JFII JLO FITNESS INSTITUTE OF INDIA

Level 4

PERSONAL TRAINER

Registered to Certify in Sports Fitness Education and Skilled Development Program

CONTENTS

CHAPTER SEVEN

Endocrine System

CHAPTER NINE

Respiratory System

CHAPTER EIGHT

The Cardiovascular System

CHAPTER TEN

Renal System

1

CHAPTER

Introduction to the Human Body

Michael, a freshman in college, overslept and is late for his first anatomy and physiology class. He has been dreading this class but it is necessary for his graduation requirements. Because he does not want to get off to a bad start, he sprints across campus. The combination of the warm day and physical exertion raises his body temperature and, as he throws himself into the nearest seat, sweat is pouring out across his body. Michael begins to feel cooler as he relaxes and he stops sweating within a few minutes. As his first lecture begins, he is introduced to the concept of homeostasis, which describes the condition of balance within the body, and the feedback cycles responsible for maintaining his internal "normal." He thinks about his morning, the sweat that cooled his body, and realizes just how amazing the human body really is. What a great semester this is going to be!

CHAPTER OUTLINE

SELECTED KEY TERMS

Anatomy (ana = apart; tom = to cut) The study of the structure of living organisms.
Appendicular (append = to hang) Pertaining to the upper and lower limbs.
Axial (ax = axis) Pertaining to the longitudinal axis of the body.
Body region (regio = boundary) A portion of the body with a special identifying name.
Directional term (directio = act of guiding) A term that references how the position of a body part relates to the position of another body part.
Effector (efet = result) A structure that functions by performing an action that is directed by an integrating center.
Homeostasis (homeo = same; sta = make stand or stop) Maintenance of a relatively stable internal environment.
Integrating center (integratus = make whole) A structure that functions to interpret information and coordinate a response.
Metabolism (metabole = change) The sum of the chemical reactions in the body.
Parietal (paries = wall) Pertaining to the wall of a body cavity.
Pericardium (peri = around; cardi = heart) The membrane surrounding the heart.
Peritoneum (peri = around; ton = to stretch) The membrane lining the abdominal cavity and covering the abdominal organs.
Physiology (physio = nature; logy = study of) The study of the functioning of living organisms.
Plane (planum = flat surface) Imaginary two-dimensional flat surface that marks the direction of a cut through a structure.
Pleura (pleura = rib) The membrane lining the thoracic cavity and covering the lungs.
Receptor (recipere = receive) A structure that functions to collect information.
Section (sectio = cutting) A flat surface of the body produced by a cut through a plane of the body.
Serous membrane (serum = watery fluid; membrana = thin layer of tissue) A two-layered membrane that lines body cavities and covers the internal organs.
Visceral (viscus = internal organ) Pertaining to organs in a body cavity.

YOU ARE BEGINNING a fascinating and challenging study–the study of the human body. As you progress through this text, you will begin to understand the complex structures and functions of the human organism.

This first chapter provides an overview of the human body to build a foundation of knowledge that is necessary for your continued study. Like the chapters that follow, this chapter introduces a number of new terms for you to learn. It is important that you start to build a vocabulary of technical terms and continue to develop it throughout your study. This vocabulary will help you reach your goal of understanding human anatomy and physiology.

1.1 Anatomy and Physiology

Learning Objective

1. Define anatomy and physiology.

Knowledge of the human organism is obtained primarily from two scientific disciplines–anatomy and physiology–and each consists of a number of subdisciplines.

Human **anatomy** (ah-nat′-ō-mē) is the study of the structure and organization of the body and the study of the relationships of body parts to one another. There are two subdivisions of anatomy. *Gross anatomy* involves the dissection and examination of various parts of the body without magnifying lenses. *Microanatomy,* also known as *histology,* consists of the examination of tissues and cells with various magnification techniques.

Human **physiology** (fiz-ē-ol′-ō-jē) is the study of the function of the body and its parts. Physiology involves observation and experimentation, and it usually requires the use of specialized equipment and materials.

In your study of the human body, you will see that there is always a definite relationship between the anatomy and physiology of the body and body parts. Just as the structure of a knife is well suited for cutting, the structure (anatomy) of a body part enables it to perform specific functions (physiology). For example, the arrangement of bones, muscles, and nerves in your hands enables the grasping of large objects with considerable force and also the delicate manipulation of small objects. Correlating the relationship between structure and function will make your study of the human body much easier.

1.2 Levels of Organization

Learning Objectives

2. Describe the levels of organization in the human body.
3. List the major organs and functions for each organ system.

The human body is complex, so it is not surprising that there are several levels of structural organization, as shown in figure 1.1. The levels of organization from simplest to most complex are chemical, cellular, tissue, organ, organ system, and organismal (the body as a whole).

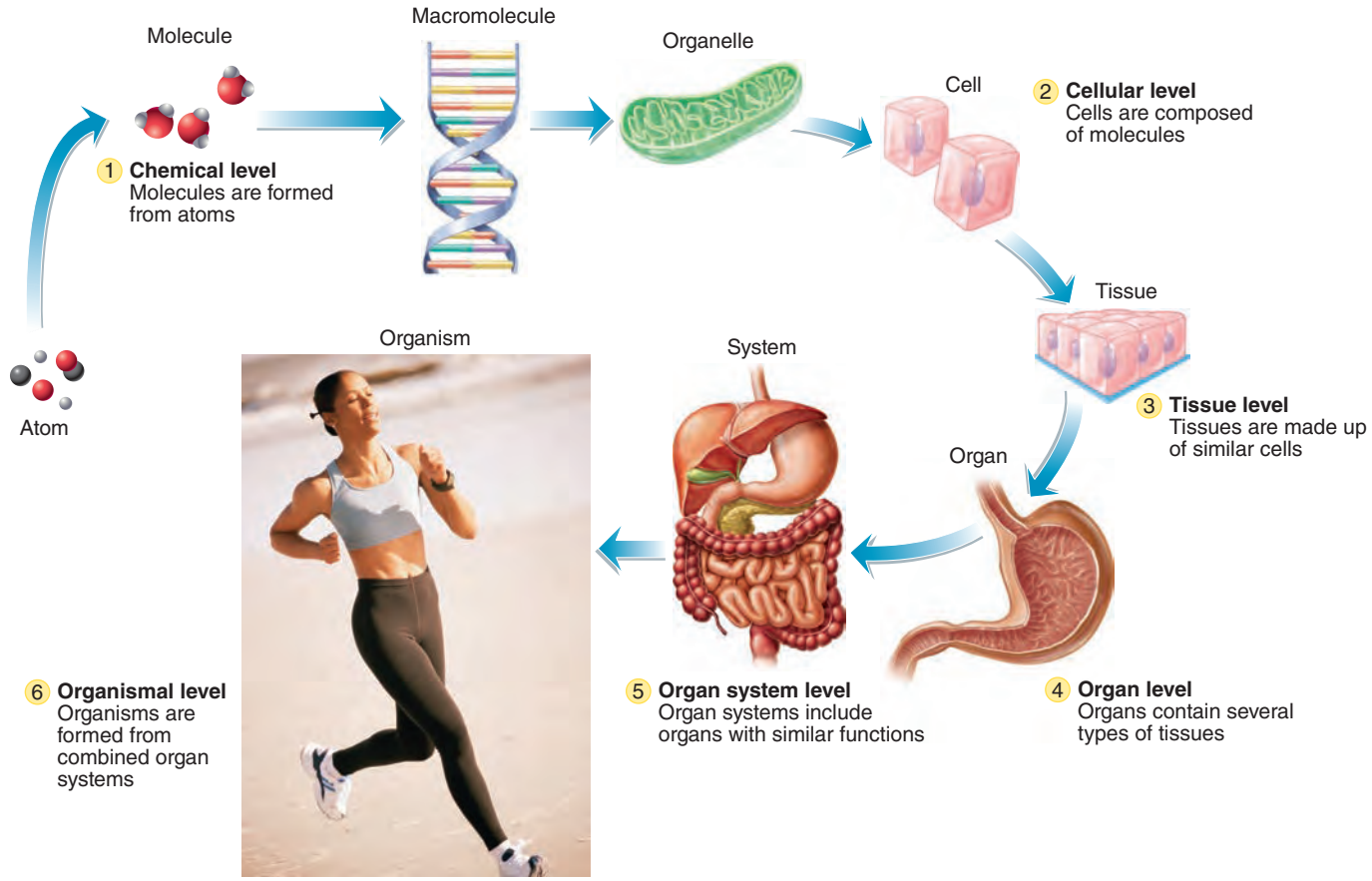


Figure 1.1 Six levels of organization in the human body range from chemical (simplest) to organismal (most complex).

Chemical Level

The *chemical level* consists of *atoms, molecules,* and *macromolecules.* At the simplest level, the body is composed of chemical substances that are formed of atoms and molecules. *Atoms* are the fundamental building blocks of chemicals, and atoms combine in specific ways to form *molecules.* Some molecules are very small, such as water molecules, but others may be very large, such as the macromolecules of proteins. Various small and large molecules are grouped together to form organelles. An **organelle** (or″-ga-nel′) is a microscopic subunit of a cell, somewhat like a tiny organ, that carries out specific functions within a cell. Nuclei, mitochondria, and ribosomes are examples.

Cellular Level

Cells are the basic structural and functional units of the body because all of the processes of life occur within cells. A cell is the lowest level of organization that is alive. The human body is composed of trillions of cells and many different types of cells, such as muscle cells, blood cells, and nerve cells. Each type of cell has a unique structure that enables it to perform specific functions.

Tissue Level

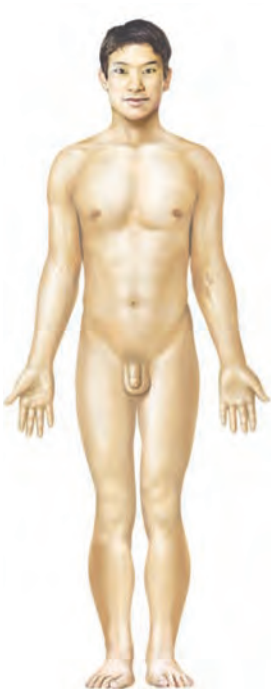
Similar types of cells are usually grouped together in the body to form a tissue. Each body **tissue** consists of an aggregation of similar cells that perform similar functions. There are four major classes of tissues in the body: epithelial, connective, muscle, and nervous tissues.

Organ Level

Each **organ** of the body is composed of two or more tissues that work together, enabling the organ to perform its specific functions. The body contains numerous organs, and each has a definite form and function. The stomach, heart, brain, and even bones are examples of organs.

