below with the laryngopharynx (**Figure 13.13**). The inferior border of the laryngopharynx connects to the esophagus, whereas the anterior portion connects to the larynx, allowing air to flow into the bronchial tree.
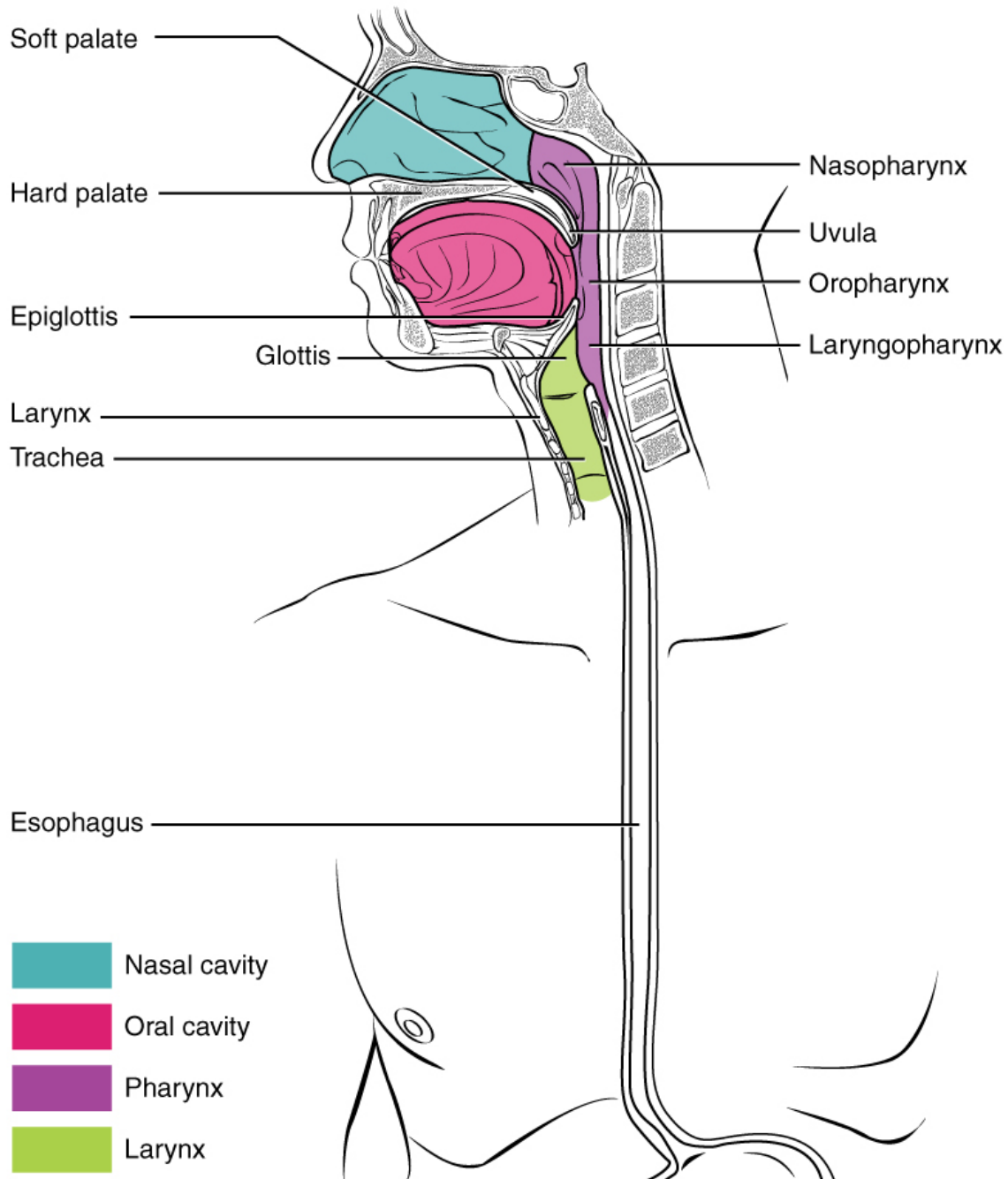

Figure 13.13 Pharynx The pharynx runs from the nostrils to the esophagus and the larynx.

Histologically, the wall of the oropharynx is similar to that of the oral cavity. The mucosa includes a stratified

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squamous epithelium that is endowed with mucus-producing glands. During swallowing, the elevator skeletal muscles of the pharynx contract, raising and expanding the pharynx to receive the bolus of food. Once received, these muscles relax and the constrictor muscles of the pharynx contract, forcing the bolus into the esophagus and initiating peristalsis.

Usually during swallowing, the soft palate and uvula rise reflexively to close off the entrance to the nasopharynx. At the same time, the larynx is pulled superiorly and the cartilaginous epiglottis, its most superior structure, folds inferiorly, covering the glottis (the opening to the larynx); this process effectively blocks access to the trachea and bronchi. When the food "goes down the wrong way," it goes into the trachea. When food enters the trachea, the reaction is to cough, which usually forces the food up and out of the trachea, and back into the pharynx.

The Esophagus

The **esophagus** is a muscular tube that connects the pharynx to the stomach. It is approximately 25.4 cm (10 in) in length, located posterior to the trachea, and remains in a collapsed form when not engaged in swallowing. The esophagus runs a mainly straight route through the mediastinum of the thorax. To enter the abdomen, the esophagus penetrates the diaphragm through an opening called the esophageal hiatus.

The mucosa of the esophagus is made up of an epithelial lining that contains non-keratinized, stratified squamous epithelium. This epithelium protects against erosion from food particles. The mucosa's lamina propria contains mucus-secreting glands. The muscularis layer changes according to location: In the upper third of the esophagus, the muscularis is skeletal muscle. In the middle third, it is both skeletal and smooth muscle. In the lower third, it is smooth muscle. As mentioned previously, the most superficial layer of the esophagus is called the adventitia, not the serosa. In contrast to the stomach and intestines, the loose connective tissue of the adventitia is not covered by a fold of visceral peritoneum.

The Stomach

Although a minimal amount of carbohydrate digestion occurs in the mouth, chemical digestion really gets underway in the stomach. An expansion of the alimentary canal that lies immediately inferior to the esophagus, the stomach links the esophagus to the first part of the small intestine (the duodenum) and is relatively fixed in place at its esophageal and duodenal ends. In between, however, it can be a highly active structure, contracting and continually changing position and size. These contractions provide mechanical assistance to digestion. The empty stomach is only about the size of your fist, but can stretch to hold as much as 4 liters of food and fluid, or more than 75 times its empty volume, and then return to its resting size when empty.

Popular culture tends to refer to the stomach as the location where all digestion takes place. Of course, this is not true. An important function of the stomach is to serve as a temporary holding chamber. You can ingest a meal far more quickly than it can be digested and absorbed by the small intestine. Thus, the stomach holds food and parses only small amounts into the small intestine at a time. Before food is released to the small intestine, it is mixed together with digestive juices in the stomach and converted into **chyme**. The stomach plays several important roles in chemical digestion, including the continued digestion of carbohydrates and the initial digestion of proteins and triglycerides. Little if any nutrient absorption occurs in the stomach, with the exception of the negligible amount of nutrients in alcohol.

There are four main regions in the **stomach**: the cardia, fundus, body, and pylorus (**Figure 13.14**). The **cardia** (or

cardiac region) is the point where the esophagus connects to the stomach and through which food passes into the stomach. Located inferior to the diaphragm, above and to the left of the cardia, is the dome-shaped **fundus**. Below the fundus is the **body**, the main part of the stomach. The funnel-shaped **pylorus** connects the stomach to the duodenum. The wider end of the funnel, the **pyloric antrum**, connects to the body of the stomach. The narrower end is called the **pyloric canal**, which connects to the duodenum. The smooth muscle **pyloric sphincter** is located at this latter point of connection and controls stomach emptying. In the absence of food, the stomach deflates inward, and its mucosa and submucosa fall into a large fold called a **ruga**.
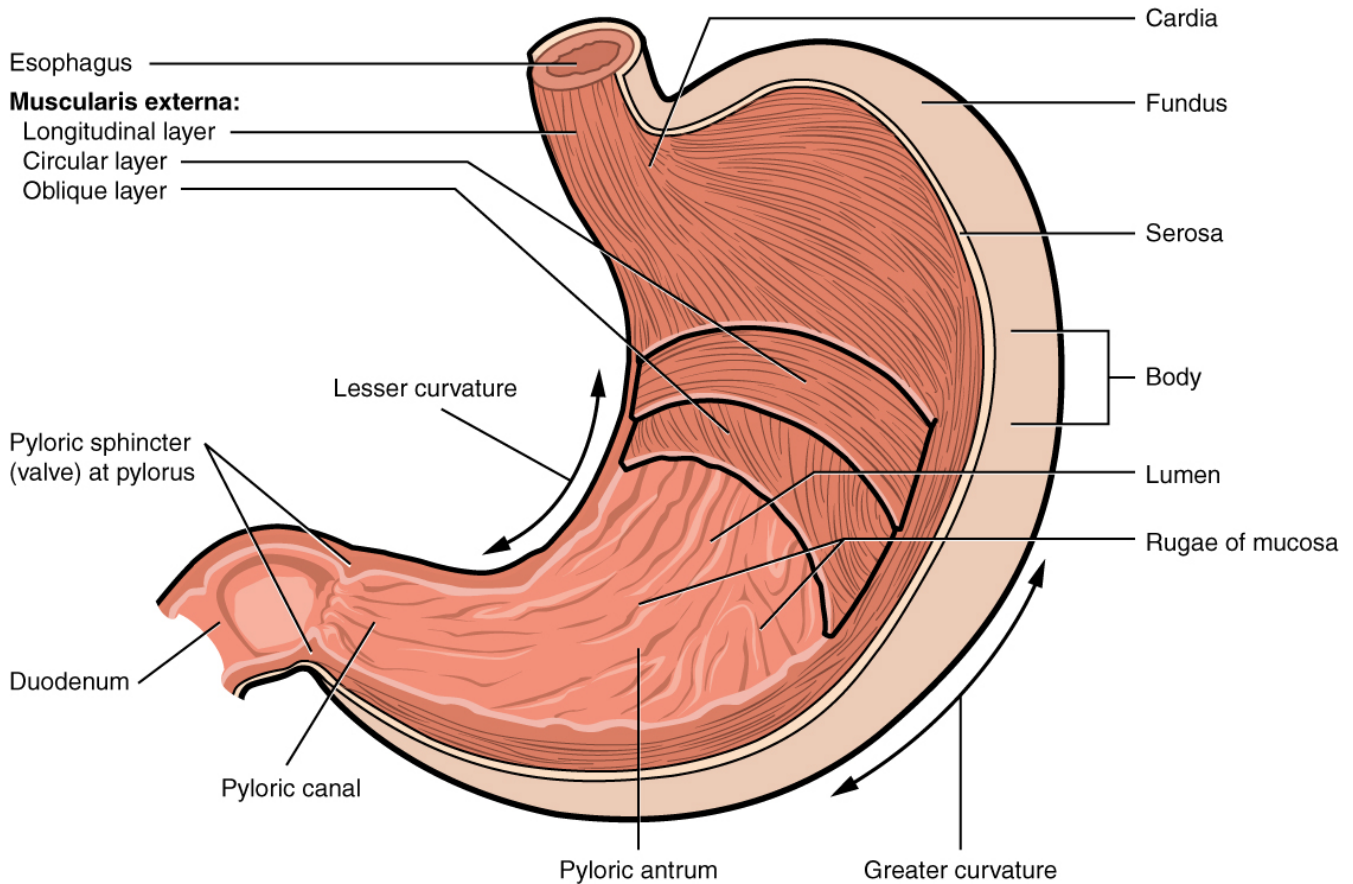

Figure 13.14 Stomach The stomach has four major regions: the cardia, fundus, body, and pylorus. The addition of an inner oblique smooth muscle layer gives the muscularis the ability to vigorously churn and mix food.

The convex lateral surface of the stomach is called the greater curvature; the concave medial border is the lesser curvature. The stomach is held in place by the lesser omentum, which extends from the liver to the lesser curvature, and the greater omentum, which runs from the greater curvature to the posterior abdominal wall.

The Small Intestine

Chyme released from the stomach enters the **small intestine**, which is the primary digestive organ in the body. Not only is this where most digestion occurs, it is also where practically all absorption occurs. The longest part of the alimentary canal, the small intestine is about 3.05 meters (10 feet) long in a living person (but about twice as long in a cadaver due to the loss of muscle tone). Since this makes it about five times longer than the large intestine, you might wonder why it is called "small." In fact, its name derives from its relatively smaller diameter

of only about 2.54 cm (1 in), compared with 7.62 cm (3 in) for the large intestine. As we'll see shortly, in addition to its length, the folds and projections of the lining of the small intestine work to give it an enormous surface area, which is approximately 200 m^2, more than 100 times the surface area of your skin. This large surface area is necessary for complex processes of digestion and absorption that occur within it.

The coiled tube of the small intestine is subdivided into three regions. From proximal (at the stomach) to distal, these are the duodenum, jejunum, and ileum (**Figure 13.15**). The shortest region is the 25.4-cm (10-in) **duodenum**, which begins at the pyloric sphincter. Just past the pyloric sphincter, it bends posteriorly behind the peritoneum, becoming retroperitoneal, and then makes a C-shaped curve around the head of the pancreas before ascending anteriorly again to return to the peritoneal cavity and join the jejunum. Of particular interest is the **hepatopancreatic ampulla**. Located in the duodenal wall, the ampulla marks the transition from the anterior portion of the alimentary canal to the mid-region, and is where the **bile duct** (through which bile passes from the liver) and the **main pancreatic duct** (through which pancreatic juice passes from the pancreas) join. This ampulla opens into the duodenum at a tiny volcano-shaped structure called the **major duodenal papilla**. The **hepatopancreatic sphincter** regulates the flow of both bile and pancreatic juice from the ampulla into the duodenum.
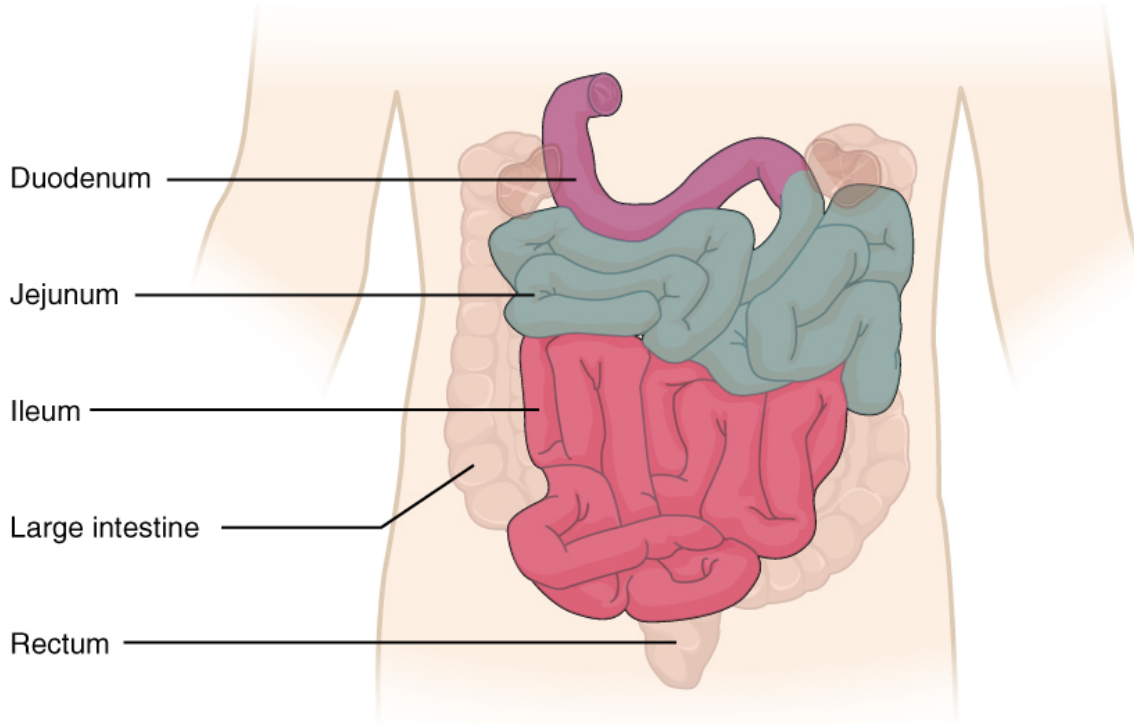

Figure 13.15 Small Intestine The three regions of the small intestine are the duodenum, jejunum, and ileum.

The **jejunum** is about 0.9 meters (3 feet) long (in life) and runs from the duodenum to the ileum. Jejunum means "empty" in Latin and supposedly was so named by the ancient Greeks who noticed it was always empty at death. No clear demarcation exists between the jejunum and the final segment of the small intestine, the ileum. The **ileum** is the longest part of the small intestine, measuring about 1.8 meters (6 feet) in length. It is thicker, more vascular, and has more developed mucosal folds than the jejunum. The ileum joins the cecum, the first portion

of the large intestine, at the **ileocecal valve** (or sphincter). The jejunum and ileum are tethered to the posterior abdominal wall by the mesentery. The large intestine frames these three parts of the small intestine.
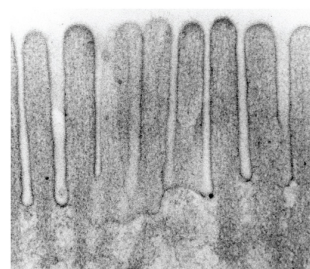
Histology of the small intestine

The wall of the small intestine is composed of the same four layers typically present in the alimentary system. However, three features of the mucosa and submucosa are unique. These features, which increase the absorptive surface area of the small intestine more than 600-fold, include circular folds, villi, and microvilli (**Figure 13.16**). These adaptations are most abundant in the proximal two-thirds of the small intestine, where the majority of absorption occurs.