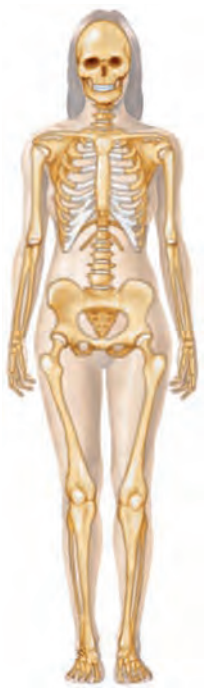
Organ System Level

The organs of the body are arranged in functional groups so that their independent functions are coordinated to perform specific system functions. These coordinated, functional groups are called **organ systems.** The digestive and nervous systems are examples of organ systems. Most organs belong to a single organ system, but a few organs are assigned to more than one organ system. For



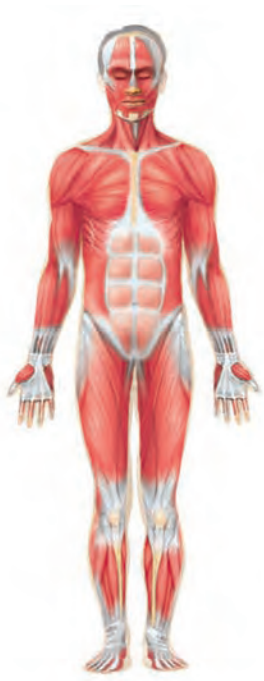
Integumentary system

Components: skin, hair, nails, and associated glands
Functions: protects underlying tissues and helps regulate body temperature



Skeletal system

Components: bones, ligaments, and associated cartilages
Functions: supports the body, protects vital organs, stores minerals, and produces formed elements



Muscular system

Components: skeletal muscles
Functions: moves the body and body parts and produces heat

Figure 1.2 The 11 Organ Systems of the Body.

example, the pancreas belongs to both the digestive and endocrine systems.

Figure 1.2 illustrates the 11 organ systems of the human body and lists the major components and functions for each system. Although each organ system has its own unique functions, all organ systems are interdependent on one another. For example, all organ systems rely on the cardiovascular system to transport materials to and from their cells. Organ systems work together to enable the functioning of the human body.

Organismal Level

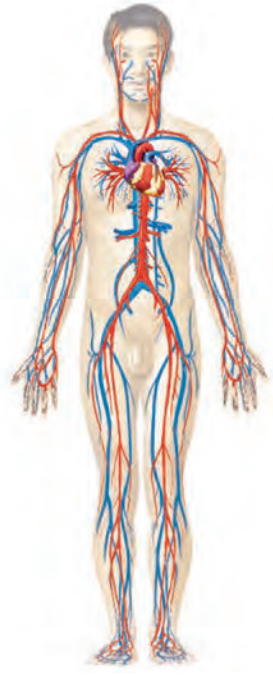
The highest organizational level dealing with an individual is the *organismal level,* the human organism as a whole. It is composed of all of the interacting organ systems. All of the organizational levels from chemicals to organ systems contribute to the functioning of the entire body.

Check My Understanding

1. What are the organizational levels of the human body?
2. What are the major organs and general functions of each organ system?

Respiratory system

Components: nose, pharynx, larynx, trachea, bronchi, and lungs
Functions: exchanges O_2 and CO_2 between air and blood in the lungs, pH regulation, and sound production

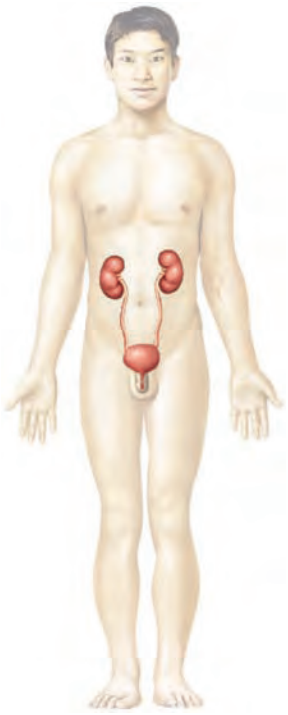


Cardiovascular system

Components: blood, heart, arteries, veins, and capillaries
Functions: transports heat and materials to and from the body cells

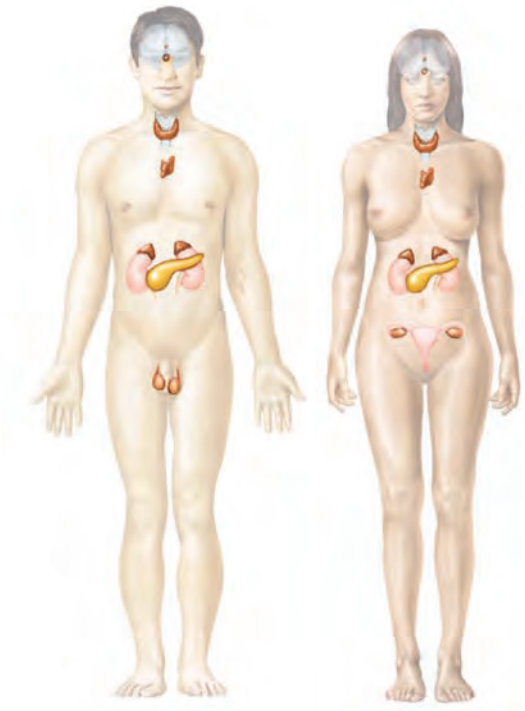
Lymphoid system

Components: lymph, lymphatic vessels, and lymphoid organs and tissues
Functions: collects and cleanses interstitial fluid, and returns it to the blood; provides immunity



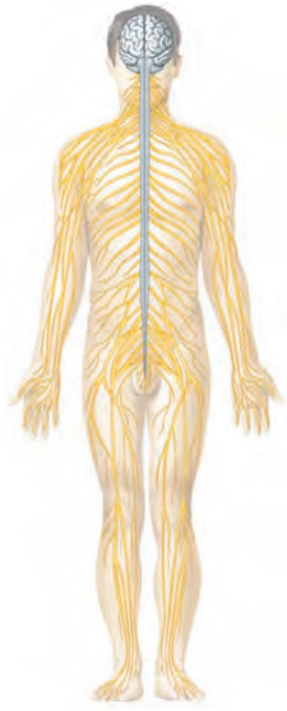
Urinary system

Components: kidneys, ureters, urinary bladder, and urethra
Functions: regulates volume and composition of blood by forming and excreting urine



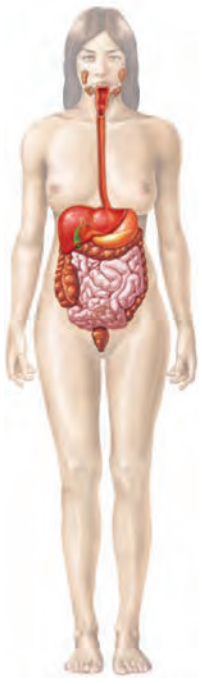
Endocrine system

Components: hormone-producing glands, such as the pituitary and thyroid glands
Functions: secretes hormones that regulate body functions



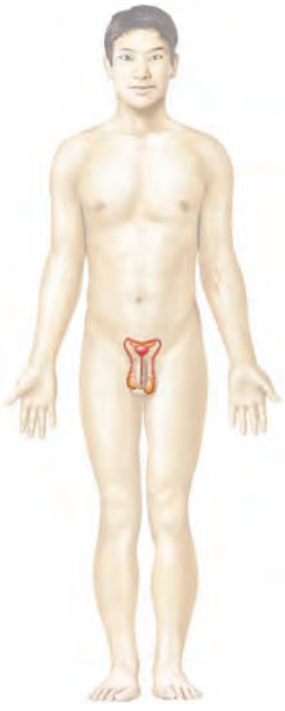
Nervous system

Components: brain, spinal cord, nerves, and sensory receptors
Functions: rapidly coordinates body functions and enables learning and memory



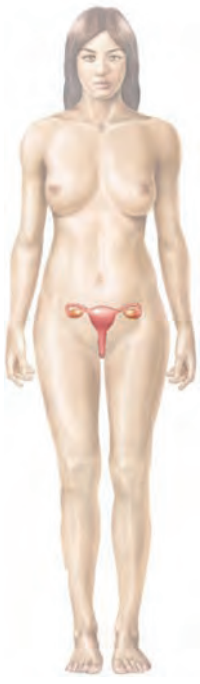
Digestive system

Components: mouth, pharynx, esophagus, stomach, intestines, liver, pancreas, gallbladder, and associated structures
Functions: digests food and absorbs nutrients



Male reproductive system

Components: testes, epididymides, vasa deferentia, prostate gland, bulbo-urethral glands, seminal vesicles, and penis
Functions: produces sperm and transmits them into the female vagina during sexual intercourse



Female reproductive system

Components: ovaries, uterine tubes, uterus, vagina, and vulva
Functions: produces oocytes, receives sperm, provides intrauterine development of offspring, and enables birth of an infant

1.3 Directional Terms

Learning Objective

4. Use directional terms to describe the locations of body parts.

Directional terms are used to describe the relative position of a body part in relationship to another body part. The use of these terms conveys a precise meaning enabling the listener or reader to locate the body part of interest. It is always assumed that the body is in a standard position, the *anatomical position,* in which the body is standing upright with upper limbs at the sides and palms of the hands facing forward, as in figure 1.3. Directional terms occur in pairs, and the members of each pair have opposite meanings, as noted in table 1.1.

1.4 Body Regions

Learning Objective

5. Locate the major body regions on a chart or anatomical model.

The human body consists of an **axial** (ak′-sē-al) **portion,** the head, neck, and trunk, and an **appendicular** (ap-pen-dik′-ū-lar) **portion,** the upper and lower limbs and their girdles. Each of these major portions of the body is divided into regions with special names to facilitate communication and to aid in locating body components.

The major **body regions** are listed in tables 1.2 and 1.3 to allow easy correlation with figure 1.4, which shows the locations of the major regions of the body. Take time to learn the names, pronunciations, and locations of the body regions.