(a)
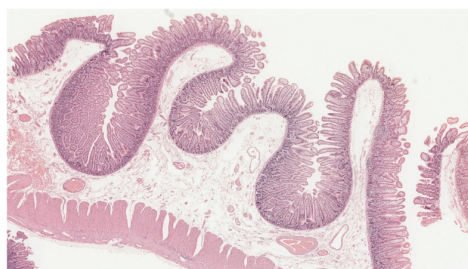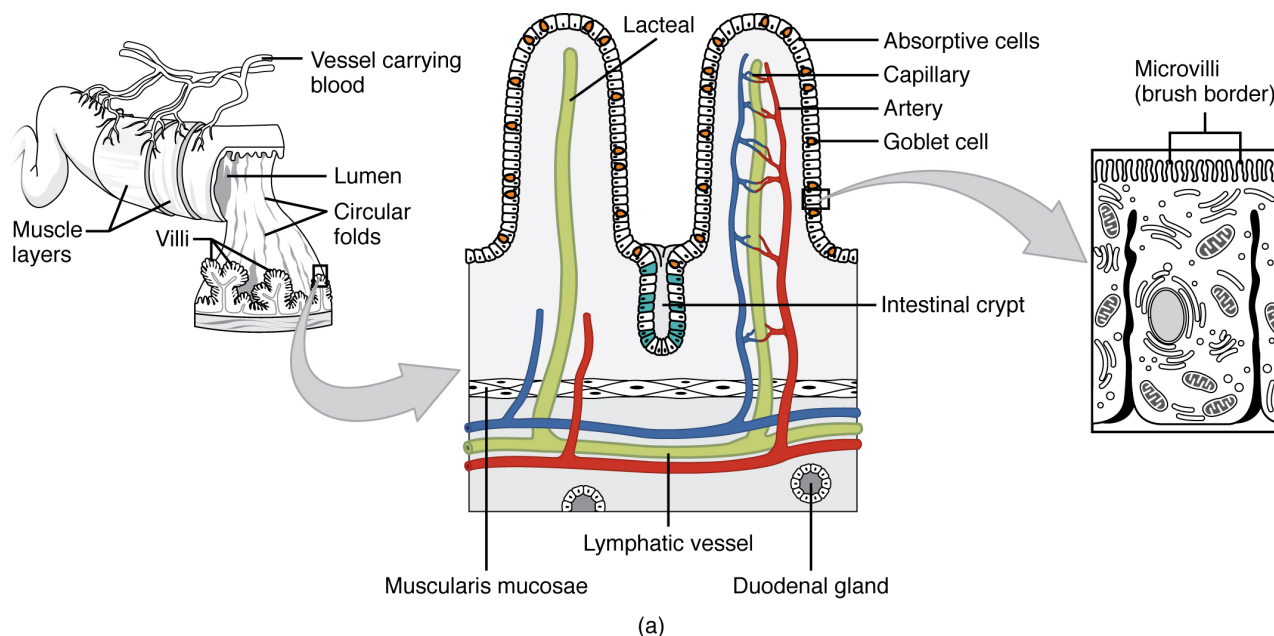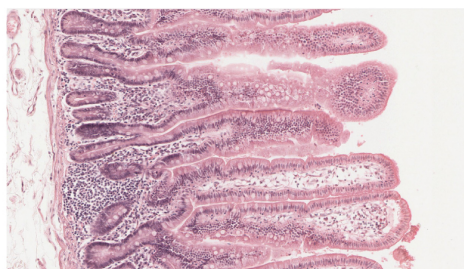
(b)   (c)   (d)

Figure 13.16 Histology of the Small Intestine (a) The absorptive surface of the small intestine is vastly enlarged by the presence of circular folds, villi, and microvilli. (b) Micrograph of the circular folds. (c) Micrograph of the villi. (d) Electron micrograph of the microvilli. From left to right, LM x 56, LM x 508, EM x 196,000. (credit b-d: Micrograph provided by the Regents of University of Michigan Medical School © 2012)

Also called a plica circulare, a **circular fold** is a deep ridge in the mucosa and submucosa. Beginning near the proximal part of the duodenum and ending near the middle of the ileum, these folds facilitate absorption. Their shape causes the chyme to spiral, rather than move in a straight line, through the small intestine. Spiraling slows the movement of chyme and provides the time needed for nutrients to be fully absorbed.

Within the circular folds are small (0.5–1 mm long) hairlike vascularized projections called **villi** (singular = villus) that give the mucosa a furry texture. There are about 20 to 40 villi per square millimeter, increasing the surface area of the epithelium tremendously. The mucosal epithelium, primarily composed of absorptive cells, covers the villi. In addition to muscle and connective tissue to support its structure, each villus contains a capillary bed composed of one arteriole and one venule, as well as a lymphatic capillary called a **lacteal**. The breakdown products of carbohydrates and proteins (sugars and amino acids) can enter the bloodstream directly, but lipid breakdown products are absorbed by the lacteals and transported to the bloodstream via the lymphatic system.

As their name suggests, **microvilli** (singular = microvillus) are much smaller (1 μm) than villi. They are cylindrical apical surface extensions of the plasma membrane of the mucosa's epithelial cells. Although their small size makes it difficult to see each microvillus, their combined microscopic appearance suggests a mass of bristles, which is termed the **brush border**. There are an estimated 200 million microvilli per square millimeter of small intestine, greatly expanding the surface area of the plasma membrane and thus greatly enhancing absorption.

Chemical Digestion in the Small Intestine

The digestion of proteins and carbohydrates, which partially occurs in the stomach, is completed in the small intestine with the aid of intestinal and pancreatic juices. Lipids arrive in the intestine largely undigested, so much of the focus here is on lipid digestion, which is facilitated by bile and the enzyme pancreatic lipase. Intestinal juice combines with pancreatic juice to provide a liquid medium that facilitates absorption. The intestine is also where most water is absorbed, via osmosis.

For optimal chemical digestion, chyme must be delivered from the stomach slowly and in small amounts. This is because chyme from the stomach is typically hypertonic, and if large quantities were forced all at once into the small intestine, the resulting osmotic water loss from the blood into the intestinal lumen would result in potentially life-threatening low blood volume. In addition, continued digestion requires an upward adjustment of the low pH of stomach chyme, along with rigorous mixing of the chyme with bile and pancreatic juices. Both processes take time, so the pumping action of the pylorus must be carefully controlled to prevent the duodenum from being overwhelmed with chyme.

The Large Intestine

The **large intestine** is the terminal part of the alimentary canal. The primary function of this organ is to finish absorption of nutrients and water, synthesize certain vitamins, form feces, and eliminate feces from the body. The small intestine absorbs about 90 percent of the water you ingest (either as liquid or within solid food). The large intestine absorbs most of the remaining water, a process that converts the liquid chyme residue into semisolid **feces** ("stool").

The large intestine runs from the appendix to the anus. It frames the small intestine on three sides. Despite its being about one-half as long as the small intestine, it is called large because it is more than twice the diameter of the small intestine, about 3 inches. The large intestine is subdivided into four main regions: the cecum, the colon, the rectum, and the anus. The **ileocecal valve**, located at the opening between the ileum and the large intestine, controls the flow of chyme from the small intestine to the large intestine.

The first part of the large intestine is the **cecum**, a sac-like structure that is suspended inferior to the ileocecal valve. It is about 6 cm (2.4 in) long, receives the contents of the ileum, and continues the absorption of water

and salts. The **appendix** (or vermiform appendix) is a winding tube that attaches to the cecum. Although the 7.6-cm (3-in) long appendix contains lymphoid tissue, suggesting an immunologic function, this organ is generally considered vestigial.

The cecum blends seamlessly with the **colon**. Upon entering the colon, the food residue first travels up the **ascending colon** on the right side of the abdomen. At the inferior surface of the liver, the colon bends to form the **right colic flexure** (hepatic flexure) and becomes the **transverse colon**. Food residue passing through the transverse colon travels across to the left side of the abdomen, where the colon angles sharply immediately inferior to the spleen, at the **left colic flexure** (splenic flexure). From there, food residue passes through the **descending colon**, which runs down the left side of the posterior abdominal wall. After entering the pelvis inferiorly, it becomes the s-shaped **sigmoid colon**, which extends medially to the midline (**Figure 13.17**). The ascending and descending colon, and the rectum are located in the retroperitoneum. The transverse and sigmoid colon are tethered to the posterior abdominal wall by the mesocolon.
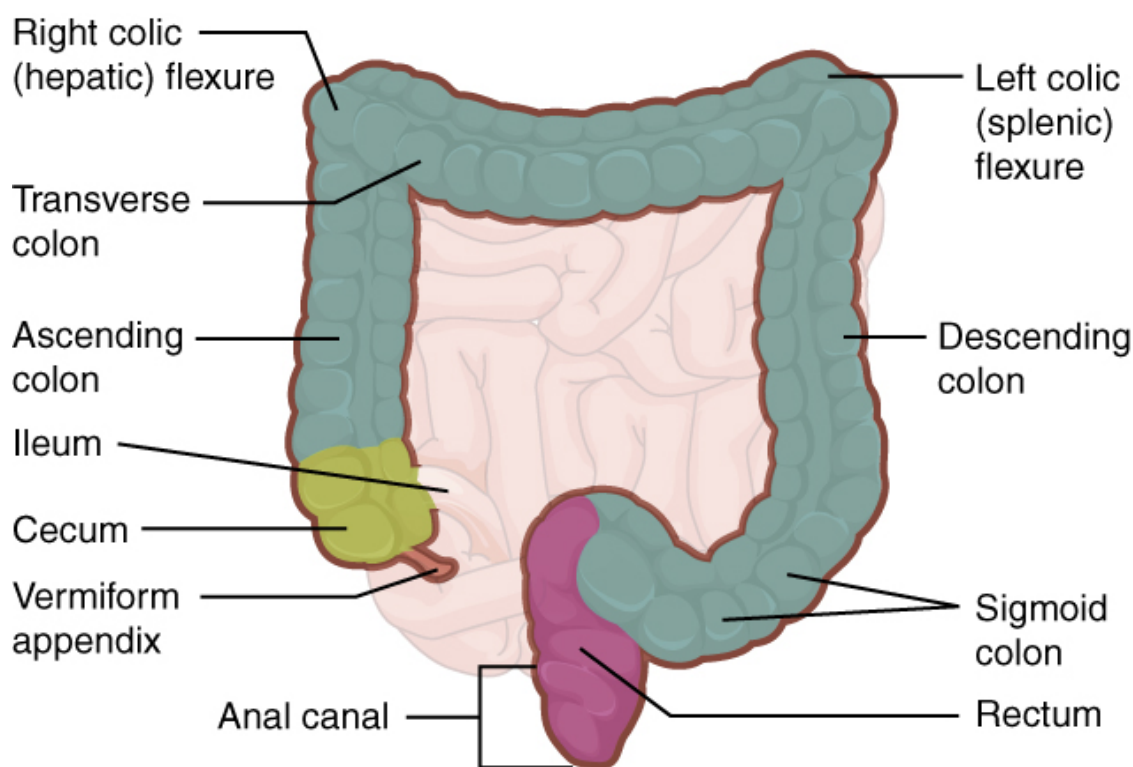

Figure 13.17 Large Intestine The large intestine includes the cecum, colon, and rectum.

Food residue leaving the sigmoid colon enters the **rectum** in the pelvis, near the third sacral vertebra. The final 20.3 cm (8 in) of the alimentary canal, the rectum extends anterior to the sacrum and coccyx. Even though rectum is Latin for "straight," this structure follows the curved contour of the sacrum and has three lateral bends that create a trio of internal transverse folds called the **rectal valves**. These valves help separate the feces from gas to prevent the simultaneous passage of feces and gas.

Finally, food residue reaches the last part of the large intestine, the **anal canal**, which is located in the perineum, completely outside of the abdominopelvic cavity. This 3.8–5 cm (1.5–2 in) long structure opens to the exterior of the body at the anus. The anal canal includes two sphincters. The **internal anal sphincter** is made of smooth

muscle, and its contractions are involuntary. The **external anal sphincter** is made of skeletal muscle, which is under voluntary control. Except when defecating, both usually remain closed.

Three features are unique to the large intestine: teniae coli, haustra, and epiploic appendages (**Figure 13.18**). The **teniae coli** are three bands of smooth muscle that make up the longitudinal muscle layer of the muscularis of the large intestine, except at its terminal end. Tonic contractions of the teniae coli bunch up the colon into a succession of pouches called **haustra** (singular = haustrum), which are responsible for the wrinkled appearance of the colon. Attached to the teniae coli are small, fat-filled sacs of visceral peritoneum called **epiploic appendages**. The purpose of these is unknown. Although the rectum and anal canal have neither teniae coli nor haustra, they do have well-developed layers of muscularis that create the strong contractions needed for defecation.
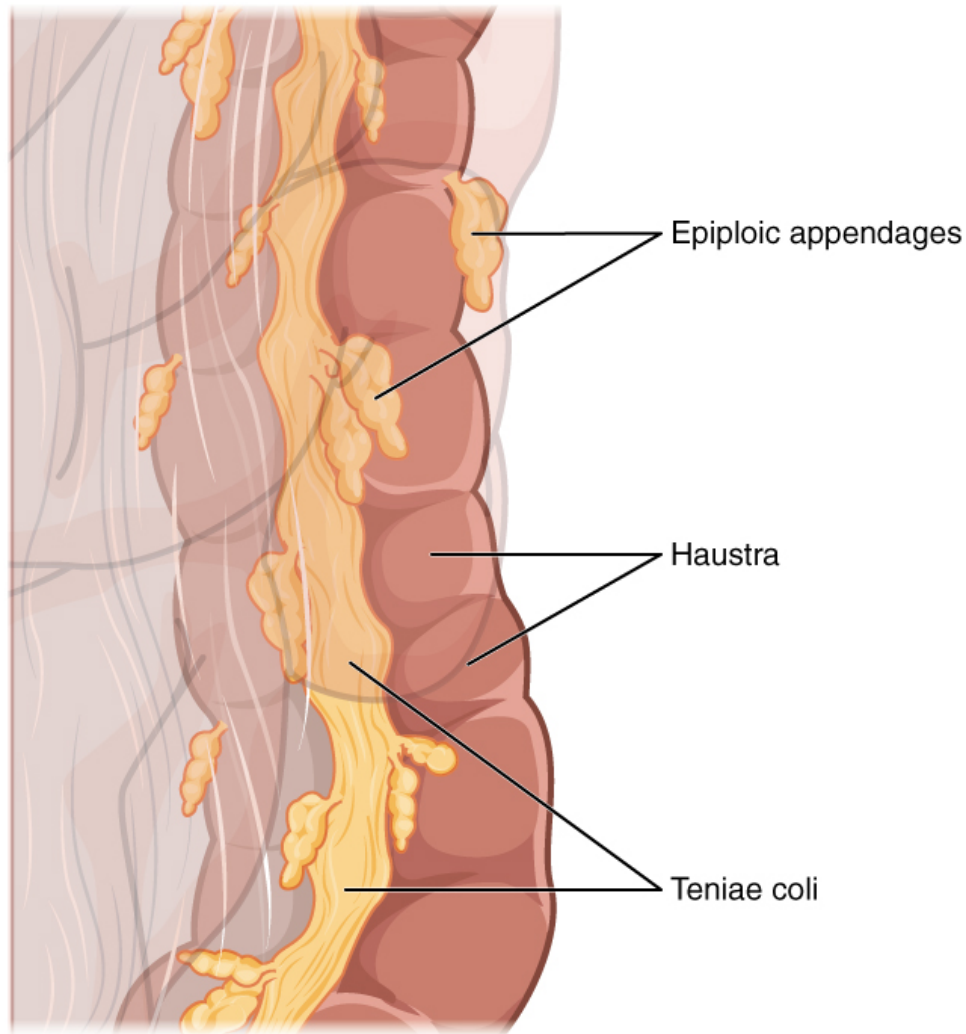

Figure 13.18 Teniae Coli, Haustra, and Epiploic Appendages

Accessory Organs of the Digestive System

Chemical digestion in the small intestine relies on the activities of three accessory digestive organs: the liver, pancreas, and gallbladder (**Figure 13.19**). The digestive role of the liver is to produce bile and export it to the

duodenum. The gallbladder primarily stores, concentrates, and releases bile. The pancreas produces pancreatic juice, which contains digestive enzymes and bicarbonate ions, and delivers it to the duodenum.
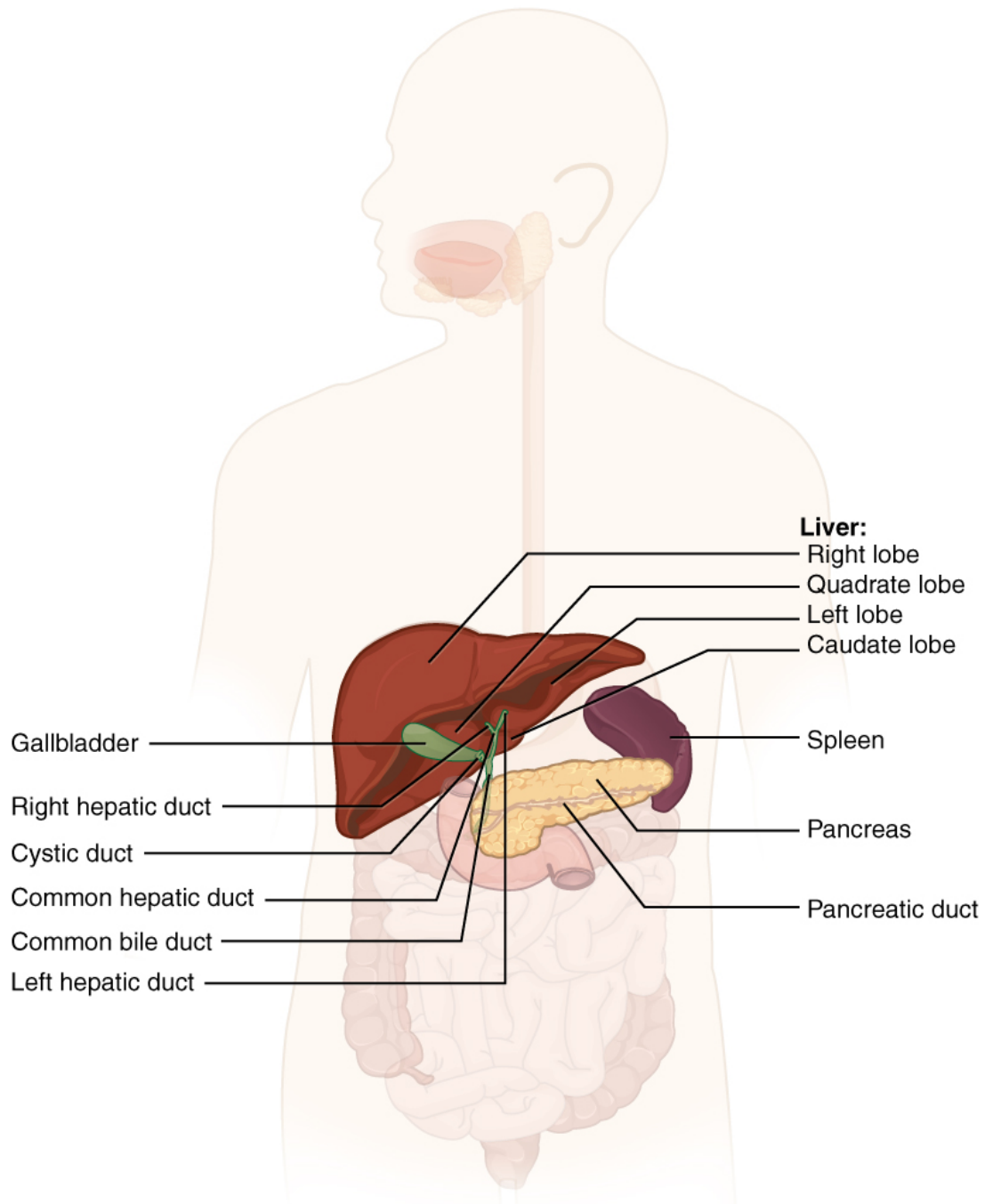
Liver:
- Right lobe
- Quadrate lobe
- Left lobe
- Caudate lobe

Gallbladder

Right hepatic duct

Cystic duct

Common hepatic duct

Common bile duct

Left hepatic duct

Spleen

Pancreas

Pancreatic duct

Figure 13.19 Accessory Organs The liver, pancreas, and gallbladder are considered accessory digestive organs, but their roles in the digestive system are vital.

The Liver

The **liver** is the largest gland in the body, weighing about three pounds in an adult. It is also one of the most

important organs. In addition to being an accessory digestive organ, it plays a number of roles in metabolism and regulation. The liver lies inferior to the diaphragm in the right upper quadrant of the abdominal cavity and receives protection from the surrounding ribs.

The liver is divided into two primary lobes: a large right lobe and a much smaller left lobe. In the right lobe, some anatomists also identify an inferior quadrate lobe and a posterior caudate lobe, which are defined by internal features. The liver is connected to the abdominal wall and diaphragm by five peritoneal folds referred to as ligaments. These are the falciform ligament, the coronary ligament, two lateral ligaments, and the ligamentum teres hepatis. The falciform ligament and ligamentum teres hepatis are actually remnants of the umbilical vein, and separate the right and left lobes anteriorly. The lesser omentum tethers the liver to the lesser curvature of the stomach.

The **porta hepatis** ("gate to the liver") is where the **hepatic artery** and **hepatic portal vein** enter the liver. These two vessels, along with the **common hepatic duct**, run behind the lateral border of the lesser omentum on the way to their destinations. The hepatic artery delivers oxygenated blood from the heart to the liver. The hepatic portal vein delivers partially deoxygenated blood containing nutrients absorbed from the small intestine and actually supplies more oxygen to the liver than do the much smaller hepatic arteries. In addition to nutrients, drugs and toxins are also absorbed. After processing the bloodborne nutrients and toxins, the liver releases nutrients needed by other cells back into the blood, which drains into the central vein and then through the hepatic vein to the inferior vena cava. With this hepatic portal circulation, all blood from the alimentary canal passes through the liver. This largely explains why the liver is the most common site for the metastasis of cancers that originate in the alimentary canal.

The **common hepatic duct** transports bile from the liver (coming from the left and right hepatic ducts) towards the small intestine. **Bile** is a mixture secreted by the liver to accomplish the emulsification of lipids in the small intestine. Recall that lipids are hydrophobic, that is, they do not dissolve in water. Thus, before they can be digested in the watery environment of the small intestine, large lipid globules must be broken down into smaller lipid globules, a process called emulsification. Hepatocytes secrete about one liter of bile each day. Hepatocytes work non-stop, but bile production increases when fatty chyme enters the duodenum and stimulates the secretion of the gut hormone secretin. Between meals, bile is produced but conserved. The valve-like hepatopancreatic ampulla closes, allowing bile to divert to the gallbladder, where it is concentrated and stored until the next meal.

The Gallbladder

The **gallbladder** is 8–10 cm (~3–4 in) long and is nested in a shallow area on the posterior aspect of the right lobe of the liver. This muscular sac stores, concentrates, and, when stimulated, propels the bile into the duodenum via the common bile duct. It is divided into three regions. The fundus is the widest portion and tapers medially into the body, which in turn narrows to become the neck. The neck angles slightly superiorly as it approaches the hepatic duct. The cystic duct is 1–2 cm (less than 1 in) long and turns inferiorly as it bridges the neck and hepatic duct.

The simple columnar epithelium of the gallbladder mucosa is organized in rugae, similar to those of the stomach. The gallbladder has a layer of smooth muscle fibers, which, when they contract, eject the gallbladder's contents through the **cystic duct** and into the **common bile duct** (**Figure 13.20**). Visceral peritoneum reflected from the liver capsule holds the gallbladder against the liver and forms the outer coat of the gallbladder. The gallbladder's mucosa absorbs water and ions from bile, concentrating it by up to 10-fold.
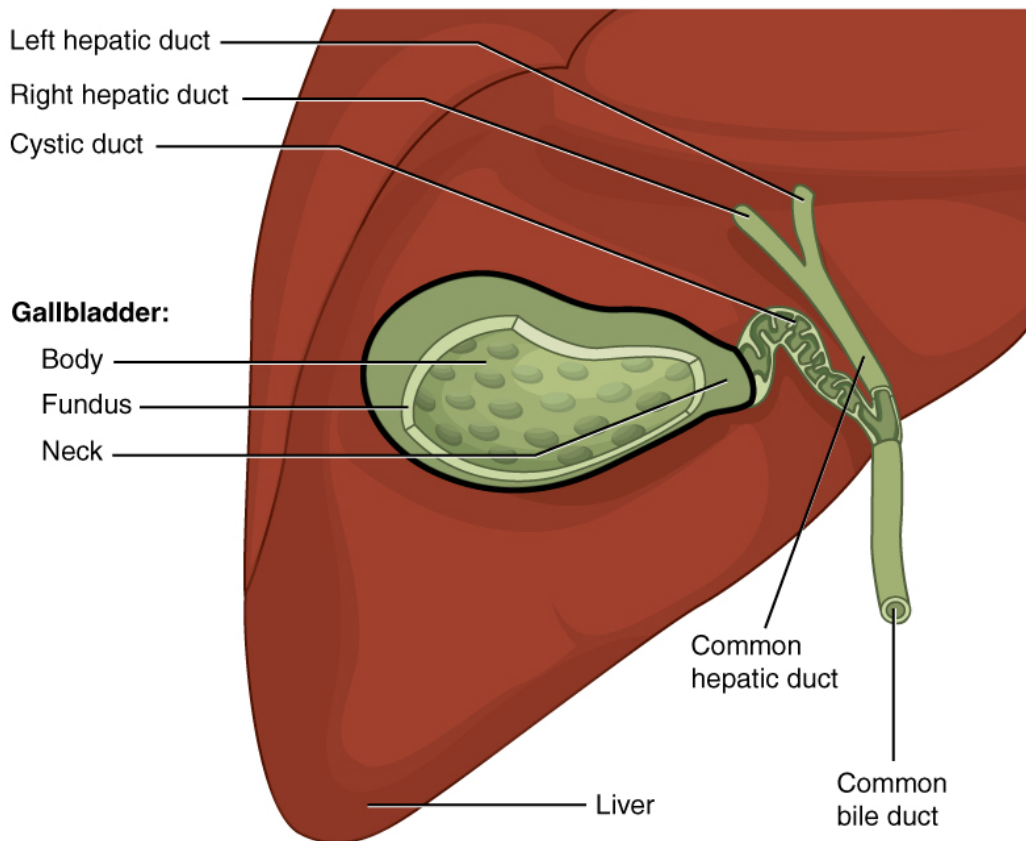
Figure 13.20 Gallbladder The gallbladder stores and concentrates bile, and releases it into the two-way cystic duct when it is needed by the small intestine.

The Pancreas

The soft, oblong, glandular **pancreas** lies transversely in the retroperitoneum behind the stomach. Its head is nestled into the "c-shaped" curvature of the duodenum with the body extending to the left about 15.2 cm (6 in) and ending as a tapering tail in the hilum of the spleen (**Figure 13.21**). It is a curious mix of exocrine (secreting digestive enzymes) and endocrine (releasing hormones into the blood) functions.
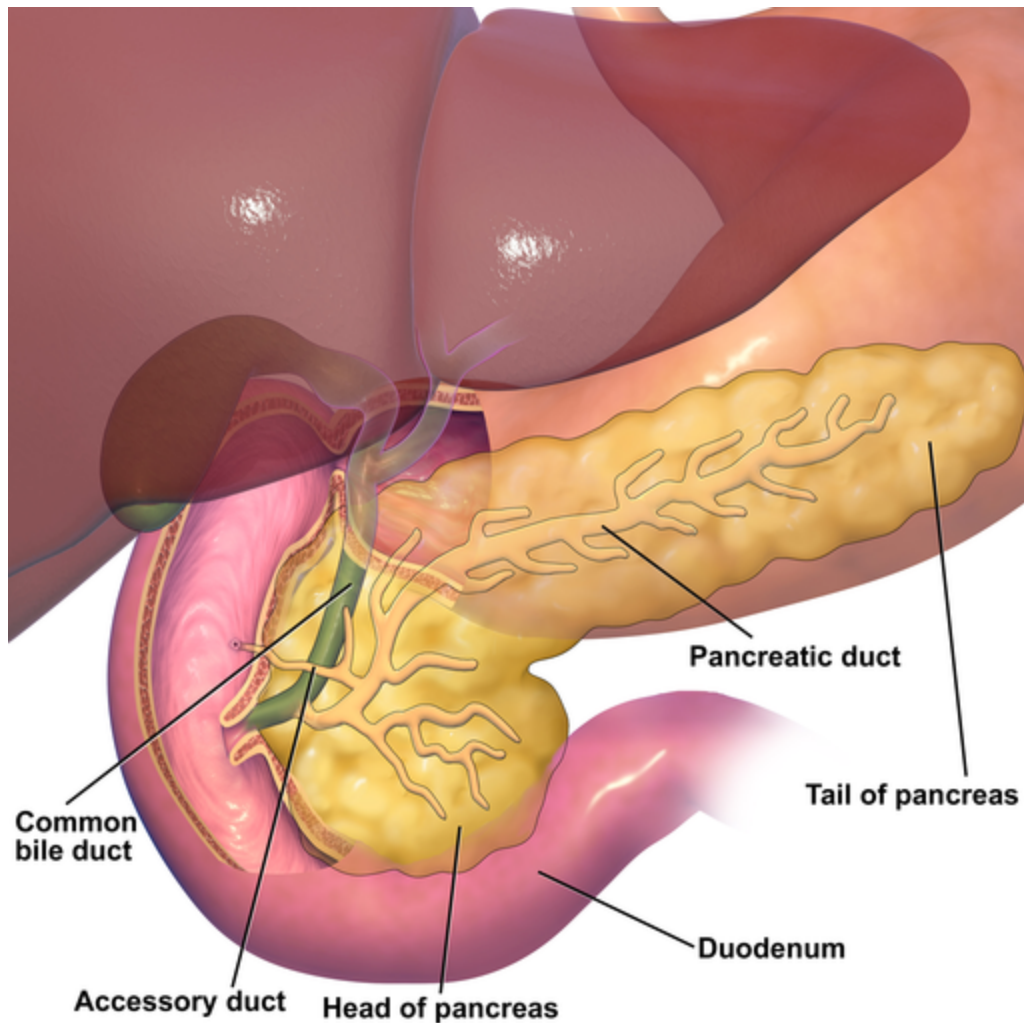
Figure 13.21 The Pancreas The pancreas is located in the abdominal cavity, near the stomach, liver, gallbladder, and duodenum. *Image source: Blausen Medical via Wikimedia Commons, CC BY 3.0.*

The exocrine part of the pancreas arises as little grape-like cell clusters, each called an **acinus** (plural = acini), located at the terminal ends of pancreatic ducts. These acinar cells secrete enzyme-rich **pancreatic juice** into tiny merging ducts that form two dominant ducts. The larger **pancreatic duct** fuses with the common bile duct (carrying bile from the liver and gallbladder) just before entering the duodenum via a common opening (the hepatopancreatic ampulla). The smooth muscle sphincter of the hepatopancreatic ampulla controls the release of pancreatic juice and bile into the small intestine. The second and smaller pancreatic duct, the **accessory duct**, runs from the pancreas directly into the duodenum, approximately 1 inch above the hepatopancreatic ampulla.

The pancreas produces over a liter of pancreatic juice each day. Unlike bile, it is clear and composed mostly of water along with some salts, sodium bicarbonate, and several digestive enzymes. Sodium bicarbonate is responsible for the slight alkalinity of pancreatic juice (pH 7.1 to 8.2), which serves to buffer the acidic gastric juice in chyme, inactivate pepsin from the stomach, and create an optimal environment for the activity of pH-sensitive digestive enzymes in the small intestine. Pancreatic enzymes are active in the digestion of sugars, proteins, and fats.

Lab 14: Urinary system & Reproductive system

The Urinary system

You are likely familiar with the urinary system's role in cleansing the blood and ridding the body of wastes through the production of urine, but there are many other important functions that the urinary system participates in. The urinary system plays a role in regulation of pH, blood pressure, the concentration of solutes in the blood, and the concentration of red blood cells. The kidneys also perform the final synthesis step of vitamin D production, converting calcidiol to calcitriol, the active form of vitamin D.

Urine is a fluid of variable composition that requires specialized structures to remove it from the body safely and efficiently. Blood is filtered, and the filtrate is transformed into urine at a relatively constant rate throughout the day in the **kidneys**. This processed liquid is transported via the **ureters** to the **urinary bladder**, where it is stored until a convenient time for excretion. Urine then exits the body via the **urethra**. All structures involved in the transport and storage of the urine are large enough to be visible to the naked eye (**Figure 14.1**).
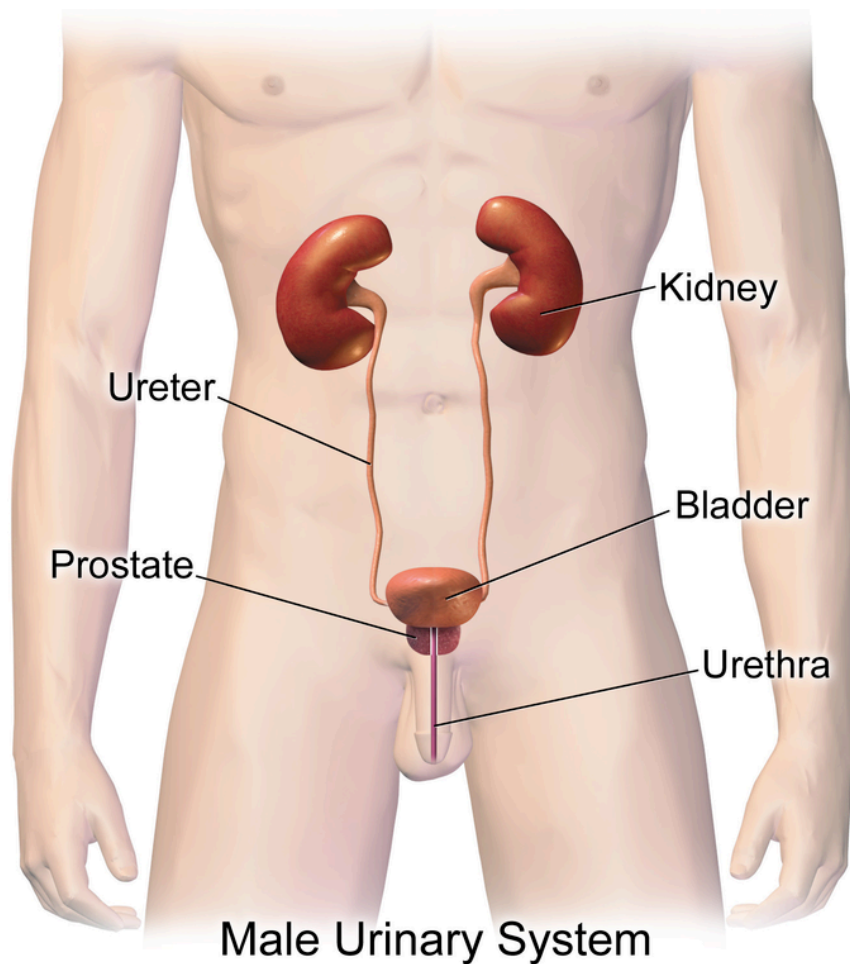
Figure 14.1. Urinary system Major structures in the urinary system include the kidneys, ureters, urinary bladder, and urethra.