1.5 Body Planes and Sections

Learning Objective

6. Describe the four planes used in making sections of the body or body parts.

In studying the body or organs, you often will be observing the flat surface of a **section** that has been produced by a cut through the body or a body part. Such sections are made along specific **planes.** These well-defined planes–transverse,

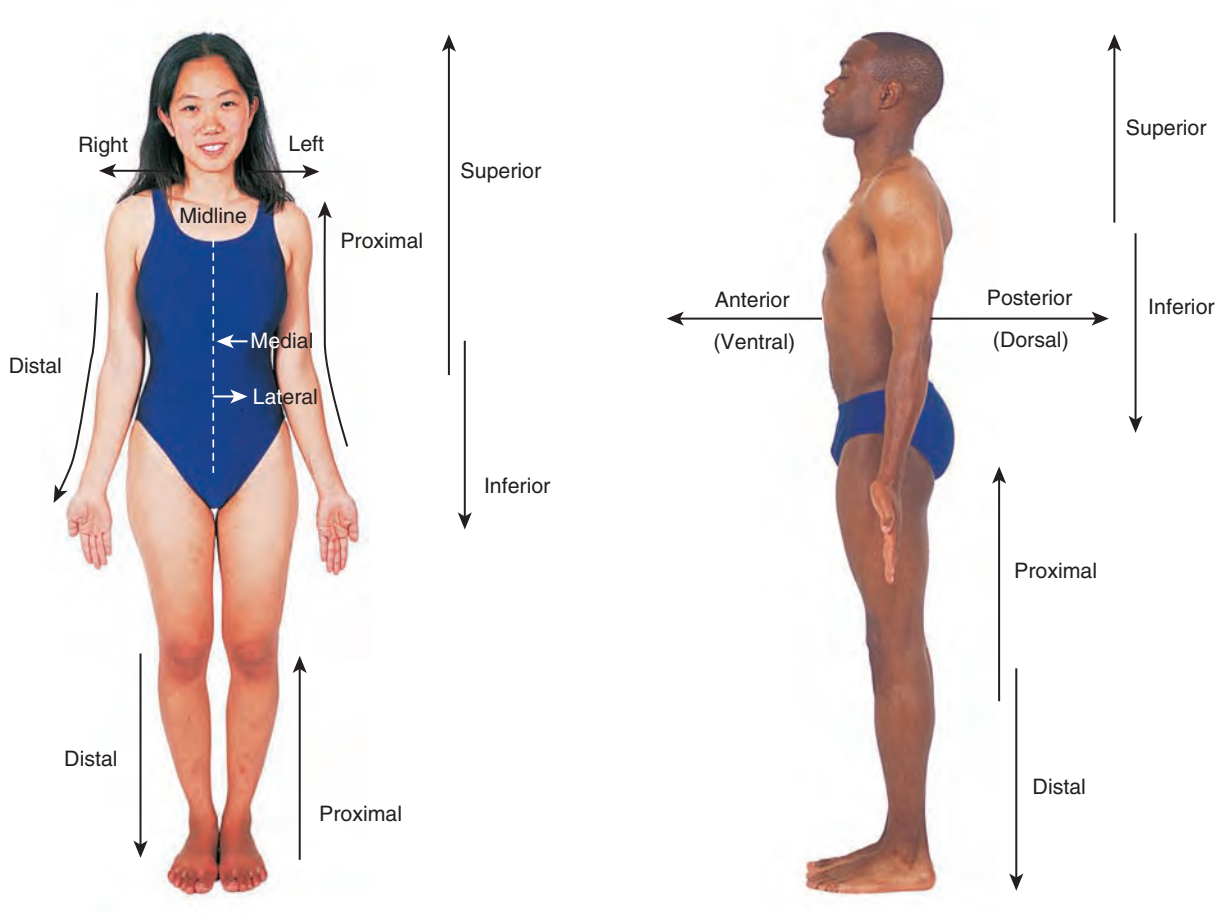


Figure 1.3 Anatomical Position and Directional Terms.

Table 1.1 Directional Terms

Term	Meaning	Example
Anterior (ventral)	Toward the front or abdominal surface of the body	The abdomen is anterior to the back.
Posterior (dorsal)	Toward the back of the body	The spine is posterior to the face.
Superior (cephalic)	Toward the top/head	The nose is superior to the mouth.
Inferior (caudal)	Away from the top/head	The navel is inferior to the nipples.
Medial	Toward the midline of the body	The breastbone is medial to the nipples.
Lateral	Away from the midline of the body	The ears are lateral to the cheeks.
Parietal	Pertaining to the outer boundary of body cavities	The parietal pleura lines the pleural cavity.
Visceral	Pertaining to the internal organs	The visceral pleura covers the lung.
Superficial (external)	Toward or on the body surface	The skin is superficial to the muscles.
Deep (internal)	Away from the body surface	The intestines are deep to the abdominal muscles.
Proximal	Closer to the beginning	The elbow is proximal to the wrist.
Distal	Farther from the beginning	The hand is distal to the wrist.
Central	At or near the center of the body or organ	The central nervous system is in the middle of the body.
Peripheral	External to or away from the center of the body or organ	The peripheral nervous system extends away from the central nervous system.

Table 1.2 Major Regions of the Head, Neck, and Trunk

Region			
Head and Neck	***Anterior Trunk***	***Posterior Trunk***	***Lateral Trunk***
Buccal (bu-kal)	Abdominal (ab-dom′-i-nal)	Dorsum (dor′-sum)	Axillary (ak′-sil-lary)
Cephalic (se-fal′-ik)	Abdominopelvic (ab-dom-i-nō-pel′-vik)	Gluteal (glu′-tē-al)	Coxal (kok′-sal)
Cervical (ser′-vi-kal)	Inguinal (ing′-gwi-nal)	Lumbar (lum′-bar)	***Inferior Trunk***
Cranial (krā′-nē-al)	Pectoral (pek′-tōr-al)	Sacral (sāk′-ral)	Genital (jen′-i-tal)
Facial (fā′-shal)	Pelvic (pel′-vik)	Vertebral (ver-tē′-bral)	Perineal (per-i-nē′-al)
Nasal (nā-zel)	Sternal (ster′-nal)		
Oral (or-al)	Umbilical (um-bil′-i-kal)		
Orbital (or-bit-al)			
Otic (o-tic)			

Table 1.3 Major Regions of the Limbs

Region		
Upper Limb	Digital (di′-ji-tal)	Femoral (fem′-ōr-al)
Antebrachial (an-tē-brā′-kē-al)	Olecranal (ō-lēk′-ran-al)	Patellar (pa-tel′-lar)
Antecubital (an-tē-kū-bi-tal)	Palmar (pal′-mar)	Pedal (pe′-dal)
Brachial (brā′-kē-al)	***Lower Limb***	Plantar (plan′-tar)
Carpal (kar′-pal)	Crural (krū′-ral)	Popliteal (pop-li-tē′-al)
Deltoid (del-tȯid)	Digital (di′-ji-tal)	Sural (sū′-ral)

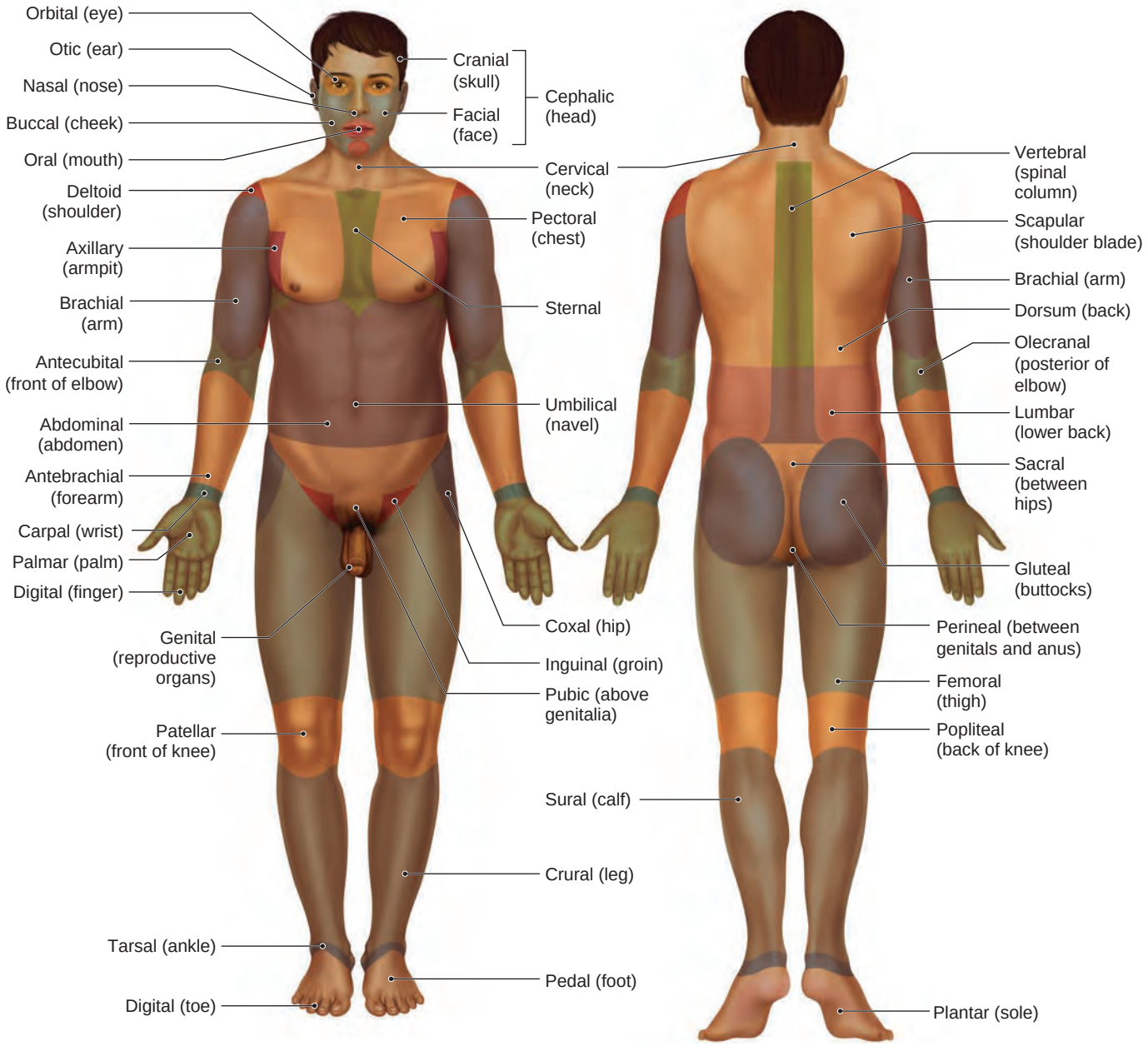


Figure 1.4 Major Regions of the Body.

sagittal, and frontal planes–lie at right angles to each other as shown in figure 1.5. It is important to understand the nature of the plane along which a section was made in order to understand the three-dimensional structure of an object being observed.

Transverse, or horizontal, **planes** divide the body into superior and inferior portions and are perpendicular to the longitudinal axis of the body.

Sagittal planes divide the body into right and left portions and are parallel to the longitudinal axis of the body. A **median** (midsagittal) **plane** passes through the midline of the body and divides the body into equal left and right halves. A **parasagittal plane** does not pass through the midline of the body.

Frontal (coronal) **planes** divide the body into anterior and posterior portions. These planes are perpendicular to sagittal planes and parallel to the longitudinal axis of the body.