This transport and storage system not only stores the waste, but it protects the tissues from damage due to the wide range of pH and osmolarity of the urine, prevents infection by foreign organisms, and for the male, provides reproductive functions.

Kidneys

The **kidneys** lie on either side of the spine in the retroperitoneal space between the parietal peritoneum and the posterior abdominal wall, well protected by muscle, fat, and ribs. The left kidney is located at about the T12 to L3 vertebrae, whereas the right is lower due to slight displacement by the liver (**Figure 14.2**). They are roughly the size of your fist. The male kidney is typically a bit larger than the female kidney. The kidneys are well vascularized, receiving about twenty-five percent of the cardiac output at rest.
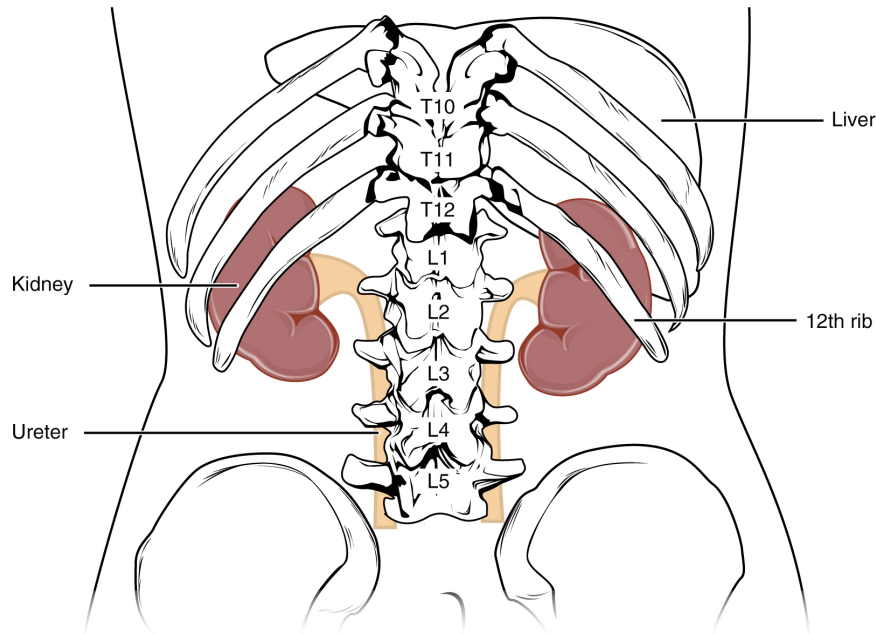
Figure 14.2 Kidneys in posterior view. The kidneys are slightly protected by the ribs and are surrounded by fat for protection (not shown).

A frontal section through the kidney reveals an outer region called the **renal cortex** and an inner region called the **medulla** (**Figure 14.3**). The **renal columns** are connective tissue extensions that radiate downward from the cortex through the medulla to separate the most characteristic features of the medulla, the **renal pyramids** (medullary pyramids) and **renal papillae**. The papillae are bundles of collecting ducts that transport urine made by nephrons to the **calyces** of the kidney for excretion. The renal columns also serve to divide the kidney into 6–8 lobes and provide a supportive framework for vessels that enter and exit the cortex. The pyramids and renal columns taken together constitute the kidney lobes.
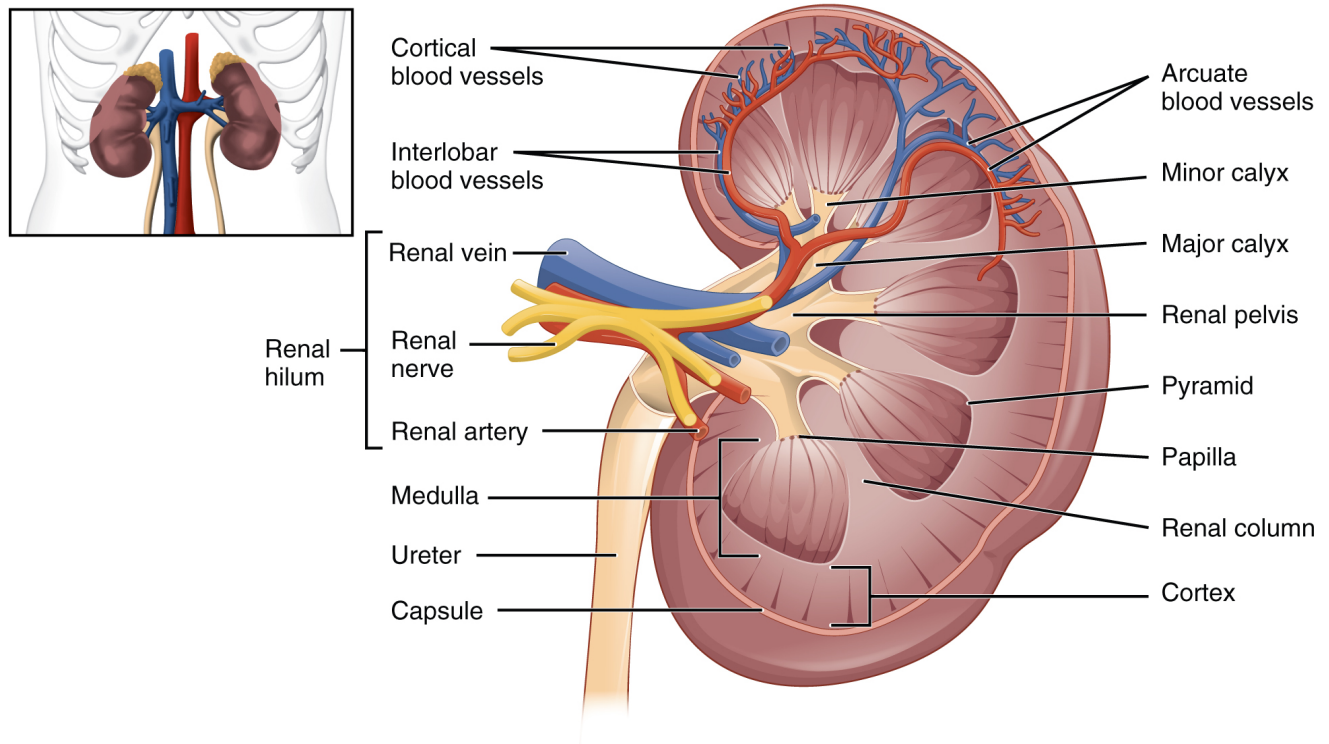
Figure 14.3 Coronal section of the left kidney, showing major internal structures. The image in the upper left shows both kidneys in anterior view, with the adrenal glands located superior to each kidney.

The **renal hilum** is the entry and exit site for structures servicing the kidneys: vessels, nerves, lymphatics, and ureters. The medial-facing hila are tucked into the sweeping convex outline of the cortex. Emerging from the hilum is the **renal pelvis**, which is formed from the major and minor **calyxes** in the kidney. The smooth muscle in the renal pelvis funnels urine via peristalsis into the ureter. The renal arteries form directly from the abdominal aorta, whereas the renal veins return cleansed blood directly to the inferior vena cava. The artery, vein, and renal pelvis are arranged in an anterior-to-posterior order.

Nephrons and Vessels

The **renal artery** first divides into segmental arteries, followed by further branching to form interlobar arteries that pass through the renal columns to reach the cortex (**Figure 14.4**). Smaller arteries branch from the interlobar arteries until eventually the blood reaches the afferent arterioles. The **afferent arterioles** service about 1.3 million **nephrons** in each kidney.
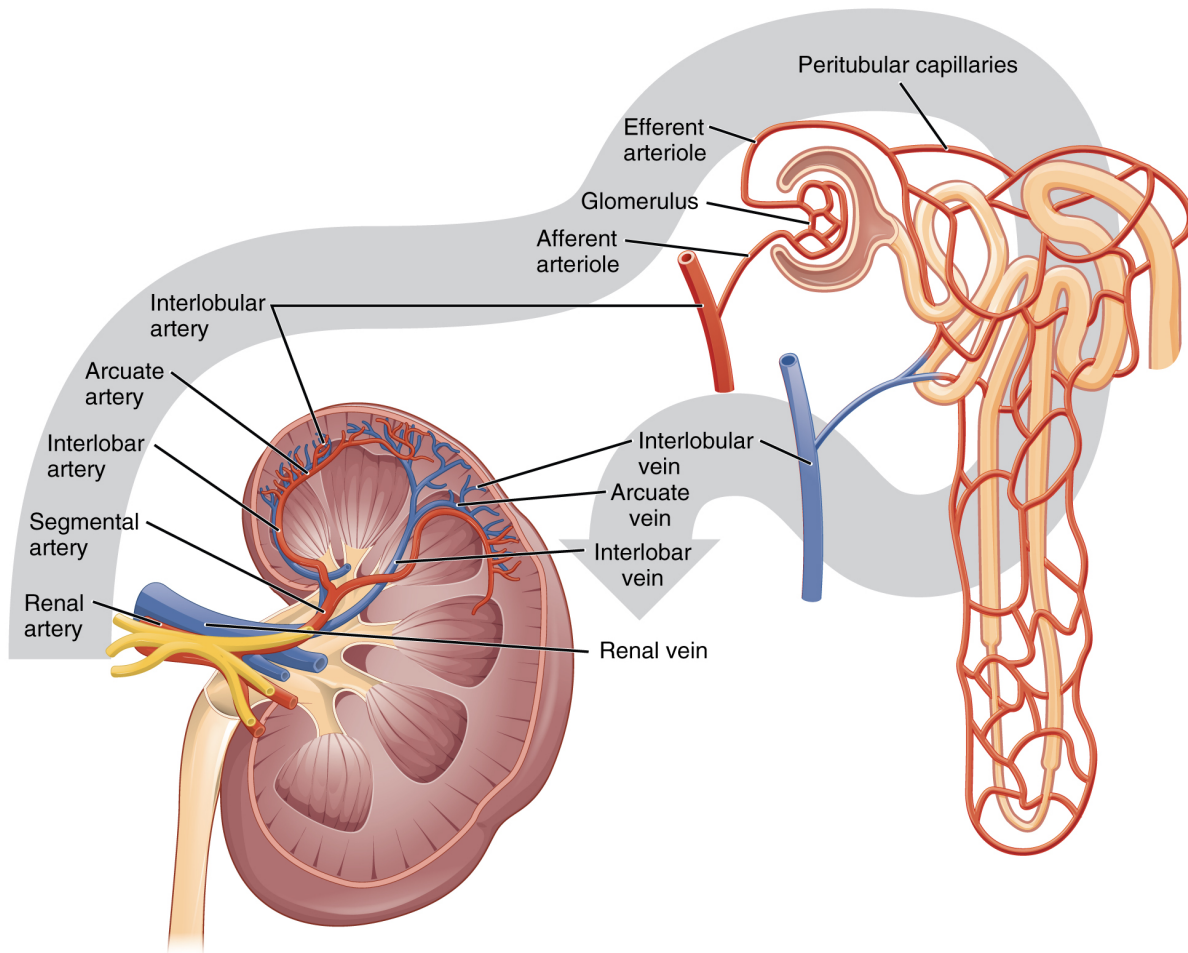
Figure 14.4 Blood Flow in the Kidney. Oxygenated blood enters the kidney via the Renal artery, travels through several branches, and reaches the nephron where it is filtered.

Nephrons are the "functional units" of the kidney; they cleanse the blood and balance the constituents of the circulation. The afferent arterioles form a tuft of high-pressure capillaries about 200 µm in diameter, the **glomerulus**. The rest of the nephron consists of a continuous tubule whose proximal end surrounds the glomerulus as a **glomerular capsule** (Bowman's capsule). The glomerulus and glomerular capsule together form the **renal corpuscle**. After passing through the renal corpuscle, the capillaries form a second arteriole, the **efferent arteriole** (**Figure 14.5**). These will next form a capillary network around the more distal portions of the nephron tubule, the **peritubular capillaries** and **vasa recta**, before returning to the venous system. As the glomerular filtrate progresses through the nephron, these capillary networks recover most of the solutes and water, and return them to the circulation. Since a capillary bed (the glomerulus) drains into a vessel that in turn forms a second capillary bed, the definition of a portal system is met. This is the only portal system in which an arteriole is found between the first and second capillary beds. (Portal systems also link the hypothalamus to the anterior pituitary, and the blood vessels of the digestive viscera to the liver).
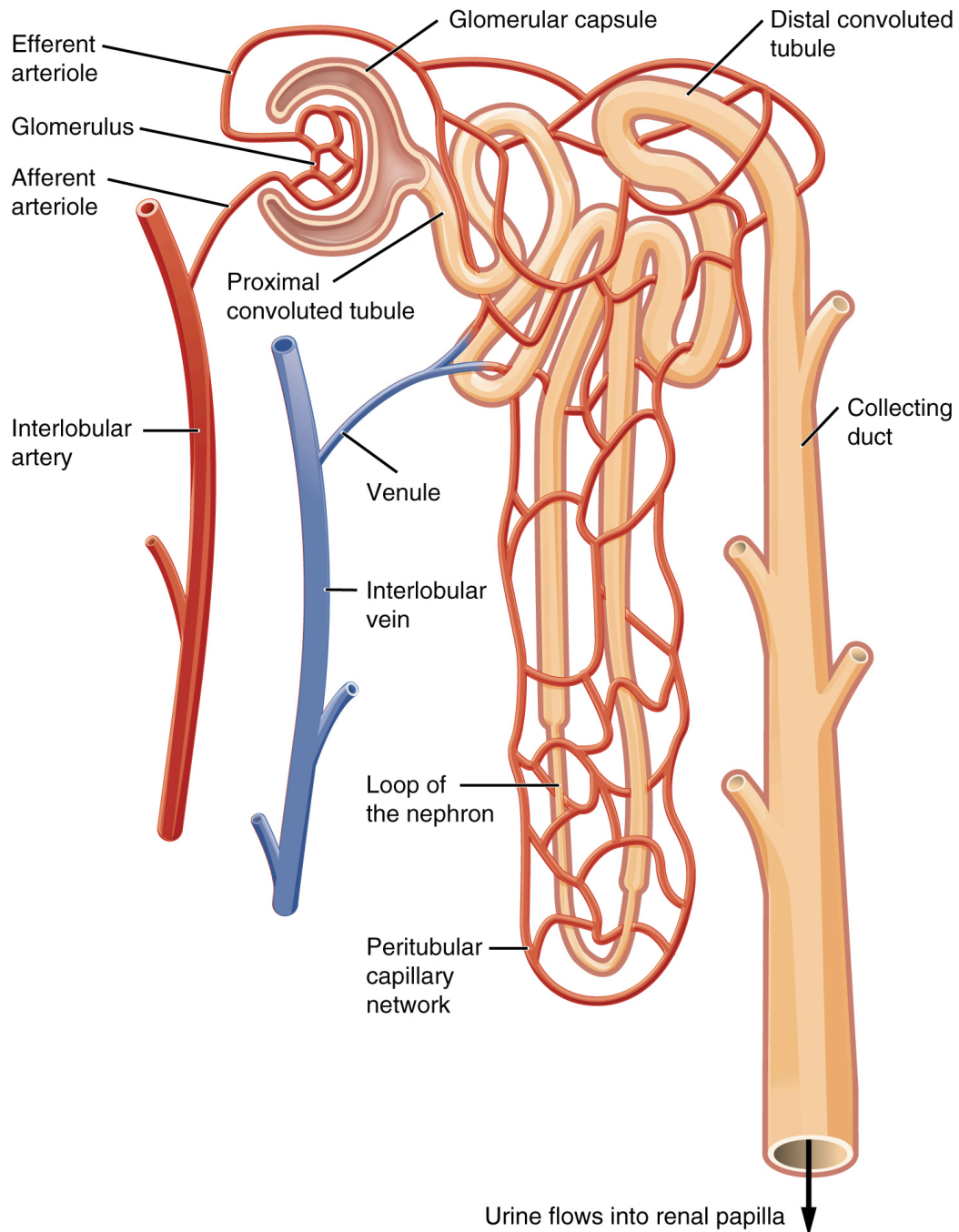
Figure 14.5 Blood Flow in the Nephron The two capillary beds are clearly shown in this figure. The efferent arteriole is the connecting vessel between the glomerulus and the peritubular capillaries and vasa recta.

Fluid that leaks out of the **glomerulus** and is captured by the **glomerular capsule** is called filtrate. As the filtrate passes through the nephron, it is modified into urine. Nephrons accomplish this with three principle functions—filtration, reabsorption, and secretion. Many changes take place in the different parts of the nephron

before urine is created for disposal. Filtered fluid collected by the glomerular capsule first travels to the **proximal convoluted tubule.** It is called convoluted due to its tortuous path. The fluid then goes to the descending and ascending portions of the **loop of Henle** (sometimes referred to as the **nephron loop**), which then leads to the final part of the nephron, the **distal convoluted tubule (Figure 14.5)**.

Much of the nephron structures are located in the cortex of the kidney. In a dissected kidney, it is easy to identify the cortex; it appears lighter in color compared to the rest of the kidney. All of the renal corpuscles as well as both the **proximal convoluted tubules (PCTs)** and **distal convoluted tubules** are found here. Some nephrons have a short **loop of Henle** that does not dip beyond the cortex. These nephrons are called **cortical nephrons**. About 15 percent of nephrons have long loops of Henle that extend deep into the medulla and are called **juxtamedullary nephrons**.

The **collecting ducts** are continuous with the nephron but not technically part of it. In fact, each duct collects filtrate from several nephrons for final modification. Collecting ducts merge as they descend deeper in the medulla to form about 30 terminal ducts, which empty at a papilla. Once the fluid passes through the **renal papilla**, it is no longer modified and it is classified as **urine**.

Ureters

As urine is formed, it drains into the calyces of the kidney, which merge to form the funnel-shaped renal pelvis in the hilum of each kidney. The hilum narrows to become the **ureter** of each kidney. As urine passes through the ureter, it does not passively drain into the bladder but rather is propelled by waves of peristalsis. The ureters are approximately 30 cm long. The inner mucosa is lined with transitional epithelium and scattered goblet cells that secrete protective mucus. The muscular layer of the ureter consists of longitudinal and circular smooth muscles that create the peristaltic contractions to move the urine into the bladder without the aid of gravity (**Figure 14.6**). Finally, a loose adventitial layer composed of collagen and fat anchors the ureters between the parietal peritoneum and the posterior abdominal wall. The kidneys and ureters are completely **retroperitoneal**, and the bladder has a **peritoneal** covering only over the dome.
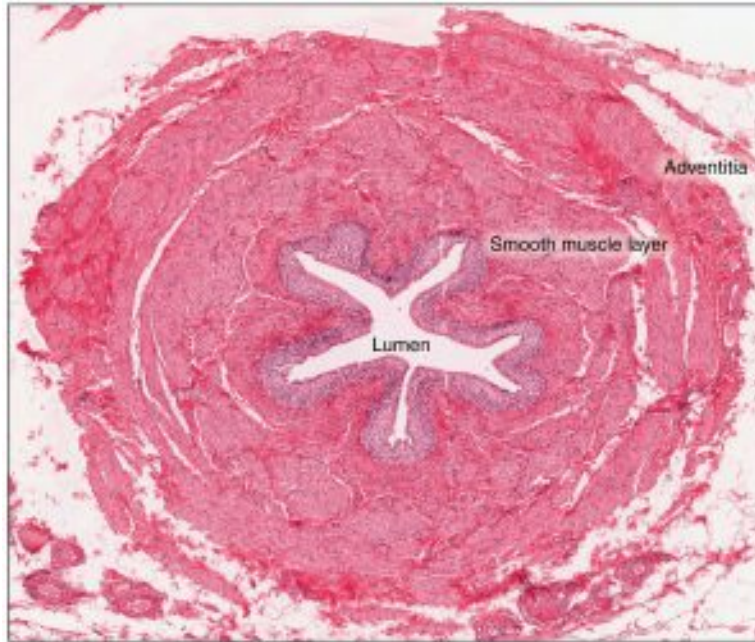
Figure 14.6 Ureter Peristaltic contractions help to move urine through the lumen with contributions from fluid pressure and gravity. LM × 128. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

Urinary Bladder

The **urinary bladder** collects urine from both ureters (**Figure 14.7**). The bladder lies anterior to the uterus in females, posterior to the pubic bone and anterior to the rectum. During late pregnancy, its capacity is reduced due to compression by the enlarging uterus, resulting in increased frequency of urination. In males, the anatomy is similar, minus the uterus, and with the addition of the prostate inferior to the bladder. The bladder is partially retroperitoneal (outside the peritoneal cavity) with its peritoneal-covered "dome" projecting into the abdomen when the bladder is distended with urine.
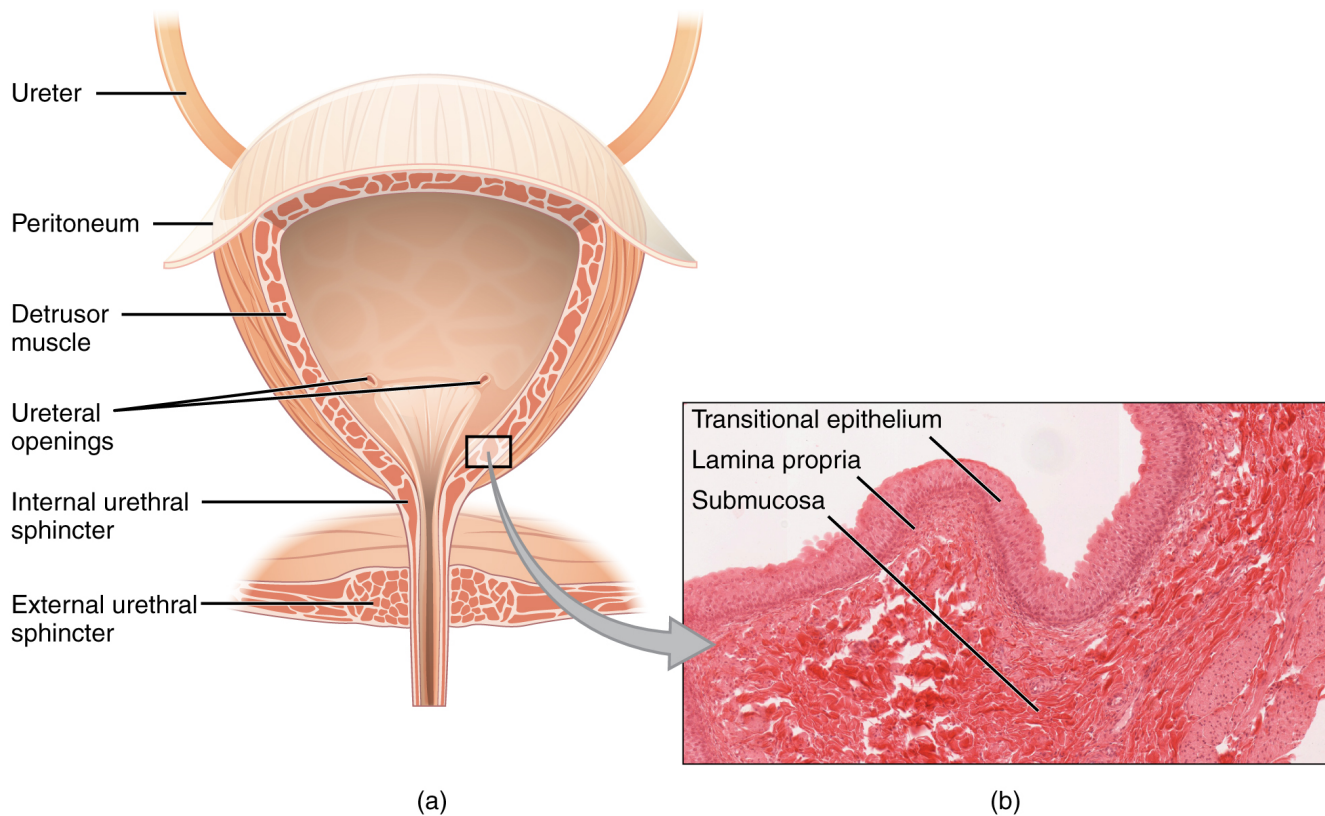
Figure 14.7 Bladder (a) Anterior cross section of the bladder. (b) The detrusor muscle of the bladder (source: monkey tissue) LM × 448. (Micrograph provided by the Regents of the University of Michigan Medical School © 2012)

The bladder is a highly distensible organ comprised of irregular crisscrossing bands of smooth muscle collectively called the detrusor muscle. The interior surface is made of transitional cellular epithelium that is structurally suited for the large volume fluctuations of the bladder. When empty, it resembles columnar epithelia, but when stretched, it "transitions" (hence the name) to a squamous appearance. Volumes in adults can range from nearly zero to 500−600 mL.

Urethra

The urethra transports urine from the bladder to the outside of the body for disposal. The urethra is the only urologic organ that shows any significant anatomic difference between males and females; all other urine transport structures are identical (**Figure 14.8**).

Figure 14.8 Female and Male Urethras The urethra transports urine from the bladder to the outside of the body. This image shows (a) a female urethra and (b) a male urethra.
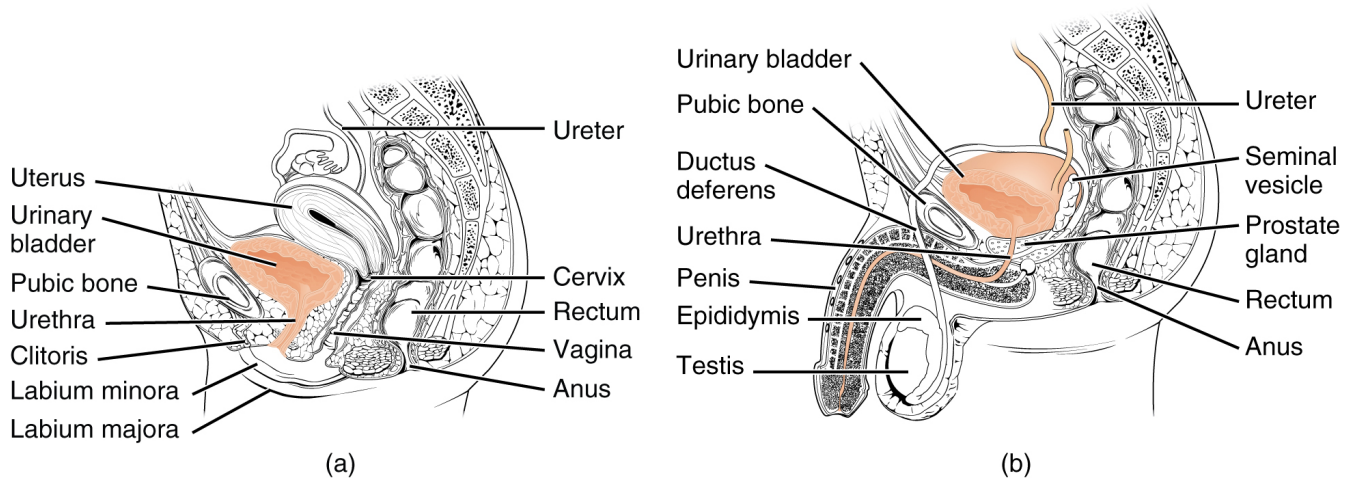
The urethra in both males and females begins inferior and central to the two ureteral openings forming the three points of a triangular-shaped area at the base of the bladder called the **trigone** (Greek tri- = "triangle"). The urethra tracks posterior and inferior to the pubic symphysis. In both males and females, the proximal urethra is lined by transitional epithelium, whereas the terminal portion is a nonkeratinized, stratified squamous epithelium. In the male, pseudostratified columnar epithelium lines the urethra between these two cell types. Voiding is regulated by an involuntary autonomic] nervous system-controlled **internal urinary sphincter**, consisting of smooth muscle and voluntary skeletal muscle that forms the **external urinary sphincter** below it.

Female Urethra

The female external urethral orifice is embedded in the anterior vaginal wall inferior to the clitoris, superior to the vaginal opening (introitus), and medial to the labia minora. The short length of the female urethra, about 4 cm, is less of a barrier to fecal bacteria than the longer male urethra and the best explanation for the greater incidence of UTI in women.

Male Urethra

The male urethra passes through the prostate gland immediately inferior to the bladder before passing below the pubic symphysis. The length of the male urethra varies between men but averages 20 cm in length. It is divided into three regions: the **prostatic urethra**, the **membranous urethra**, and the **spongy (penile) urethra**. The prostatic urethra passes through the prostate gland. During sexual intercourse, it receives sperm via the ejaculatory ducts and secretions from the seminal vesicles. The membranous urethra passes through the deep muscles of the perineum, where it is invested by the overlying urethral sphincters. The spongy urethra exits at the tip (external urethral orifice) of the penis after passing through the corpus spongiosum.

The Reproductive System

Small, uncoordinated, and slick with amniotic fluid, a newborn encounters the world outside of her mother's womb. We do not often consider that a child's birth is proof of the healthy functioning of both her mother's and father's reproductive systems. Moreover, her parents' endocrine systems had to secrete the appropriate regulating hormones to induce the production and release of unique male and female gametes, reproductive cells containing the parents' genetic material (one set of 23 chromosomes). Her parent's reproductive behavior had to facilitate the transfer of male gametes—the sperm—to the female reproductive tract at just the right time to encounter the female gamete, an oocyte (egg). Finally, combination of the gametes (fertilization) had to occur, followed by implantation and development.

The Male Reproductive System

Unique for its role in human reproduction, a **gamete** is a specialized sex cell carrying 23 chromosomes—one half the number in body cells. At fertilization, the chromosomes in one male gamete, called a **sperm** (or spermatozoon), combine with the chromosomes in one female gamete, called an oocyte. The function of the male reproductive system is to produce sperm and transfer them to the female reproductive tract. The paired testes are a crucial component in this process, as they produce both sperm and androgens, the hormones that support male reproductive physiology. In humans, the most important male androgen is testosterone. Several accessory organs and ducts aid the process of sperm maturation and transport the sperm and other seminal components to the penis, which delivers sperm to the female reproductive tract.
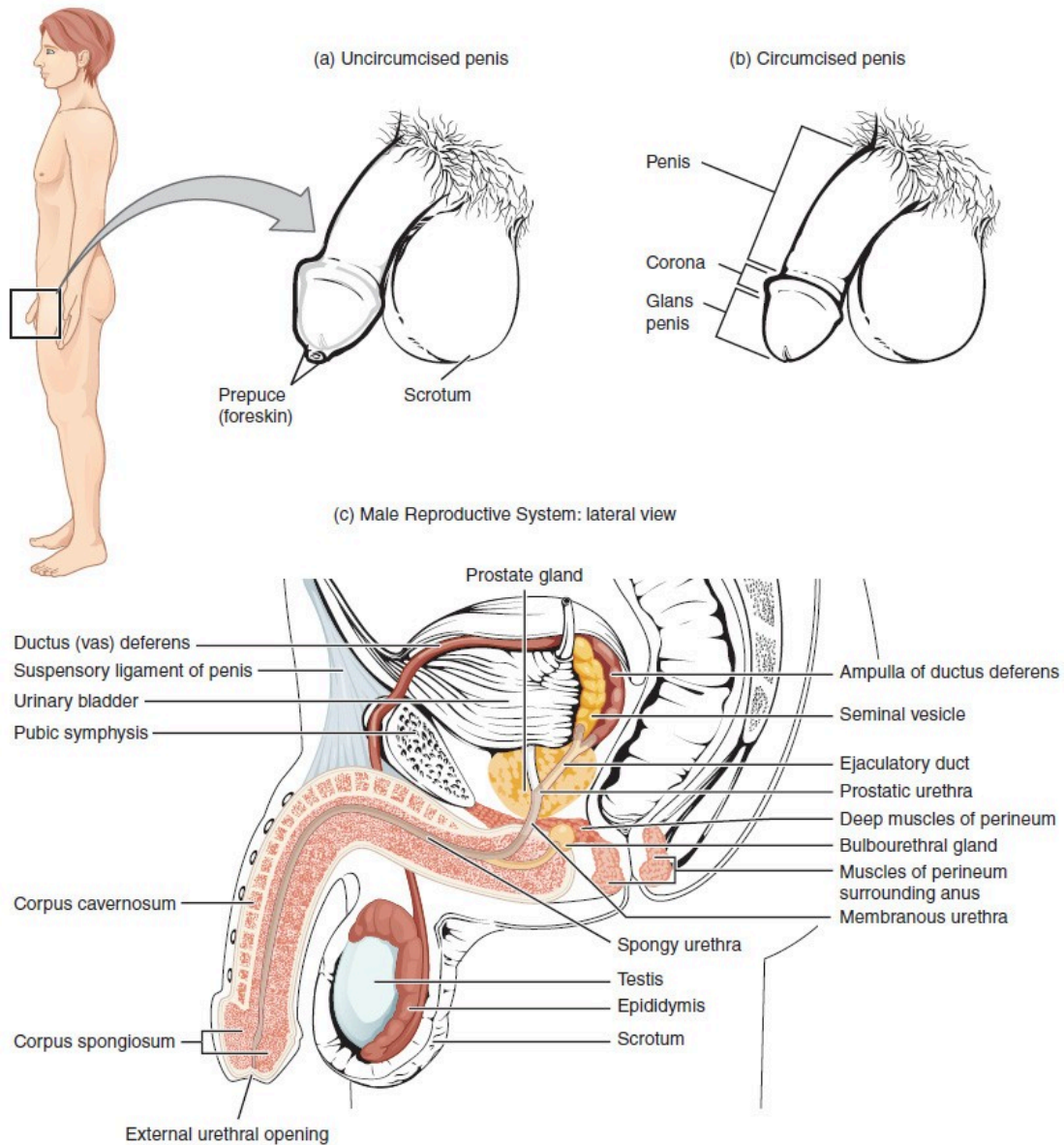
(a) Uncircumcised penis
(b) Circumcised penis

Penis
Corona
Glans penis

Prepuce (foreskin)
Scrotum

(c) Male Reproductive System: lateral view

Prostate gland

Ductus (vas) deferens
Suspensory ligament of penis
Urinary bladder
Pubic symphysis

Ampulla of ductus deferens
Seminal vesicle
Ejaculatory duct
Prostatic urethra
Deep muscles of perineum
Bulbourethral gland
Muscles of perineum surrounding anus
Membranous urethra

Corpus cavernosum

Spongy urethra
Testis
Epididymis
Scrotum

Corpus spongiosum

External urethral opening

Figure 14.9. The structures of the male reproductive system include the testes, the epididymides, the penis, and the ducts and glands that produce and carry semen. Sperm exit the scrotum through the ductus deferens, which is bundled in the spermatic cord. The seminal vesicles and prostate gland add fluids to the sperm to create semen.