Cuts made through sagittal and frontal planes, which are parallel to the longitudinal axis of the body, produce *longitudinal sections*. However, the term longitudinal section also refers to a section made through the longitudinal axis of an individual organ, tissue, or other structure. Similarly, cuts made through the transverse plane produce *cross*

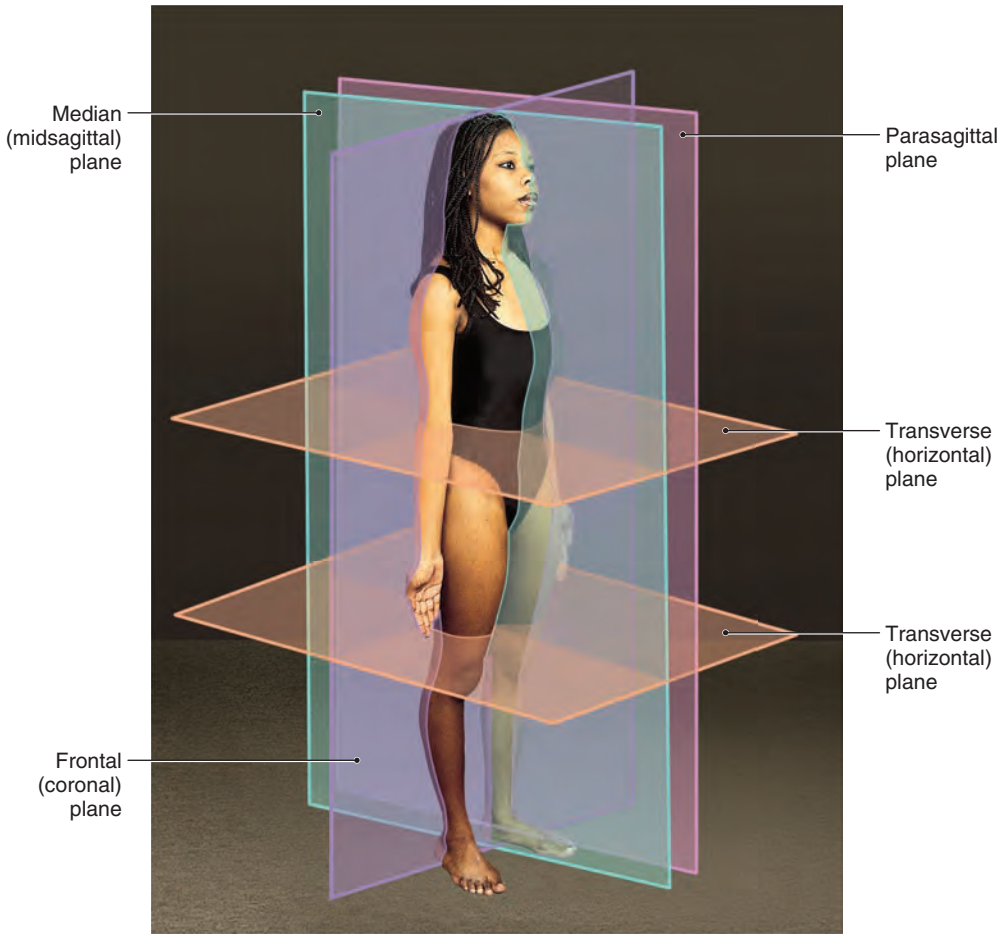


Figure 1.5 Anatomical Planes of Reference.

sections of the body and can also be produced in organs and tissues when cutting at a 90° angle to the longitudinal axis. *Oblique sections* are created when cuts are made in between the longitudinal and cross-sectional axes.

Check My Understanding

3. How do sagittal, transverse, and frontal planes differ from one another?

1.6 Body Cavities

Learning Objectives

7. Name the two major body cavities, their subdivisions and membranes.
8. Locate the body cavities, their subdivisions and membranes on a diagram.
9. Name the organs located in each body cavity.

There are two major cavities of the body that contain internal organs: the dorsal (posterior) and ventral (anterior) cavities. The body cavities protect and cushion the contained organs and permit changes in their size and shape without impacting surrounding tissues. Note the locations and subdivisions of these cavities in figure 1.6.

The **dorsal cavity** is subdivided into the **cranial cavity,** which houses the brain, and the **vertebral canal,** which contains the spinal cord. Note in figure 1.6 how the cranial bones and the vertebral column form the walls of the dorsal cavity and provide protection for these delicate organs.

The **ventral cavity** is divided by the *diaphragm*, a thin dome-shaped sheet of muscle, into a superior **thoracic cavity** and an inferior **abdominopelvic cavity.** The thoracic cavity is protected by the *rib cage* and contains the heart and lungs. The abdominopelvic cavity is subdivided into a superior **abdominal cavity** and an inferior **pelvic cavity,** but there is no structural separation between them. To visualize the separation, imagine a transverse plane passing through the body just superior to the pelvis. The abdominal cavity contains the stomach, intestines, liver, gallbladder, pancreas, spleen, and kidneys. The pelvic cavity contains the urinary bladder, sigmoid colon, rectum, and internal reproductive organs.

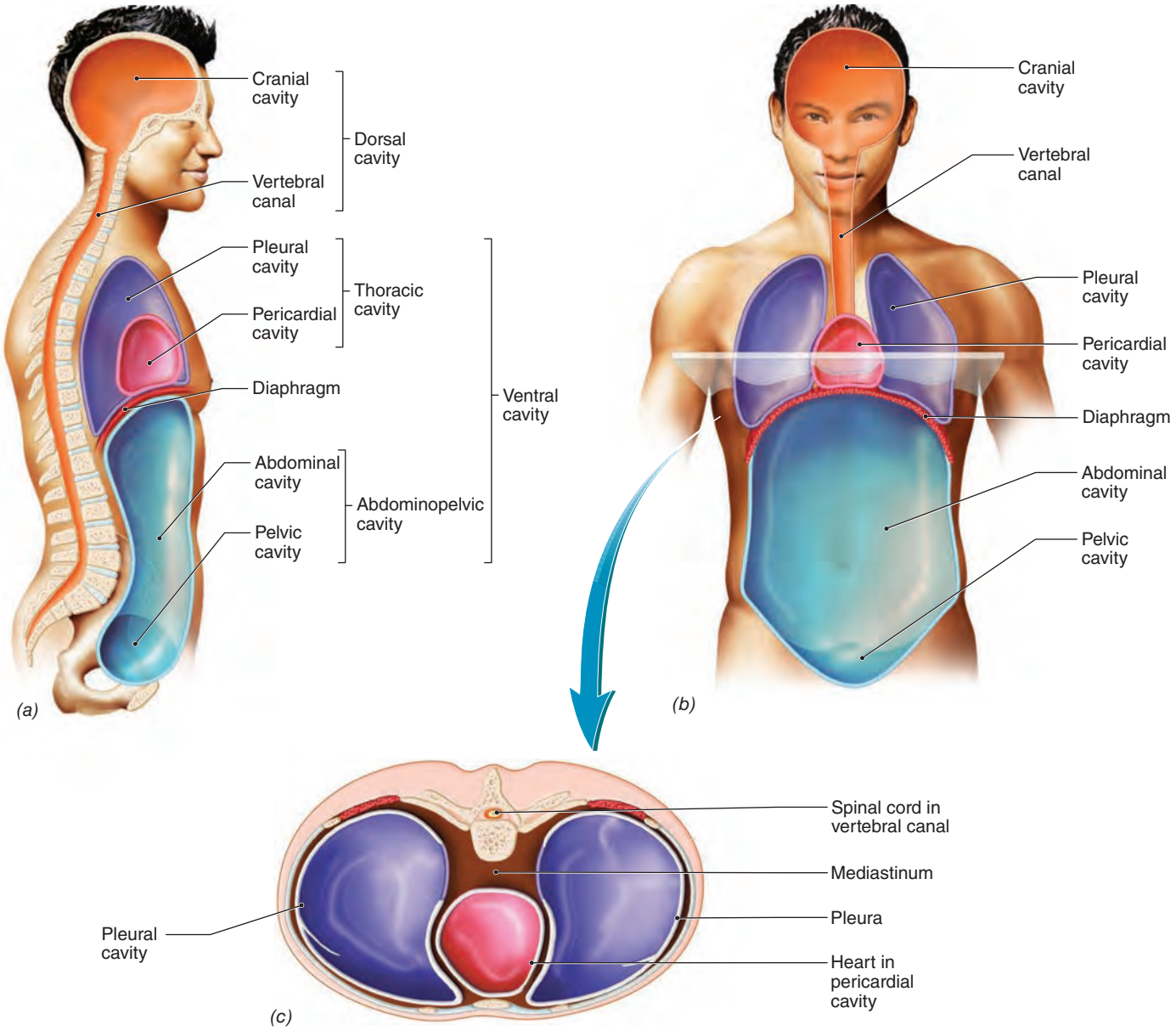


Figure 1.6 Body Cavities and Their Subdivisions.
(a) Sagittal section. *(b)* Frontal section. *(c)* Transverse section through the thoracic cavity.

Check My Understanding

4. What organs are located in each subdivision of the dorsal cavity?
5. What organs are located in each subdivision of the ventral cavity?

Membranes of Body Cavities

The membranes lining body cavities support and protect the internal organs in the cavities.

Dorsal Cavity Membranes

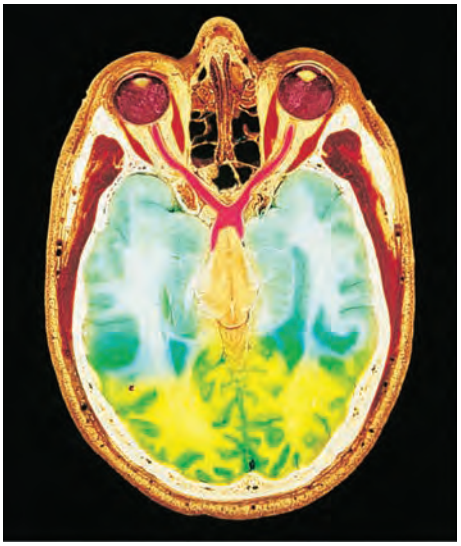
The dorsal cavity is lined by three layers of protective membranes that are collectively called the **meninges** (me-nin′-jēz; singular, *meninx*). The most superficial membrane is attached to the wall of the dorsal cavity, and the deepest membrane tightly envelops the brain and spinal cord. The meninges will be covered in chapter 8.

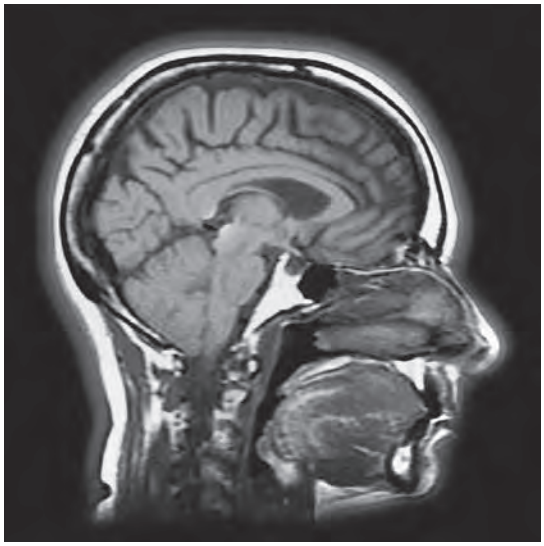
Ventral Cavity Membranes

The ventral body cavity organs are supported and protected by **serosae** (singular, *serosa*), or **serous membranes.**

Clinical Insight

Physicians use certain types of diagnostic imaging systems, for example, *computerized tomography (CT), magnetic resonance imaging (MRI),* and *positron emission tomography (PET)*, to produce images of sections of the body to help them diagnose disorders. In computerized tomography, an X-ray emitter and an X-ray detector rotate around the patient so that the X-ray beam passes through the body from hundreds of different angles. X-rays collected by the detector are then processed by a computer to produce sectional images on a screen for viewing by a radiologist. A good understanding of sectional anatomy is required to interpret CT scans. Transverse sections, such as the image on the left, are always shown in the same way. Convention is to use supine (face up), inferior views as if looking up at the section from the foot of the patient's bed. What structures can you identify in the CT image shown on the right?





The serous membranes are thin layers of tissue that line the body cavity and cover the internal organs. Serous membranes have a superficial *parietal* (pah-rī′-e-tal) *lay*er that lines the cavity and a deep *visceral* (vis′-er-al) *layer* that covers the organ. The parietal and visceral layers secrete a watery lubricating fluid that is generically called *serous fluid* into the cavity formed between the layers. This arrangement is similar to that of a fist pushed into a balloon (figure 1.7). The serous membranes of the body are the pleura, pericardium, and peritoneum.

The serous membranes lining the thoracic cavity are called **pleurae** (singular, *pleura*), or **pleural membranes.** The walls of the left and right portions of the thoracic cavity are lined by the *parietal pleurae.* The surfaces of the lungs are covered by the *visceral pleurae.* The parietal and visceral pleurae are separated by a thin film of serous fluid called pleural fluid, which reduces friction as the pleurae rub against each other as the lungs expand and contract during breathing. The potential space (not an actual space) between the parietal and visceral pleurae is known as the **pleural cavity.**

The left and right portions of the thoracic cavity are divided by a membranous partition, the *mediastinum* (mē-dē-a-stī′-num). Organs located within the mediastinum include the heart, thymus, esophagus, and trachea.

The heart is enveloped by the **pericardium** (per-i-kar′-dē-um), which is formed by membranes of the mediastinum. The thin *visceral pericardium* is tightly adhered to the surface of the heart. The *parietal pericardium* lines the deep surface of a loosely fitting sac around the heart. The potential space between the visceral and parietal pericardia is the **pericardial cavity,** and it contains serous fluid, called pericardial fluid, that reduces friction as the heart contracts and relaxes.

The walls of the abdominal cavity and the surfaces of abdominal organs are lined with the **peritoneum** (per-i-tō-nē′-um), or **peritoneal membrane.** The *parietal peritoneum* lines the walls of the abdominal cavity but not the pelvic cavity. It descends only to cover the superior portion of the urinary bladder. The kidneys, pancreas, and parts of the intestines are located posterior to the parietal peritoneum in a space known as the *retroperitoneal space.* The *visceral peritoneum,* an extension of the parietal peritoneum, covers the surface of the abdominal organs. Double-layered folds of the visceral peritoneum, the *mesenteries* (mes′-en-ter″-ēs), extend between the abdominal organs

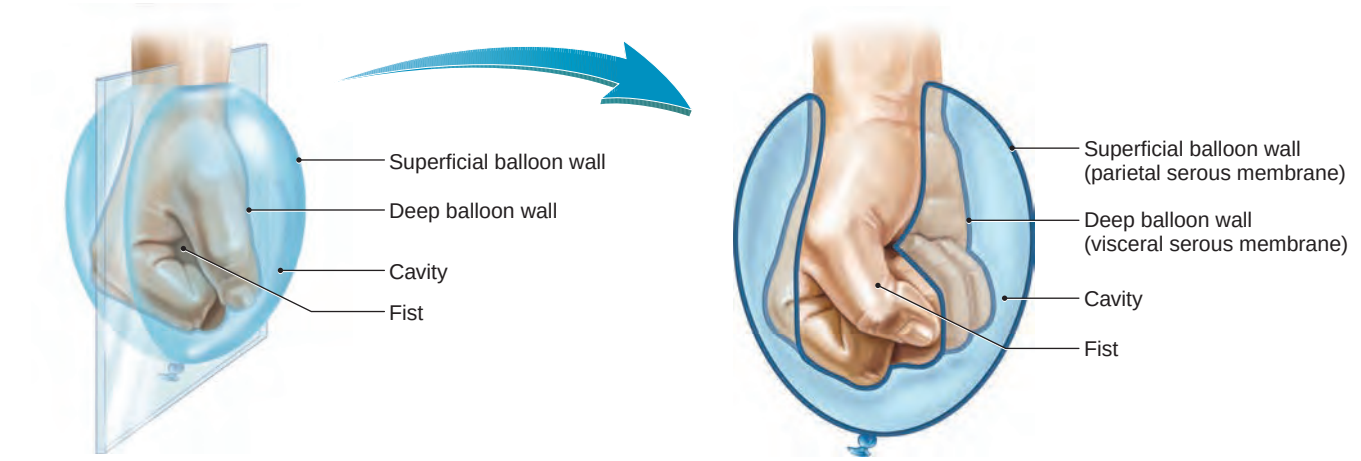


Figure 1.7 Illustration of a fist pushed into a balloon as an analogy to serous membranes.

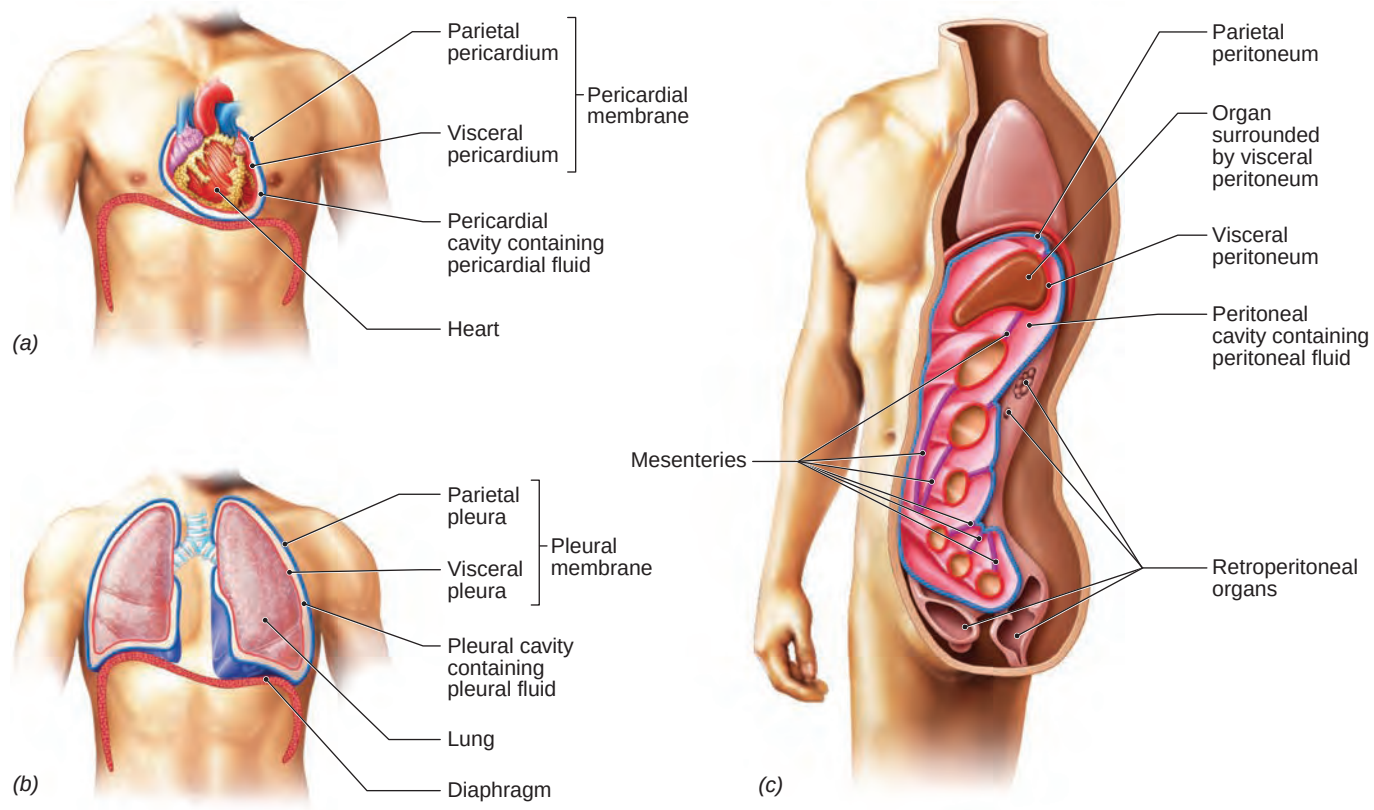


Figure 1.8 Serous Membranes of The Ventral Cavity.
(a) Anterior view of pericardium. *(b)* Anterior view of pleura. *(c)* Sagittal view of peritoneum.

and provide support for them (see figure 1.8*c*). The potential space between the parietal and visceral peritoneal membranes is called the **peritoneal cavity** and contains a small amount of serous fluid called peritoneal fluid (figure 1.8).

Check My Understanding

6. What membranes line the dorsal and ventral cavities?
7. What is the function of serous fluid?

1.7 Abdominopelvic Subdivisions

Learning Objectives

10. Name the abdominopelvic quadrants and regions.
11. Locate the abdominopelvic quadrants and regions on a diagram.

The abdominopelvic cavity is subdivided into either four quadrants or nine regions to aid health care providers in locating underlying organs in the abdominopelvic cavity. Physicians may feel (palpate) or listen to (auscultate) the abdominopelvic region to examine it. Changes in firmness or sounds may indicate abnormalities in the structures of a quadrant or region.

The four quadrants are formed by two planes that intersect just superior to the umbilicus (navel), as shown in figure 1.9*a*. Note the organs within each quadrant.

The nine regions are formed by the intersection of two sagittal and two transverse planes as shown in figure 1.9*c*. The sagittal planes extend inferiorly from the midpoints of the collarbones. The superior transverse plane lies just inferior to the borders of the 10th costal cartilages, and the inferior transverse plane lies just inferior to the superior border of the hip bones.