Scrotum

The testes are located in a skin-covered, highly pigmented, muscular sack called the **scrotum** that extends from the body behind the penis. This location is important in sperm production, which occurs within the testes, and proceeds more efficiently when the testes are kept 2 to 4°C below core body temperature.

The dartos muscle and cremaster muscles, part of the walls of the scrotum, can contract to elevate the testes in cold weather (or water), moving the testes closer to the body and decreasing the surface area of the scrotum to retain heat. Alternatively, as the environmental temperature increases, the scrotum relaxes, moving the testes

farther from the body core and increasing scrotal surface area, which promotes heat loss. Externally, the scrotum has a raised medial thickening on the surface called the raphae.
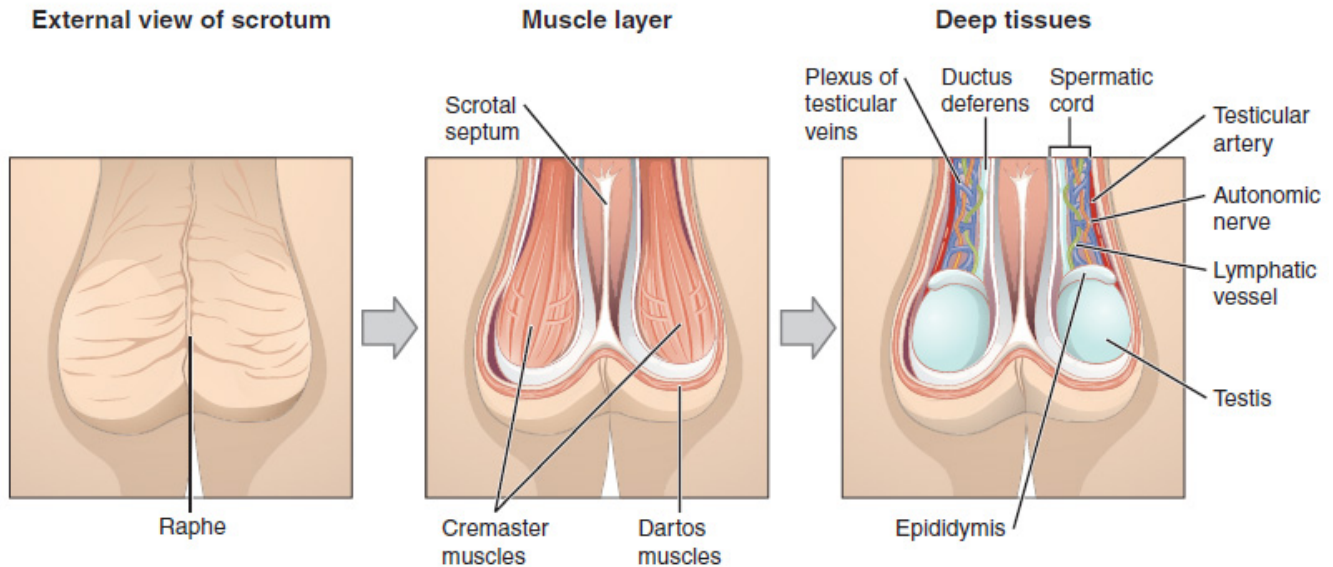

Figure 14.10 The Scrotum and Testes. This anterior view shows the structures of the scrotum and testes.

Testes

The **testes** (singular = testis) are the male **gonads**—that is, the male reproductive organs. They produce both sperm and androgens, such as testosterone, and are active throughout the reproductive lifespan of the male.

Paired ovals, the testes are each approximately 4 to 5 cm in length and are housed within the scrotum (**Figure 14.10**). They are surrounded by two distinct layers of protective connective tissue, the tunica vaginalis and the tunica albuginea. The tunica albuginea is a tough, white, dense connective tissue layer that covers the the outside of the testis, as well as invaginating to form septa that divide the testis into 300 to 400 structures called lobules. Within the lobules, sperm develop in structures called **seminiferous tubules (Flgure 14.11).**
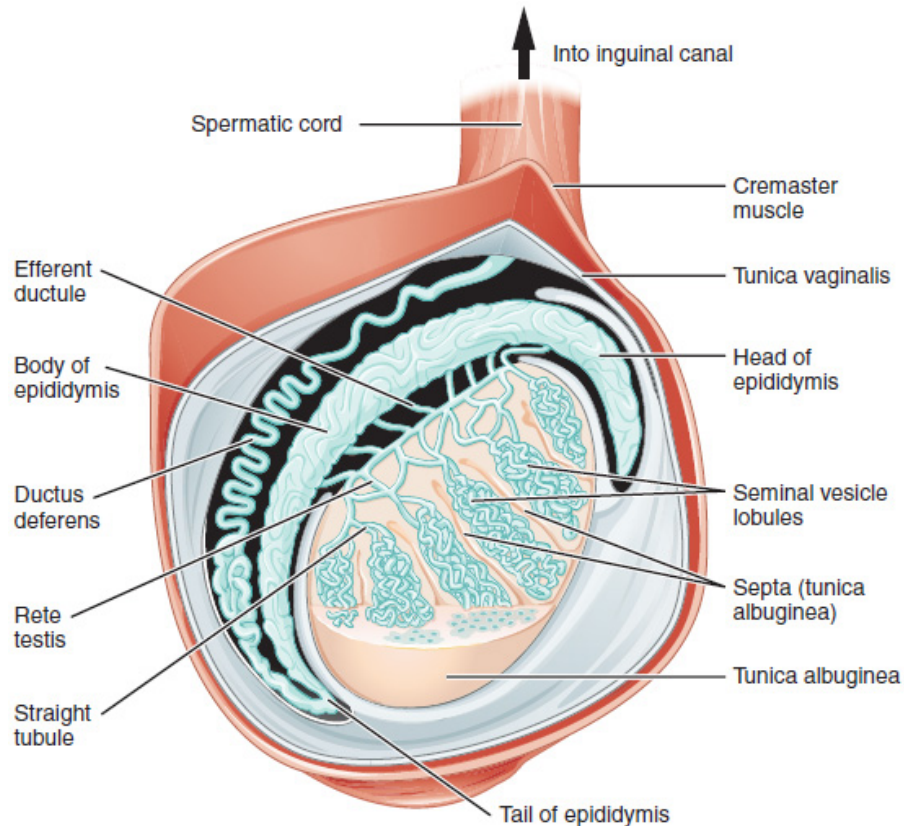
Figure 14.11. Anatomy of the Testis This sagittal view shows the seminiferous tubules, the site of sperm production. Formed sperm are transferred to the epididymis, where they mature. They leave the epididymis during an ejaculation via the ductus deferens.

The tightly coiled **seminiferous tubules** form the bulk of each testis. They are composed of developing sperm cells surrounding a lumen, the hollow center of the tubule, where formed sperm are released into the duct system of the testis. Specifically, from the lumens of the seminiferous tubules, sperm move into the straight tubules (or tubuli recti), and from there into a fine meshwork of tubules called the rete testes. Sperm leave the rete testes, and the testis itself, through the 15 to 20 efferent ductules that cross the tunica albuginea.

Structure of Formed Sperm

Sperm are smaller than most cells in the body; in fact, the volume of a sperm cell is 85,000 times less than that of the female gamete. Approximately 100 to 300 million sperm are produced each day, whereas women typically ovulate only one oocyte per month as is true for most cells in the body, the structure of sperm cells speaks to their function. Sperm have a distinctive head, mid-piece, and tail region (**Figure 14.12**). A structure called the acrosome covers most of the head of the sperm cell as a "cap" that is filled with lysosomal enzymes important for preparing sperm to participate in fertilization. Tightly packed mitochondria fill the mid-piece of the sperm. ATP produced by these mitochondria will power the flagellum, which extends from the neck and the mid-piece through the tail of the sperm, enabling it to move the entire sperm cell.
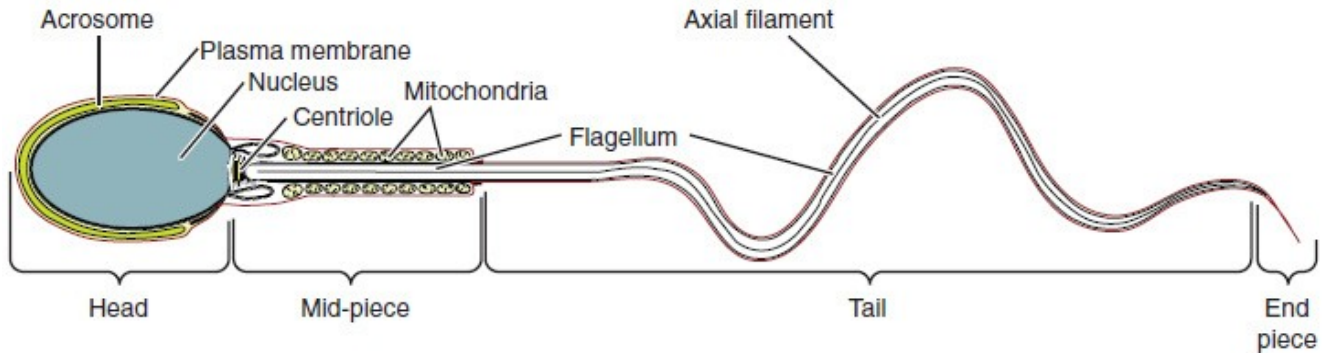
Figure 14.12 Structure of Sperm. Sperm cells are divided into a head, containing DNA; a mid-piece, containing mitochondria; and a tail, providing motility. The acrosome is oval and somewhat flattened.

To fertilize an egg, sperm must be moved from the seminiferous tubules in the testes, through the epididymis, and—later during ejaculation—along the length of the penis and out into the female reproductive tract.

Epididymis

From the lumen of the seminiferous tubules, the immotile sperm are surrounded by testicular fluid and moved to the **epididymis** (plural = epididymides), a coiled tube attached to the testis where newly formed sperm continue to mature. Though the epididymis does not take up much room in its tightly coiled state, it would be approximately 6 m (20 feet) long if straightened. Sperm enter the head of the epididymis and are moved along predominantly by the contraction of smooth muscles lining the epididymal tubes. As they are moved along the length of the epididymis, the sperm further mature and acquire the ability to move under their own power. The more mature sperm are then stored in the tail of the epididymis (the final section) until ejaculation occurs.

Duct System and Accessory Glands

During ejaculation, sperm exit the tail of the epididymis and are pushed by smooth muscle contraction to the **ductus deferens** (also called the vas deferens). The ductus deferens is a thick, muscular tube that is bundled together inside the scrotum with connective tissue, blood vessels, and nerves into a structure called the **spermatic cord** (**Figure 14.10**). Because the ductus deferens is physically accessible within the scrotum, surgical sterilization to interrupt sperm delivery can be performed by cutting and sealing a small section of the ductus (vas) deferens. This procedure is called a vasectomy, and it is an effective form of male birth control.

Each ductus deferens extends superiorly into the abdominal cavity through the **inguinal canal** in the abdominal wall. From here, the ductus deferens continues posteriorly to the pelvic cavity, ending posterior to the bladder where it dilates in a region called the ampulla (meaning "flask").

Sperm make up only 5 percent of the final volume of **semen**, the thick, milky fluid that the male ejaculates. The bulk of semen is produced by three critical accessory glands of the male reproductive system: the seminal vesicles, the prostate, and the bulbourethral glands.

As sperm pass through the ampulla of the ductus deferens at ejaculation, they mix with fluid from the associated **seminal vesicle** (**Figure 14.9**). The paired seminal vesicles are glands that contribute approximately 60 percent

of the semen volume. Seminal vesicle fluid contains large amounts of fructose, which is used by the sperm mitochondria to generate ATP to allow movement through the female reproductive tract.

The fluid, now containing both sperm and seminal vesicle secretions, next moves into the associated **ejaculatory duct**, a short structure formed from the ampulla of the ductus deferens and the duct of the seminal vesicle. The paired ejaculatory ducts transport the seminal fluid into the next structure, the prostate gland.

The centrally located **prostate gland** sits anterior to the rectum at the base of the bladder surrounding the prostatic urethra (the portion of the urethra that runs within the prostate). About the size of a walnut, the prostate is formed of both muscular and glandular tissues. It excretes an alkaline, milky fluid to the passing seminal fluid—now called semen—that is critical to first coagulate and then decoagulate the semen following ejaculation. The temporary thickening of semen helps retain it within the female reproductive tract, providing time for sperm to utilize the fructose provided by seminal vesicle secretions. When the semen regains its fluid state, sperm can then pass farther into the female reproductive tract.

The final addition to semen is made by two **bulbourethral glands** (or Cowper's glands) that release a thick, salty fluid that lubricates the end of the urethra and the vagina, and helps to clean urine residues from the penile urethra. The fluid from these accessory glands is released after the male becomes sexually aroused, and shortly before the release of the semen. It is therefore sometimes called pre-ejaculate.

The Penis

The **penis** is the male organ of copulation (sexual intercourse). It is flaccid for non-sexual actions, such as urination, and turgid and rod-like with sexual arousal. When erect, the stiffness of the organ allows it to penetrate into the vagina and deposit semen into the female reproductive tract.

The shaft of the penis surrounds the urethra (**Figure 14.13**). The shaft is composed of three column-like chambers of erectile tissue that span the length of the shaft. Each of the two larger lateral chambers is called a **corpus cavernosum** (plural = corpora cavernosa). Together, these make up the bulk of the penis. The **corpus spongiosum**, which can be felt as a raised ridge on the erect penis, is a smaller chamber that surrounds the spongy, or penile, urethra. The end of the penis, called the **glans penis**, has a high concentration of nerve endings, resulting in very sensitive skin that influences the likelihood of ejaculation. The skin from the shaft extends down over the glans and forms a collar called the **prepuce** (or foreskin).
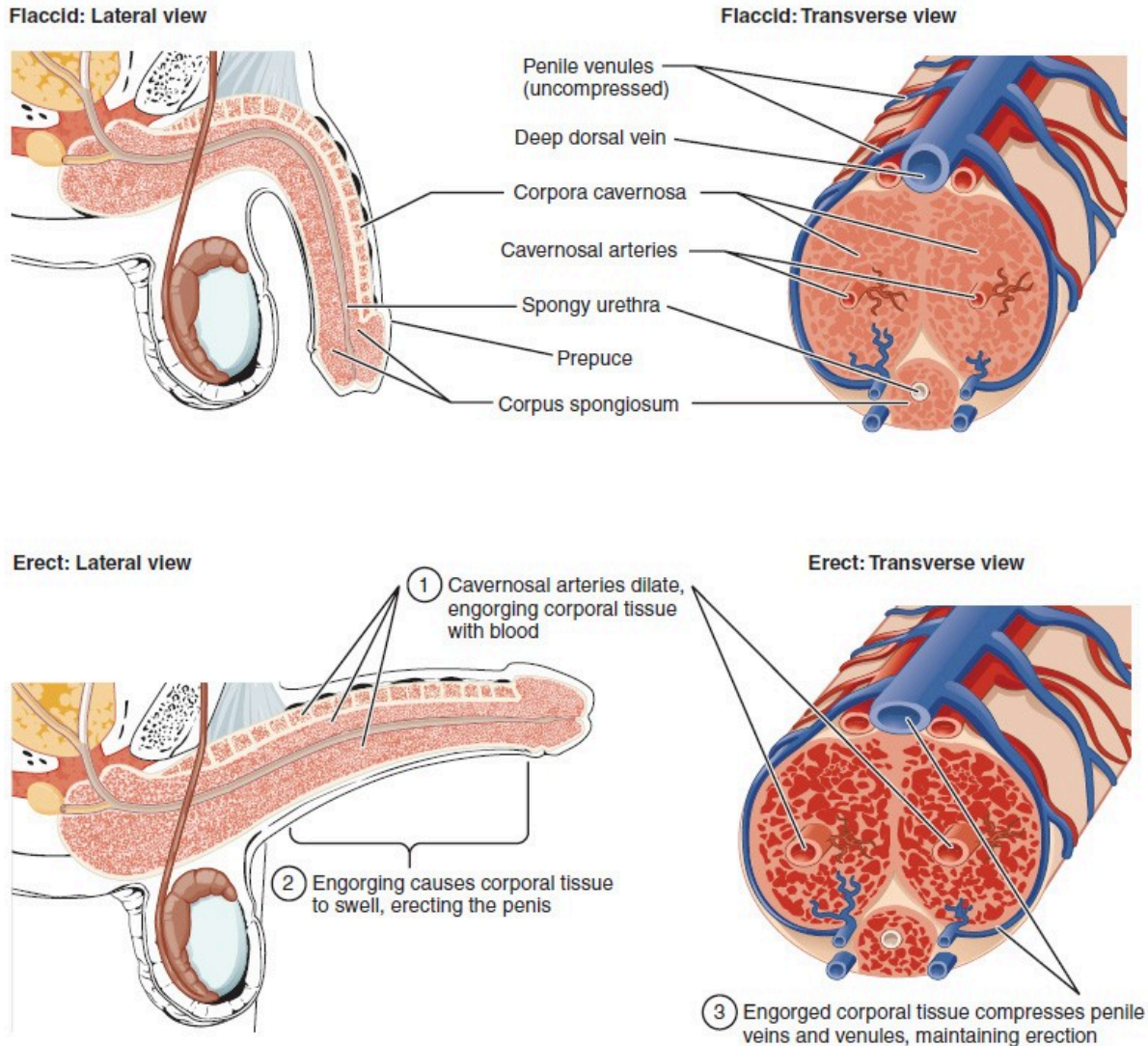
Flaccid: Lateral view

Flaccid: Transverse view

Penile venules (uncompressed)

Deep dorsal vein

Corpora cavernosa

Cavernosal arteries

Spongy urethra

Prepuce

Corpus spongiosum

Erect: Lateral view

Erect: Transverse view

① Cavernosal arteries dilate, engorging corporal tissue with blood

② Engorging causes corporal tissue to swell, erecting the penis

③ Engorged corporal tissue compresses penile veins and venules, maintaining erection

Figure 14.13. Cross-Sectional Anatomy of the Penis Three columns of erectile tissue make up most of the volume of the penis.