Study figures 1.8 and 1.9 to increase your understanding of the locations of the internal organs and associated membranes.

Now examine the colorplates that follow this chapter. They show an anterior view of the body in progressive stages of dissection that reveals major muscles, blood vessels, and internal organs. Study these plates to learn the normal locations of the organs of the ventral cavity. Also, check your understanding of the organs within each abdominopelvic quadrant and region.

Check My Understanding

8. What are the four quadrants and nine regions of the abdominopelvic region?

1.8 Maintenance of Life

Learning Objectives

12. Define metabolism, anabolism, and catabolism.
13. List the five basic needs essential for human life.
14. Define homeostasis.
15. Explain how homeostasis relates to both healthy body functions and disorders.
16. Describe the general mechanisms of negative feedback and positive feedback.

Humans, like all living organisms, exhibit the fundamental processes of life. **Metabolism** (me-tab′ō-lizm) is the term that collectively refers to the sum of all of the chemical reactions that occur in the body.

There are two phases of metabolism: anabolism and catabolism. **Anabolism** (ah-nab′-ō-lizm) refers to processes that use energy and nutrients to build the complex organic molecules that compose the body. **Catabolism** (kah-tab′-ō-lizm) refers to processes that release energy and break down complex molecules into simpler molecules.

Life is fragile. It depends upon the normal functioning of trillions of body cells, which, in turn, depends upon factors needed for survival and the ability of the body to maintain relatively stable internal conditions.

Survival Needs

There are five basic needs that are essential to human life:

1. **Food** provides chemicals that serve as a source of energy and raw materials to grow and to maintain cells of the body.
2. **Water** provides the environment in which the chemical reactions of life occur.
3. **Oxygen** is required to release the energy in organic nutrients, which powers life processes.
4. **Body temperature** must be maintained close to 36.8°C (98.2°F) to allow the chemical reactions of human metabolism to occur.
5. **Atmospheric pressure** is required for breathing to occur.

Homeostasis

Homeostasis is the maintenance of a relatively stable internal environment by self-regulating physiological processes. Homeostasis keeps body temperature and the composition of blood and interstitial fluids within their normal range. This relatively stable internal environment is maintained in spite of the fact that internal and external factors tend to alter body temperature, and materials are continuously entering and exiting the blood and interstitial fluid.

All of the organ systems work in an interdependent manner to maintain homeostasis. For example, changes in one system tend to affect one or more other body systems. Therefore, any disruption in one body system tends to be corrected but may disrupt another body system. The internal environment is maintained via a *dynamic equilibrium* where there is constant fluctuation taking place in order to maintain homeostasis. Malfunctioning or overcompensation in a homeostatic mechanism can lead to disorders and diseases.

The dynamic equilibrium of homeostasis is primarily maintained by physiologic processes called **negative-feedback mechanisms.** Body fluid composition and other physiological variables fluctuate near a normal value, called a *set point*, and negative-feedback mechanisms are

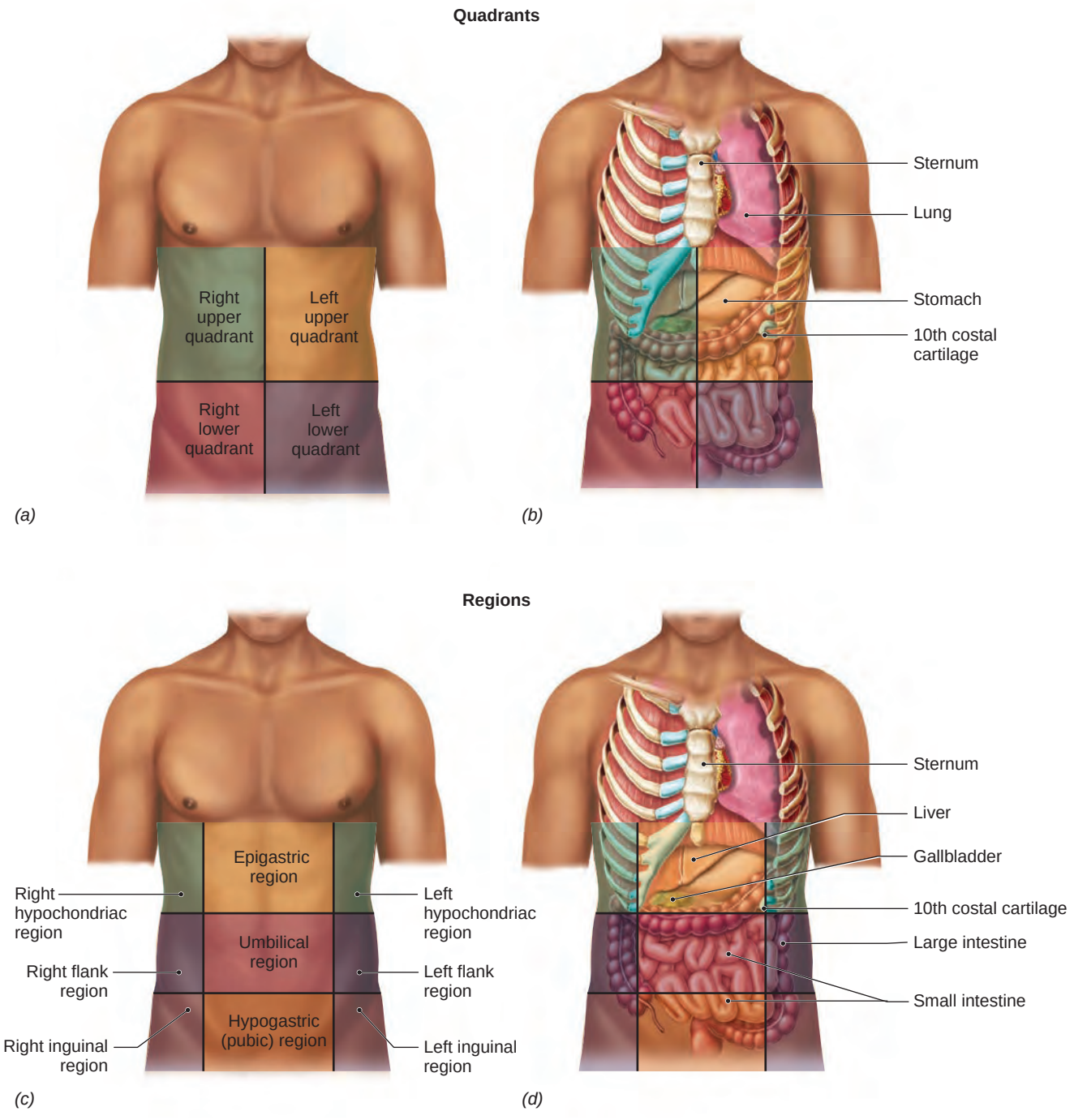
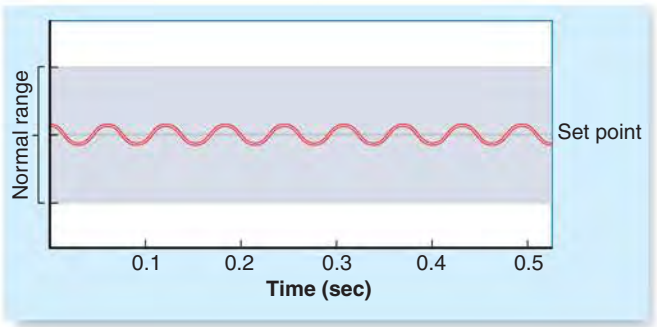
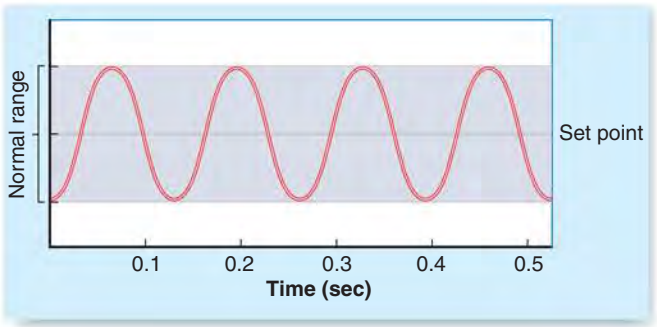


Figure 1.9 The four quadrants and nine regions of the abdominopelvic cavity.

used to keep these variables within their normal range (figure 1.10). For a negative-feedback mechanism to work, it needs to be able to monitor and respond to any changes in homeostasis. The structure of the negative-feedback mechanism allows it to function in exactly this manner and is a great example of how anatomical structure complements function. To monitor a physiological variable, a negative-feedback mechanism utilizes a **receptor** to detect deviation from the set point and send a signal notifying the integrating center about the deviation. The **integrating center,** which is the body region that knows the set point for the variable, processes the information from a receptor and determines the course of action that is needed. It then sends a signal that activates an **effector.**



(a) High sensitivity



(b) Low sensitivity

Figure 1.10 *(a)* A negative-feedback mechanism with high sensitivity. *(b)* A negative-feedback mechanism with low sensitivity.

The effector will carry out the necessary response according to the directions of the integrating center and return the variable back toward the set point. In a negative-feedback mechanism the response of the effector will always be the opposite of the change detected by the receptor (figure 1.11). Once the set point is reached, the negative-feedback mechanism will automatically turn off.

Our body's ability to maintain relatively constant blood glucose levels relies on negative-feedback mechanisms. When blood glucose levels begin to rise, as they do after a meal, there are receptors in the pancreas that can detect this *stimulus* (change). The beta cells of the pancreas act as an integrating center and release the hormone insulin in response to this change. Insulin travels through the blood to several effectors, one of which is the liver. Insulin causes the liver cells to take excess glucose out of the bloodstream

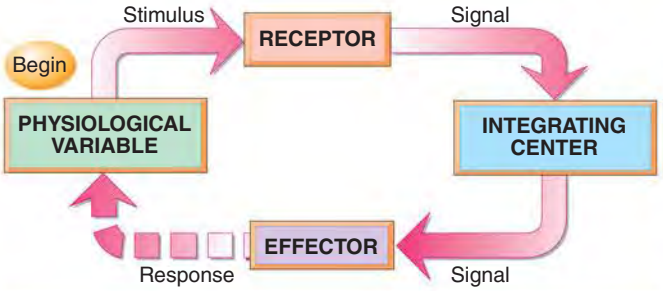


Figure 1.11 A negative-feedback mechanism controlling homeostasis.

and thus decrease the blood glucose level back toward normal. The pancreas possesses other receptors that can detect decreases in blood glucose, such as occurs between meals. The alpha cells of the pancreas, acting as the integrating center, release the hormone glucagon. Glucagon causes the liver to release glucose into the bloodstream, which will increase blood glucose back toward normal (figure 1.12).

It is important to note that the response of the integrating center will be stronger if the original stimulus is farther from normal. For example, if the blood glucose level rises sharply out of the normal range, causing *hyperglycemia* (blood glucose level above normal), the amount of insulin the beta cells release will be more than the amount released if the blood glucose level is elevated but is still within the normal range. This type of response is called a *graded response* because it can respond on different levels (figure 1.13).

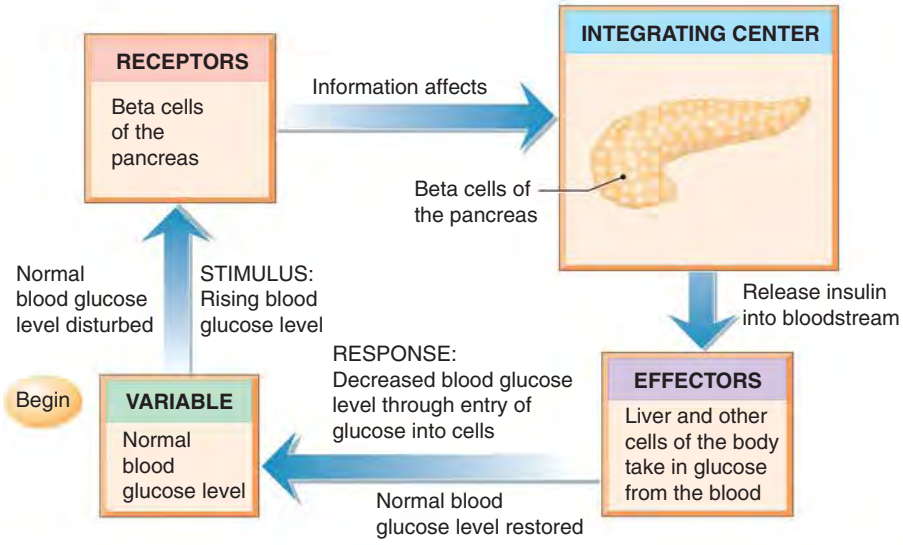


Figure 1.12 The negative-feedback mechanism that regulates blood glucose levels.

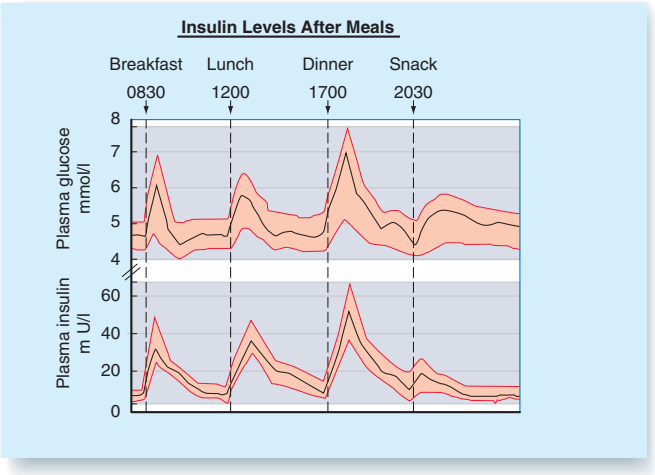


Figure 1.13 The graded response of insulin release is based on amount of blood glucose elevation.

Positive-feedback mechanisms utilize the same basic components as negative-feedback mechanisms. However, the outcome of a positive-feedback mechanism is very different from that of a negative-feedback mechanism. A positive-feedback mechanism is used when the originating stimulus needs to be amplified and continued in order for the desired result to occur. A few examples of positive-feedback mechanisms include fever, activation of the immune response, formation of blood clots, certain aspects of digestion, and uterine contractions of labor. If you think about blood clot formation, blood clots do not form "normally"; when they begin to form, this occurs quickly and completely in order to stop blood loss. This is a necessary mechanism for overall homeostasis. Figure 1.14 illustrates the specific steps of the positive-feedback mechanism of saliva production.

Positive-feedback mechanisms can be harmful because they lack the ability to stop on their own. They will continue to amplify the effect of the original stimulus, which can push the body dangerously out of homeostasis, until the cycle is interrupted by an outside factor. For example, an uncontrolled fever can increase body temperature to a point that is fatal. For this reason, positive-feedback mechanisms are used for rare events within the body, rather than for the daily maintenance of homeostasis.

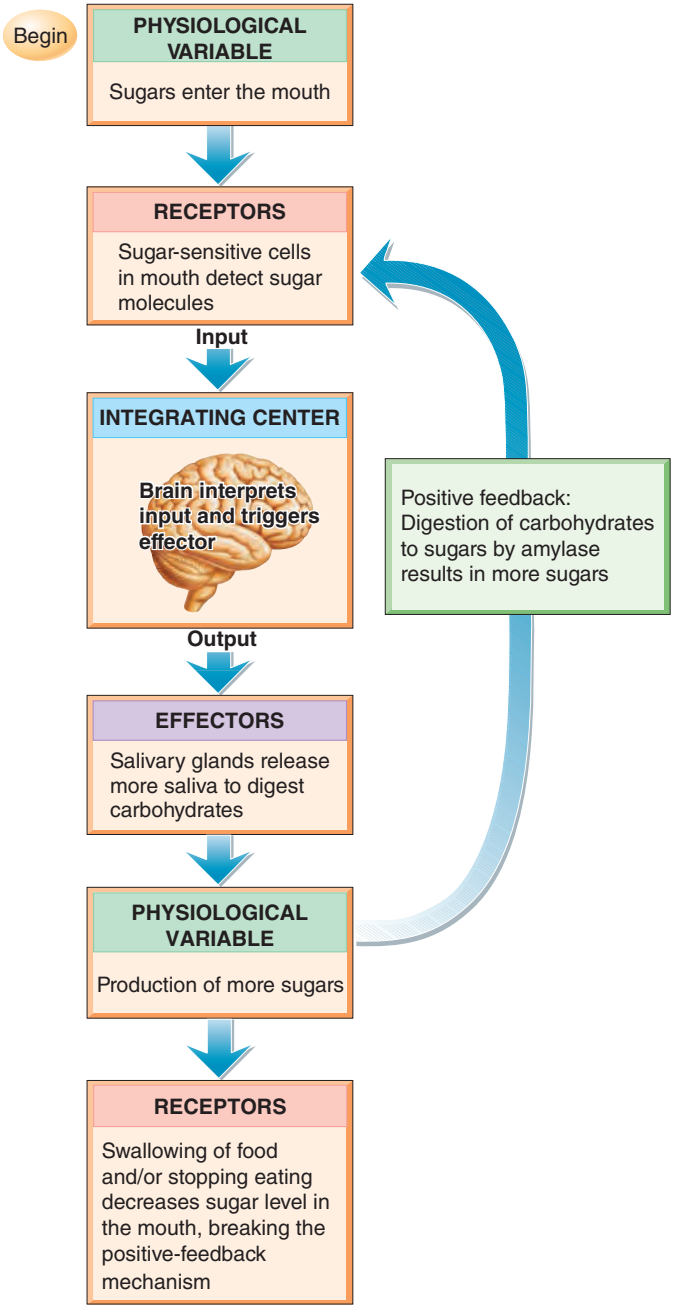


Figure 1.14 A positive-feedback mechanism illustrating the production of saliva.

Check My Understanding

9. What is homeostasis? How is homeostasis regulated?

Chapter Summary

1.1 Anatomy and Physiology

- Human anatomy is the study of body structure and organization.
- Human physiology is the study of body functions.

1.2 Levels of Organization

- The body consists of several levels of organization of increasing complexity.
- From simple to complex, the organizational levels are chemical, cellular, tissue, organ, organ system, and organismal.
- The organs of the body are arranged in coordinated groups called organ systems.
- The 11 organ systems of the body are

integumentary	cardiovascular
skeletal	lymphoid
muscular	respiratory
nervous	urinary
endocrine	reproductive
digestive	

1.3 Directional Terms

- Directional terms are used to describe the relative positions of body parts.
- Directional terms occur in pairs, with the members of a pair having opposite meanings.

anterior–posterior	proximal–distal
superior–inferior	external–internal
medial–lateral	parietal–visceral
central–peripheral	

1.4 Body Regions

- The body is divided into two major portions: the axial portion and the appendicular portion.
- The axial portion is subdivided into the head, neck, and trunk.
- The head and neck contain cervical, cranial, and facial regions. The cranial and facial regions combine to form the cephalic region.
- The facial region consists of orbital, nasal, oral, and buccal regions.
- The trunk consists of anterior, posterior, lateral, and inferior regions.
- Anterior trunk regions include the abdominal, inguinal, pectoral, pelvic, and sternal regions. The abdominal and pelvic regions combine to form the abdominopelvic region.
- Posterior trunk regions include the dorsal, gluteal, lumbar, sacral, and vertebral regions.
- Lateral trunk regions are the axillary and coxal regions.
- Inferior trunk regions are the genital and perineal regions.
- The appendicular portion of the body consists of the upper and lower limbs.
- The upper limb is attached to the trunk at the shoulder. Regions of the upper limb are the antebrachial, antecubital, brachial, carpus, digital, olecranal, and palmar regions.
- The lower limb is attached to the trunk at the hip. Regions of the lower limb are the crural, digital, femoral, patellar, pedal, plantar, popliteal, sural, and tarsal regions.

1.5 Body Planes and Sections

- Well-defined planes are used to guide sectioning of the body or organs.
- The common planes are transverse, sagittal, and frontal.
- The common planes produce longitudinal sections and cross sections of the body.

1.6 Body Cavities

- There are two major body cavities: dorsal and ventral.
- The dorsal cavity consists of the cranial cavity and vertebral canal.
- The ventral cavity consists of the thoracic and abdominopelvic cavities.
- The thoracic cavity lies superior to the diaphragm. It consists of two lateral pleural cavities and the mediastinum, which contains the pericardial cavity.
- The abdominopelvic cavity lies inferior to the diaphragm. It consists of a superior abdominal cavity and an inferior pelvic cavity.
- The body cavities are lined with protective and supportive membranes.
- The meninges consist of three membranes that line the dorsal cavity and enclose the brain and spinal cord.
- The parietal pleurae line the internal walls of the rib cage, while the visceral pleurae cover the external surfaces of the lungs.
- The pleural cavity is the potential space between the parietal and visceral pleurae.
- The parietal pericardium is a saclike membrane in the mediastinum that surrounds the heart. The visceral pericardium is attached to the surface of the heart.
- The pericardial cavity is the potential space between the parietal and visceral pericardia.
- The parietal peritoneum lines the walls of the abdominal cavity but does not extend into the pelvic cavity. The visceral peritoneum covers the surface of abdominal organs.
- The peritoneal cavity is the potential space between the parietal and visceral peritoneal membranes.
- The mesenteries are double-layered folds of the visceral peritoneum that support internal organs.
- Kidneys, pancreas, and parts of the intestines are located posterior to the parietal peritoneum in the retroperitoneal space.