The Female Reproductive System

The female reproductive system produces **gametes** and reproductive hormones. In addition, the female reproductive system supports the developing fetus and delivers it to the outside world. The female reproductive system is located primarily inside the pelvic cavity. The female gonads are called **ovaries** and the gamete they produce is called an **oocyte**.

External Female Genitals

The external female reproductive structures are referred to collectively as the **vulva** and they include:

- The **mons pubis** is a pad of fat that is located at the anterior, over the pubic bone. After puberty, it becomes covered in pubic hair.
- The **labia majora** (labia = "lips"; majora = "larger") are folds of hair-covered skin that begin just posterior to the mons pubis.
- The **labia minora** (labia = "lips"; minora = "smaller") is thinner and more pigmented and extends medially to the labia majora.
  - Although they naturally vary in shape and size from woman to woman, the labia minora serve to protect the female urethra and the entrance to the female reproductive tract.
  - The superior, anterior portions of the labia minora come together to encircle the **clitoris** (or glans clitoris), an organ that originates from the same cells as the glans penis and has abundant nerves that make it important in sexual sensation and orgasm. The **hymen** is a thin membrane that sometimes partially covers the entrance to the **vagina**.
- The vaginal opening is located between the opening of the urethra and the anus (**Figure 14.14**).
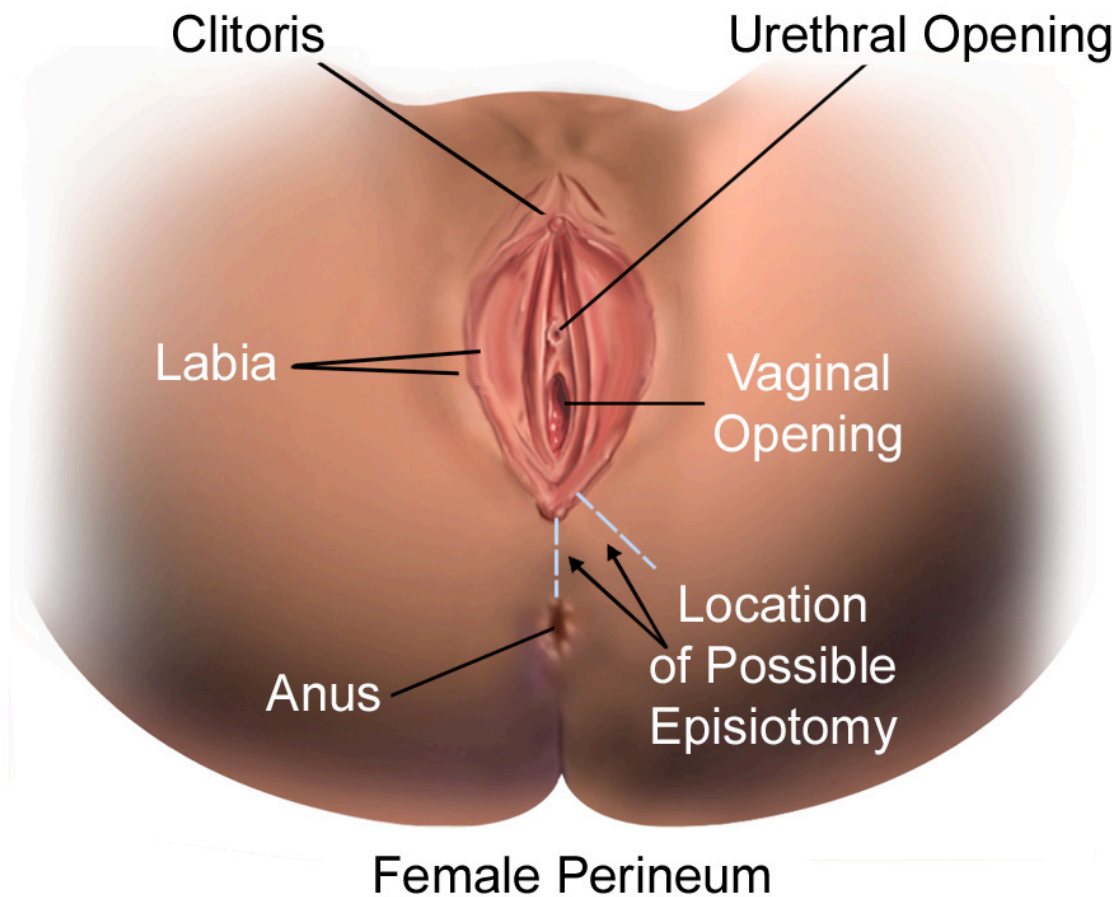

Figure 14.14 The external female genitalia are referred to collectively as the vulva. The perineum is the space between the reproductive organs and the anus. This image shows the vulva, perineum, and potential locations for an episiotomy, a medical procedure sometimes performed during childbirth to expand the birth passage. Image source: Blausen medical via Wikimedia, CC BY 3.0.

Internal Female Reproductive Organs

Ovaries

The **ovaries** are the female gonads. There are two, one at each entrance to the uterine (fallopian) tube (**Figure 14.15**). They are each about 2 to 3 cm in length, about the size of an almond. The ovaries are located within the pelvic cavity. The ovary itself is attached to the uterus via the ovarian ligament. Oocytes, surrounded by supporting cells, develop within each ovary. This grouping of an oocyte and its supporting cells is called a **follicle.**
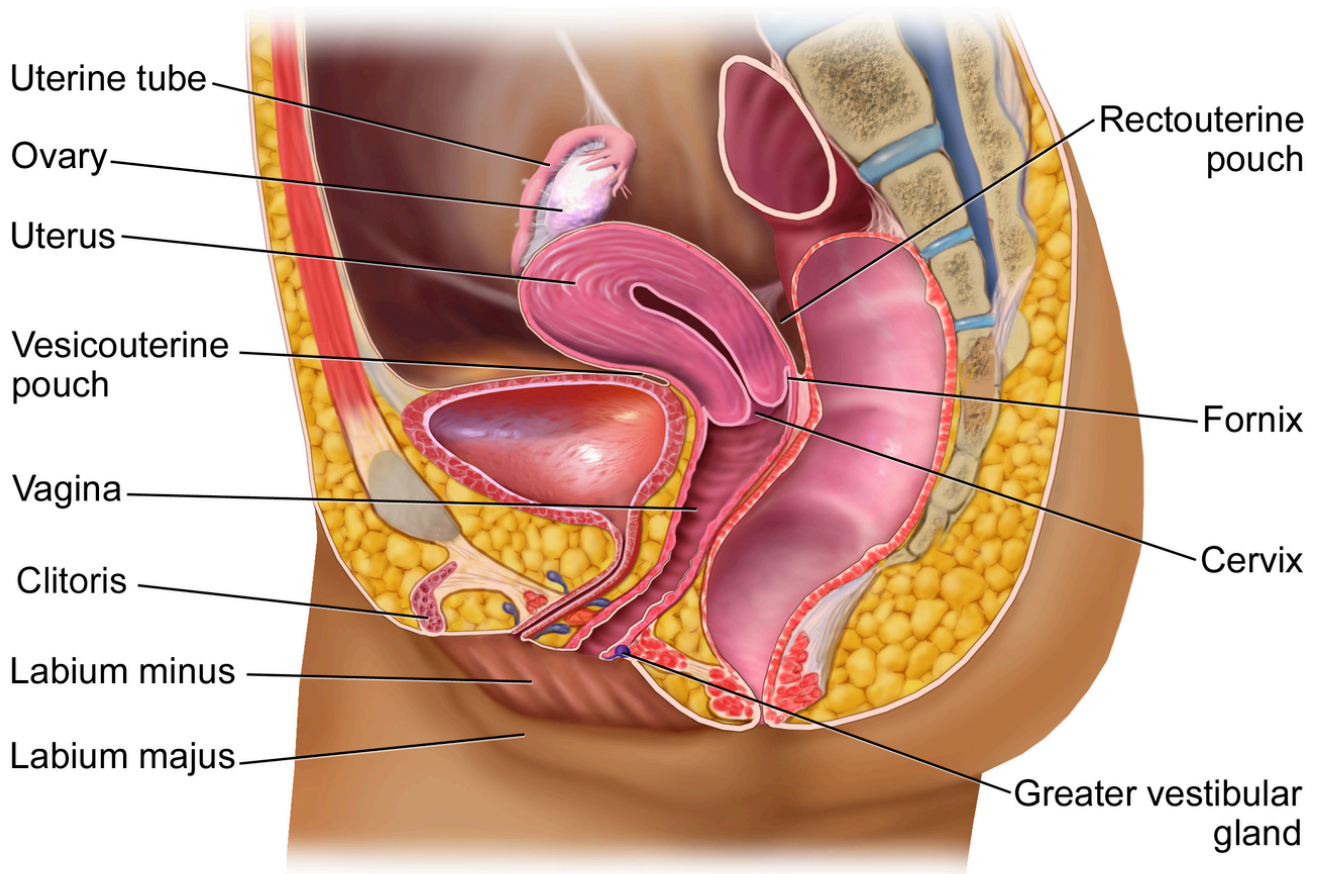

Figure 14.15 Mid-sagittal view of the the major organs of the female reproductive system inside the pelvic cavity. Image source: Blausen medical via Wikimedia, CC BY 3.0.

The Uterine Tubes

The **uterine (fallopian) tubes** are the conduit of the oocyte from the ovary to the uterus. Each of the two fallopian tubes is close to, but not directly connected to, the ovary. The uterine tubes are lined with ciliated cells that beat in the direction of the uterus, producing a current that will be critical to moving the oocyte towards the uterus. The wide distal **infundibulum** of the tube flares out with slender, finger-like projections called **fimbriae,** which envelop

the ovary. The middle region of the tube, called the **ampulla**, is where fertilization often occurs. The **isthmus** is the narrow medial end of each uterine tube that is connected to the uterus.

The Uterus and Cervix

The **uterus** is the muscular organ that nourishes and supports the growing embryo. Its average size is approximately 5 cm wide by 7 cm long and it has three sections (**Figure 14.16**). The portion of the uterus superior to the opening of the uterine tubes is called the **fundus**. The middle section of the uterus is called the **body of uterus** (or corpus). The **cervix** is the narrow inferior portion of the uterus that projects into the vagina. The cervix produces mucus secretions that become thin and stringy under the influence of high systemic plasma estrogen concentrations, and these secretions can facilitate sperm movement through the reproductive tract.

The wall of the uterus is made up of three layers:

- **Perimetrium:** the most superficial layer and serous membrane.
- **Myometrium:** a thick layer of smooth muscle responsible for uterine contractions.
- **Endometrium:** the innermost layer containing a connective tissue lining covered by epithelial tissue that lines the lumen. It provides the site of implantation for a fertilized egg, and sheds during menstruation if no egg is fertilized.
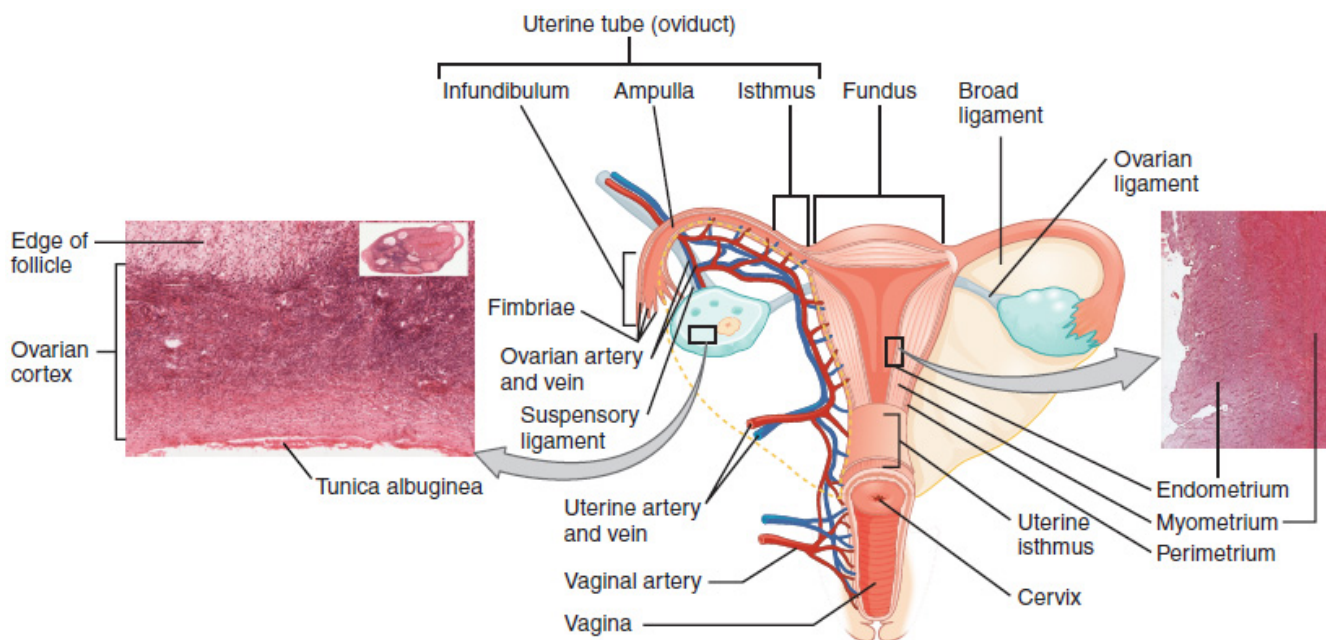

Figure 14.16 Ovaries, Uterine Tubes, and Uterus This anterior view shows the relationship of the ovaries, uterine tubes (oviducts), and uterus. Sperm enter through the vagina, and fertilization of an ovulated oocyte usually occurs in the distal uterine tube. From left to right, LM × 400, LM × 20. (Micrographs provided by the Regents of University of Michigan Medical School © 2012)

Vagina

The **vagina** is a muscular canal (approximately 10 cm long) that is the entrance to the reproductive tract. It also

serves as the exit from the uterus during menses and childbirth. The outer walls of the anterior and posterior vagina are columns with ridges. The superior fornix meets the uterine cervix.

The walls of the vagina are lined with:

- An outer, fibrous adventitia
- A middle layer of smooth muscle
- An inner mucous membrane with transverse folds called **rugae**.

Together, the middle and inner layers allow the expansion of the vagina to accommodate intercourse and childbirth. The thin, perforated hymen can partially surround the opening to the vaginal orifice. The lesser and greater vestibular glands (located near the clitoris and external opening of the vagina, respectively) secrete mucus, which keeps the vestibular area moist.

Development of Oocytes

Gametogenesis in females is called **oogenesis**. The process begins with the ovarian stem cells, or oogonia. Oogonia are formed during fetal development, and divide via mitosis, much like spermatogonia in the testis. Unlike spermatogonia, however, oogonia form **primary oocytes** in the fetal ovary prior to birth. These primary oocytes are then arrested in this stage of meiosis I, only to resume it years later, beginning at puberty and continuing until the woman is near menopause (the cessation of a woman's reproductive functions). The number of primary oocytes present in the ovaries declines from one to two million in an infant, to approximately 400,000 at puberty, to zero by the end of menopause.

The initiation of ovulation—the release of an oocyte from the ovary—marks the transition from puberty into reproductive maturity for women. From then on, throughout a woman's reproductive years, ovulation occurs approximately once every 28 days. Just prior to ovulation, a surge of luteinizing hormone triggers the resumption of meiosis in a primary oocyte. This initiates the transition from primary to **secondary oocyte**. However, this cell division does not result in two identical cells. Instead, the cytoplasm is divided unequally, and one daughter cell is much larger than the other. This larger cell, the secondary oocyte, eventually leaves the ovary during ovulation. The smaller cell, called the first polar body, may or may not complete meiosis and produce second polar bodies; in either case, it eventually disintegrates. Therefore, even though oogenesis produces up to four cells, only one survives.

Ovarian **follicles** are oocytes and their supporting cells. They grow and develop in a process called folliculogenesis, which typically leads to ovulation of one follicle approximately every 28 days, along with death to multiple other follicles. Follicles progress from primordial, to primary, to secondary and tertiary (antral, or mature) stages prior to ovulation—with the oocyte inside the follicle remaining as a primary oocyte until right before ovulation.

Folliculogenesis begins with follicles in a resting state. These small **primordial follicles** are present in newborn females and are the prevailing follicle type in the adult ovary (**Figure 14.17**). Primordial follicles have only a single flat layer of support cells, called granulosa cells, that surround the oocyte, and they can stay in this resting state for years—some until right before menopause. After puberty, a few primordial follicles will respond to a recruitment signal each day, and will join a pool of immature growing follicles called primary follicles. **Primary follicles** start with a single layer of granulosa cells, but the granulosa cells then become active and transition from a flat or squamous shape to a rounded, cuboidal shape as they increase in size and proliferate. As the

granulosa cells divide, the follicles—now called **secondary follicles** – increase in diameter, adding a new outer layer of connective tissue, blood vessels, and theca cells—cells that work with the granulosa cells to produce estrogens.

Within the growing secondary follicle, the primary oocyte now secretes a thin acellular membrane called the zona pellucida that will play a critical role in fertilization. A thick fluid, called follicular fluid, that has formed between the granulosa cells also begins to collect into one large pool, or antrum. Follicles in which the antrum has become large and fully formed are considered **tertiary follicles** (or **antral follicles**). Several follicles reach the tertiary stage at the same time, and most of these will undergo atresia (death). The one that does not die will continue to grow and develop until ovulation, when it will expel its **secondary oocyte** surrounded by several layers of granulosa cells from the ovary. Keep in mind that most follicles don't make it to this point. In fact, roughly 99 percent of the follicles in the ovary will undergo atresia, which can occur at any stage of folliculogenesis.

Once the secondary oocyte has been ovulated, there is a change in the follicular support cells the formed the tertiary follicle. The collapsed follicle is transformed into a new endocrine structure called the **corpus luteum**, a term meaning "yellowish body". The corpus luteum produces a hormone (progesterone) that is critical for the establishment and maintenance of pregnancy. If pregnancy does not occur within 10 to 12 days, the corpus luteum will stop secreting progesterone and degrade into the **corpus albicans**, a nonfunctional "whitish body" that will disintegrate in the ovary over a period of several months (**Figure 14.17**).
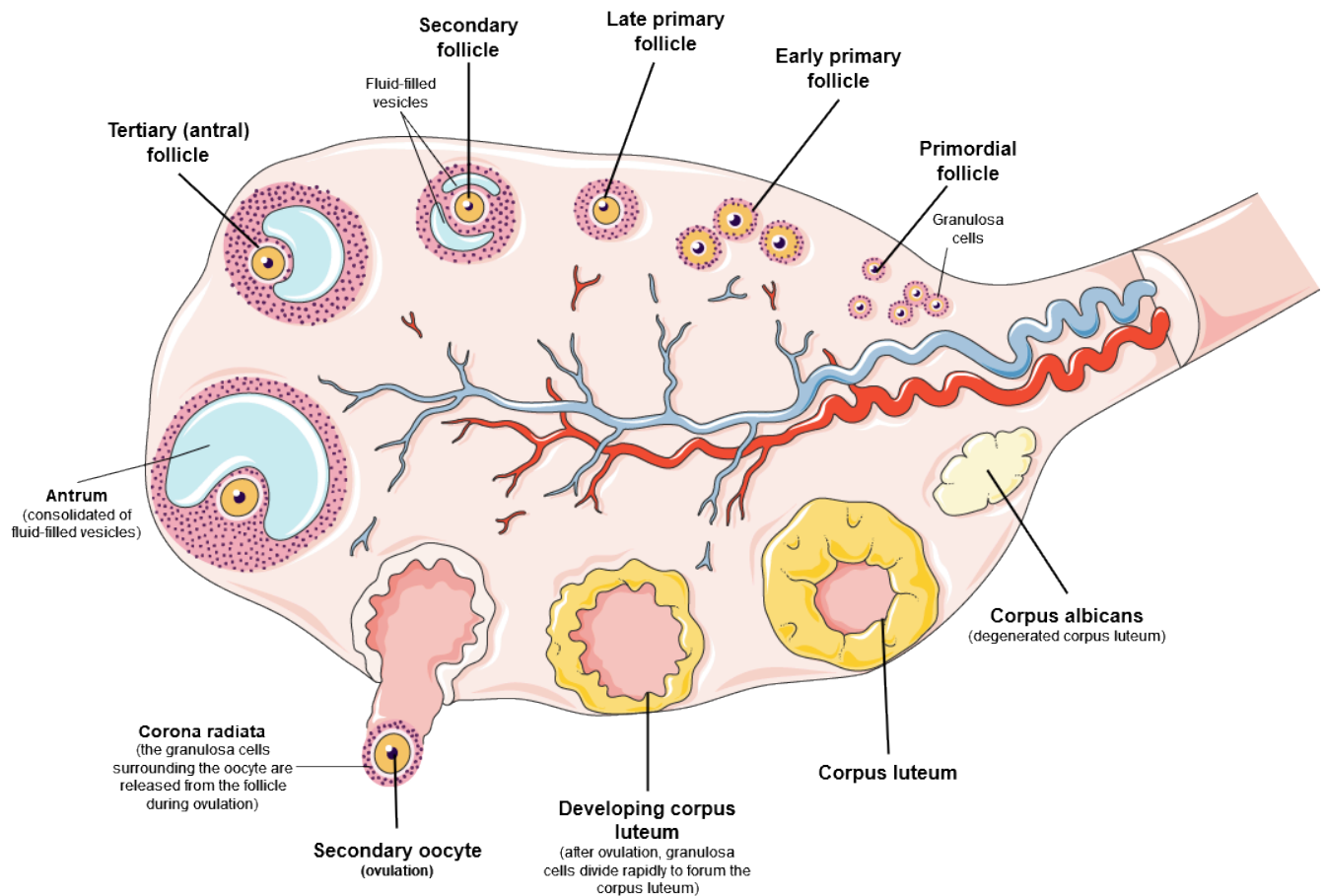

Figure 14.17 The process of ovulation and gamete production. Image source: Smart Sevier via Wikimedia Commons, CC BY SA 3.0. Labels added by Abbey Elder.

Ovulation

Following ovulation, the uterine tube receives the oocyte. Oocytes lack flagella, and therefore cannot move on their own. High concentrations of estrogen that occur around the time of ovulation induce contractions of the smooth muscle along the length of the uterine tube. These contractions occur every 4 to 8 seconds, causing the oocyte to flow towards the uterus, through the coordinated beating of the cilia that line the outside and lumen of the length of the Fallopian tube which pulls the oocyte into the interior of the tube. Once inside, the muscular contractions and beating cilia move the oocyte slowly toward the uterus. When fertilization does occur, sperm typically meet the egg while it is still moving through the ampulla (**Figure 14.18**).
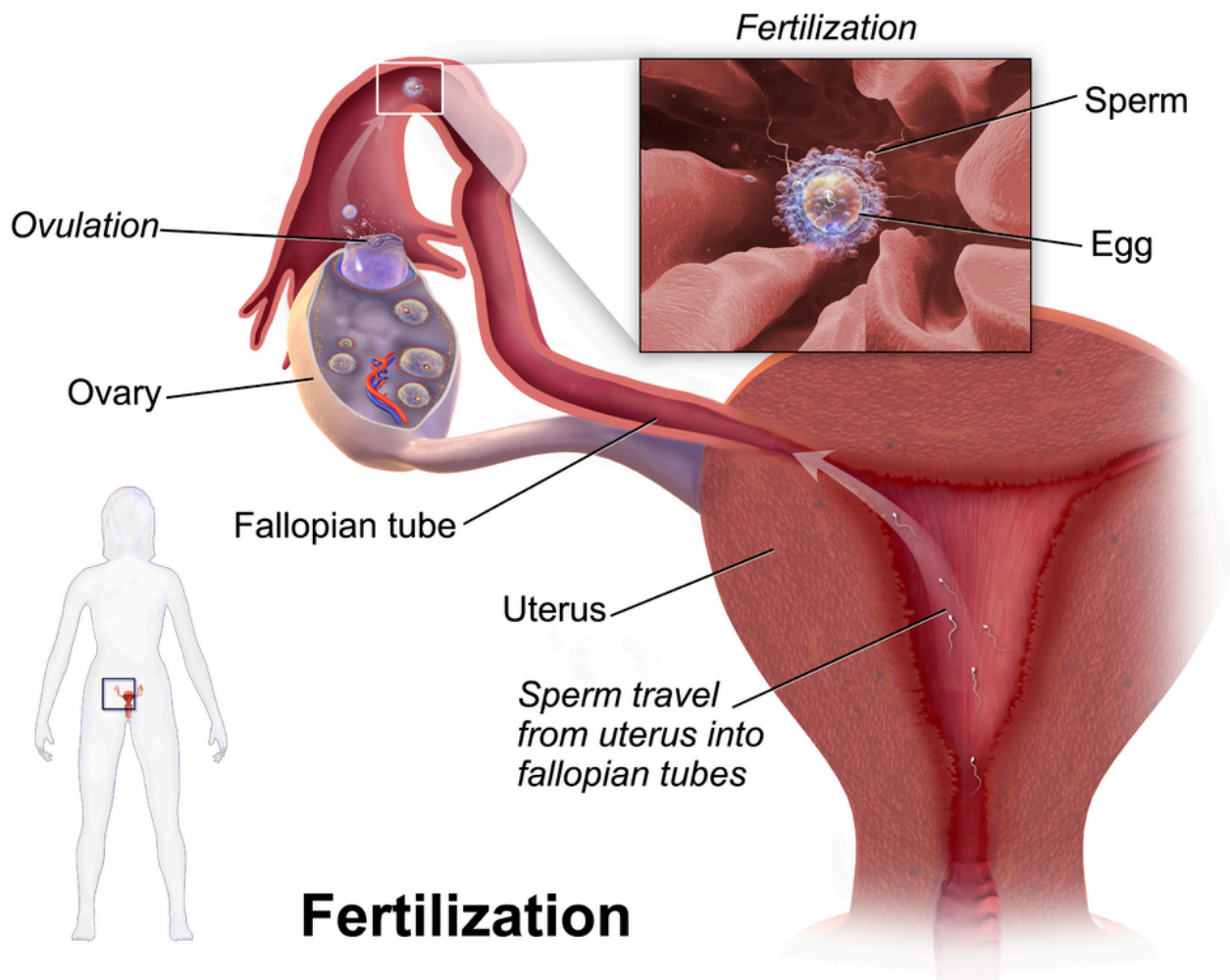

Figure 14.18 Fertilization For fertilization to occur, spern must travel from the vagina, through the uterus, and into the uterine tubes. A sperm cell can fertilize the oocyte in the ampulla of the uterine tube up to one day after ovulation. Image source: Blausen medical via Wikimedia, CC BY 3.0

Terms that may be asked on the BIOL 255L practical

There will be 80 1-point identification questions similar to weekly test questions. We will not ask any function questions.When you are prepared for the Lab Practical Exam you will be able to identify these structures:

Directional Terminology (use appropriately)			
Anterior	Posterior	Superior	Inferior
Medial	Lateral	Proximal	Distal

Cell structures			
Centriole	Cytoplasm	Golgi apparatus	Microvilli
Mitochondria	Nucleolus	Nucleus	Plasma membrane
Ribosomes	Rough endoplasmic reticulum	Smooth endoplasmic reticulum	

Stages of mitosis			
Prophase	Metaphase	Anaphase	Telophase

Skin structures			
Apocrine sweat gland	Arrector pili muscle	Dermis	Eccrine sweat gland
Epidermis	Hair root	Tactile corpuscle	Lamellated corpuscle
Sebaceous gland			

Tissue types			
Adipose CT	Areolar CT	Blood	Compact bone
Cardiac muscle	Elastic cartilage	Hyaline cartilage	Nervous tissue
Ciliated pseudostratified columnar epithelium	Simple columnar epithelium	Simple cuboidal epithelium	Simple squamous epithelium
Skeletal muscle	Smooth muscle	Stratified squamous epithelium	Transitional epithelium

Structures of long bones			
Articular cartilage	Compact bone	Diaphysis	Endosteum
Epiphysis	Metaphysis	Periosteum	Red bone marrow
Spongy bone	Yellow bone marrow		

Axial bones

Ethmoid	Frontal	Lacrimal (R/L)	Mandible
Maxilla (R/L)	Nasal (R/L)	Occipital	Palatine (R/L)
Parietal (R/L)	Sphenoid	Temporal (R/L)	Zygomatic (R/L)
Hyoid	Sternum		

Appendicular Bones

Calcaneus	Capitate	Clavicle (R/L)	Cuboid
Cuneiform (medial, intermediate, lateral)	Femur (R/L)	Fibula (R/L)	Hamate
Humerus (R/L)	Ilium (R/L)	Ischium (R/L)	Lunate
Navicular	Patella (R/L)	Pisiform	Pubis (R/L)
Radius (R/L)	Scaphoid	Scapula (R/L)	Talus
Tibia (R/L)	Trapezium	Trapezoid	Triquetrum
Ulna (R/L)			

Muscle Cell

Endomysium	Myofibril	Sarcolemma	Sarcoplasmic reticulum
T tubule	Z disc		

Muscles and muscle groups

Biceps brachii (R/L)	Biceps femoris* (R/L)	Deltoid (R/L)	Diaphragm
Extensor digitorum (R/L)	External oblique (R/L)	Flexor digitorum superficialis (R/L)	Gluteus maximus (R/L)
Gastrocnemius (R/L)	Gracilis (R/L)	Infraspinatus* (R/L)	Internal oblique (R/L)
Latissimus dorsi (R/L)	Masseter (R/L)	Orbicularis oculi (R/L)	Orbicularis oris
Pectoralis major (R/L)	Pectoralis minor (R/L)	Rectus abdominis (R/L)	Rectus femoris* (R/L)
Sartorius (R/L)	Semimembranosus* (R/L)	Semitendinosus* (R/L)	Sternocleidomastoid (R/L)
Soleus (R/L)	Subscapularis* (R/L)	Supraspinatus* (R/L)	Trapezius
Transversus abdominis (R/L)	Triceps brachii (R/L)	Vastus lateralis* (R/L)	Vastus medialis* (R/L)
*Identify which group these muscles belong to →	Hamstring Group	Quadriceps Group	Rotator Cuff Group

Neuron structures

Axon	Dendrites	Neurofibril node (Node of Ranvier)	Neurolemmocyte (Schwann cell, myelin sheath)

Parts of the Brain

Frontal lobe of cerebrum	Parietal lobe of cerebrum	Occipital lobe of cerebrum	Temporal lobe of cerebrum
Cerebellum	Corpus callosum	Thalamus	Hypothalamus
Medulla oblongata	Pons	Dura mater	

Cranial Nerves

Olfactory (CN I)	Optic (CN II)	Oculomotor (CN III)	Trochlear (CN IV)
Trigeminal (CN V)	Abducens (CN VI)	Facial (CN VII)	Vestibulocochlear (CN VIII)
Glossopharyngeal (CN IX)	Vagus (X)	Accessory (XI)	Hypoglossal (XII)

Ear Structures

Auditory tube	Cochlea	External auditory meatus	Semicircular canals
Tympanic membrane	Malleus	Incus	Stapes

Eye Structures

Cornea	Iris	Lacrimal gland	Lens
Optic disc	Pupil	Retina	Sclera
Superior rectus	Inferior rectus	Medial rectus	Lateral rectus
Superior oblique	Inferior oblique		

Blood cells

Basophil	Eosinophil	Erythrocyte	Lymphocyte
Monocyte	Neutrophil	Platelet	

Heart

Aortic semilunar valve	Bicuspid valve	Chordae tendineae	L/R atrium
L/R ventricle	Papillary muscle	Pulmonary semilunar valve	Tricuspid valve

Blood vessels

Abdominal aorta	Arch of aorta	Brachiocephalic artery	Brachiocephalic vein (R/L)
Common carotid artery (R/L)	Common iliac artery/vein (R/L)	Coronary artery (R/L)	Coronary Sinus
External iliac artery/vein (R/L)	Internal jugular vein (R/L)	Femoral artery/vein (R/L)	Subclavian artery/vein (R/L)
Pulmonary artery (R/L)	Pulmonary trunk	Pulmonary veins (R/L)	Renal artery/vein (R/L)
Inferior vena cava	Superior vena cava		

Lymphatic System

Cisterna chyli	Palatine tonsil	Pharyngeal tonsil	Spleen
Germinal center	Afferent lymphatic vessel	Efferent lymphatic vessel	Cortical sinus

Respiratory system

Carina	Cricoid cartilage	Epiglottis	Hard palate
Laryngopharynx	Lung (R/L)	Nasopharynx	Oropharynx
Nasal concha (superior, middle, or inferior)	Primary (main) bronchus (R/L)	Soft palate	Thyroid cartilage
Trachea	Vestibular fold	Vocal fold	

Endocrine System

Adrenal (suprarenal) gland	Parathyroid gland	Pineal gland	Pituitary gland
Thymus	Thyroid gland		

Digestive system

Ascending colon	Cecum	Common bile duct	Cystic duct
Descending colon	Duodenum	Esophagus	Gallbladder
Ileum	Liver	Pancreas	Pancreatic duct
Parotid gland	Rectum	Sigmoid colon	Stomach
Transverse colon	Vermiform appendix		

Urinary system

Kidney (R/L)	Renal cortex	Renal column	Renal papilla
Renal pelvis	Renal (medullary) pyramid	Afferent arteriole	Collecting duct
Distal convoluted tubule	Proximal convoluted tubule	Efferent arteriole	Loop of Henle (nephron loop)
Glomerulus	Ureter (R/L)	Urethra	Urinary bladder

Male Reproductive System

Bulbourethral gland	Corpus cavernosum	Corpus spongiosum	Ductus (Vas) deferens
Ejaculatory duct	Epididymis	Glans penis	Prostate gland
Seminal vesicle	Testis		

Female Reproductive System			
Cervix	Clitoris	Fimbriae	Labia minora
Uterine (Fallopian) tube	Uterus	Vagina	Ovary
Primordial follicle	Secondary oocyte	Corpus luteum	Corpus albicans

Acknowledgments