1.7 Abdominopelvic Subdivisions

- The abdominopelvic cavity is subdivided into either four quadrants or nine regions as an aid in locating organs.
- The four quadrants are
  right upper — left upper
  right lower — left lower
- The nine regions are
  epigastric — right flank
  left hypochondriac — hypogastric (pubic)
  right hypochondriac — left inguinal
  umbilical — right inguinal
  left flank

1.8 Maintenance of Life

- Metabolism is the sum of all of the body's chemical reactions. It consists of anabolism, the synthesis of body chemicals, and catabolism, the breakdown of body chemicals.
- The basic needs of the body are food, water, oxygen, body temperature, and atmospheric pressure.
- Homeostasis is the maintenance of a relatively stable internal environment.
- Homeostasis is regulated by negative-feedback mechanisms.
- Negative-feedback mechanisms consist of three components: receptors, integrating center, and effectors.
- Positive-feedback mechanisms promote an ever-increasing change from the norm.

Self-Review

Answers are located in Appendix B.

1. A study of body functions is called _____.
2. Blood, the heart, and blood vessels compose the _____ system.
3. Rapid coordination of body functions is the function of the _____ system.
4. The fingers are located _____ to the wrist.
5. The upper and lower limbs compose the _____ portion of the body.
6. The posterior surface of the knee is known as the _____ region.
7. The thigh is known as the _____ region.
8. The _____ body cavity is divided into the cranial cavity and _____ canal.
9. The gallbladder is located in the _____ quadrant and the _____ region.
10. The _____ separates the left and right portions of the thoracic cavity.
11. The abdominal cavity is lined by the _____.
12. The maintenance of a relatively stable internal environment is called _____.

Critical Thinking

1. A hypoglycemic (low blood glucose level) patient is given orange juice to drink. Explain how this increases blood glucose level and the organ systems involved.
2. Describe the location of the kneecap in as many ways as you can using directional terms.
3. Describe where serous membranes are located in the body, name the three types of serous fluid, and explain the function of serous fluid.
4. Explain how negative-feedback mechanisms regulate homeostasis.

COLORPLATES OF THE HUMAN BODY

The five colorplates that follow show the basic structure of the human body. The first plate shows the anterior body surface and the superficial anterior muscles of a female. Succeeding plates show the internal structure as revealed by progressively deeper dissections.

Refer to these plates often as you study this text in order to become familiar with the relative locations of the body organs. ■

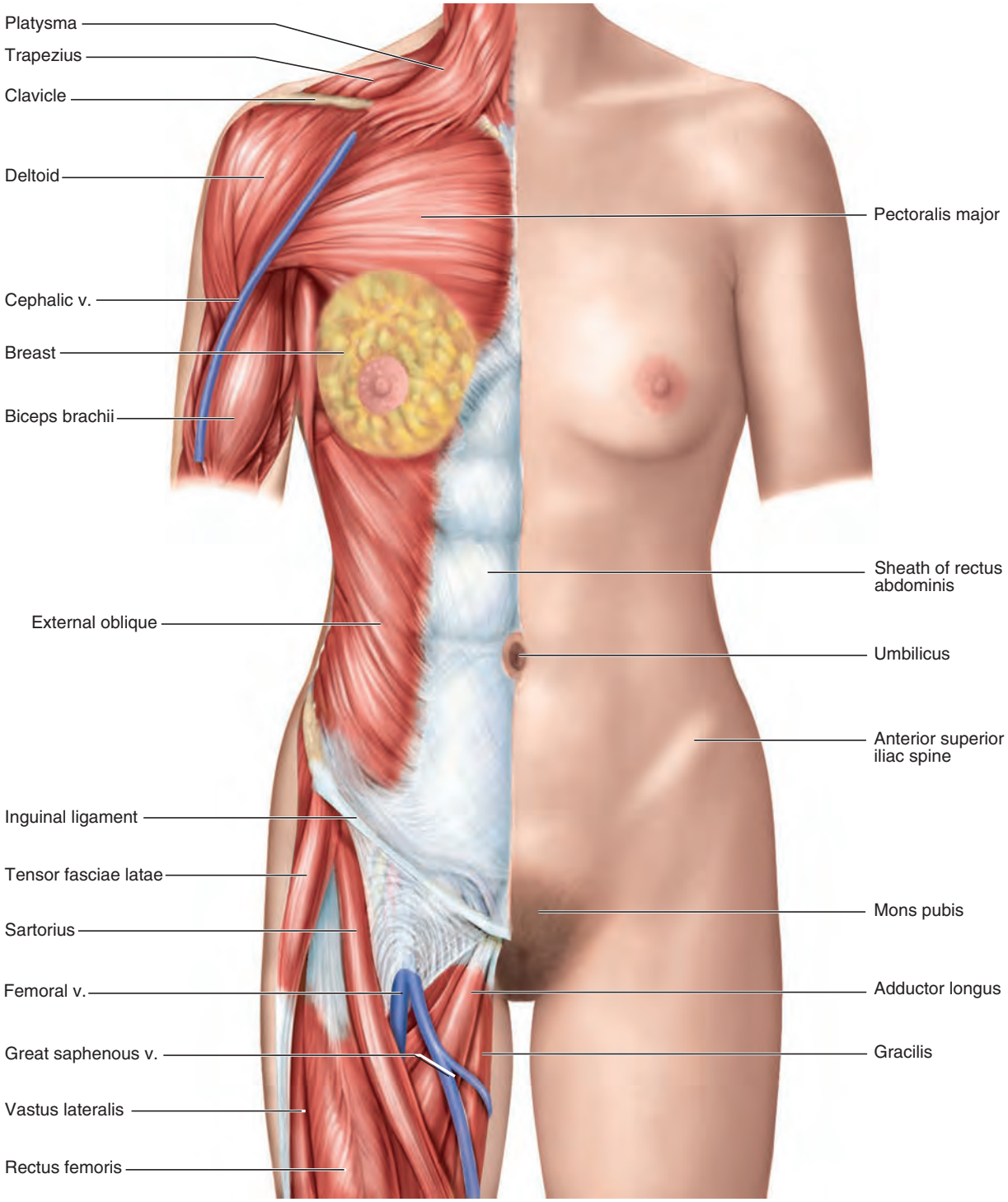


Plate 1 Superficial Anatomy of the Trunk (Female).
Surface anatomy is shown on the anatomical left, and structures immediately deep to the skin on the right (v. = vein).

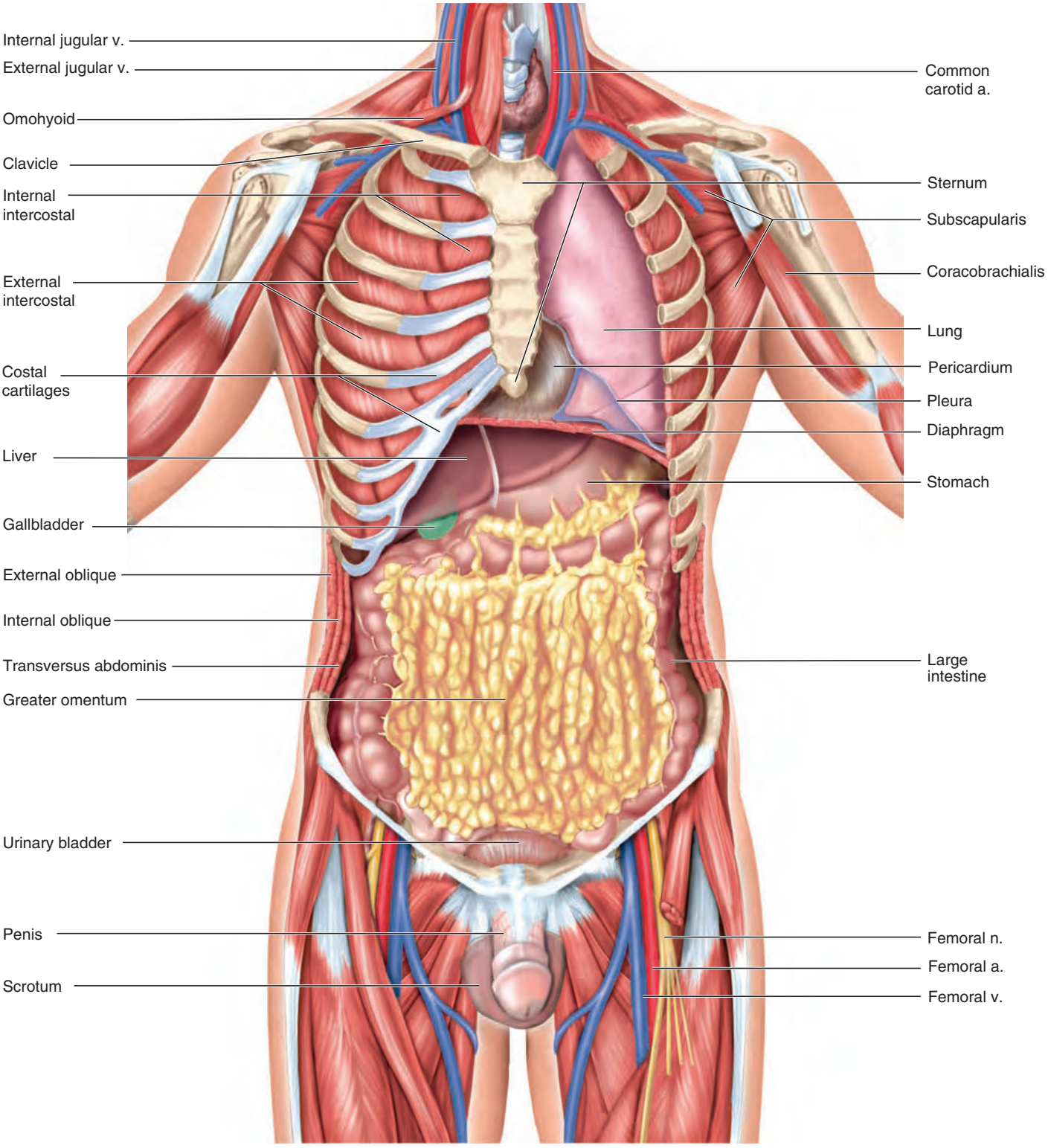


Plate 2 Anatomy at the Level of the Rib Cage and Greater Omentum (Male).
The anterior body wall is removed, and the ribs, intercostal muscles, and pleurae are removed from the anatomical left (a. = artery; v. = vein; n. = nerve).

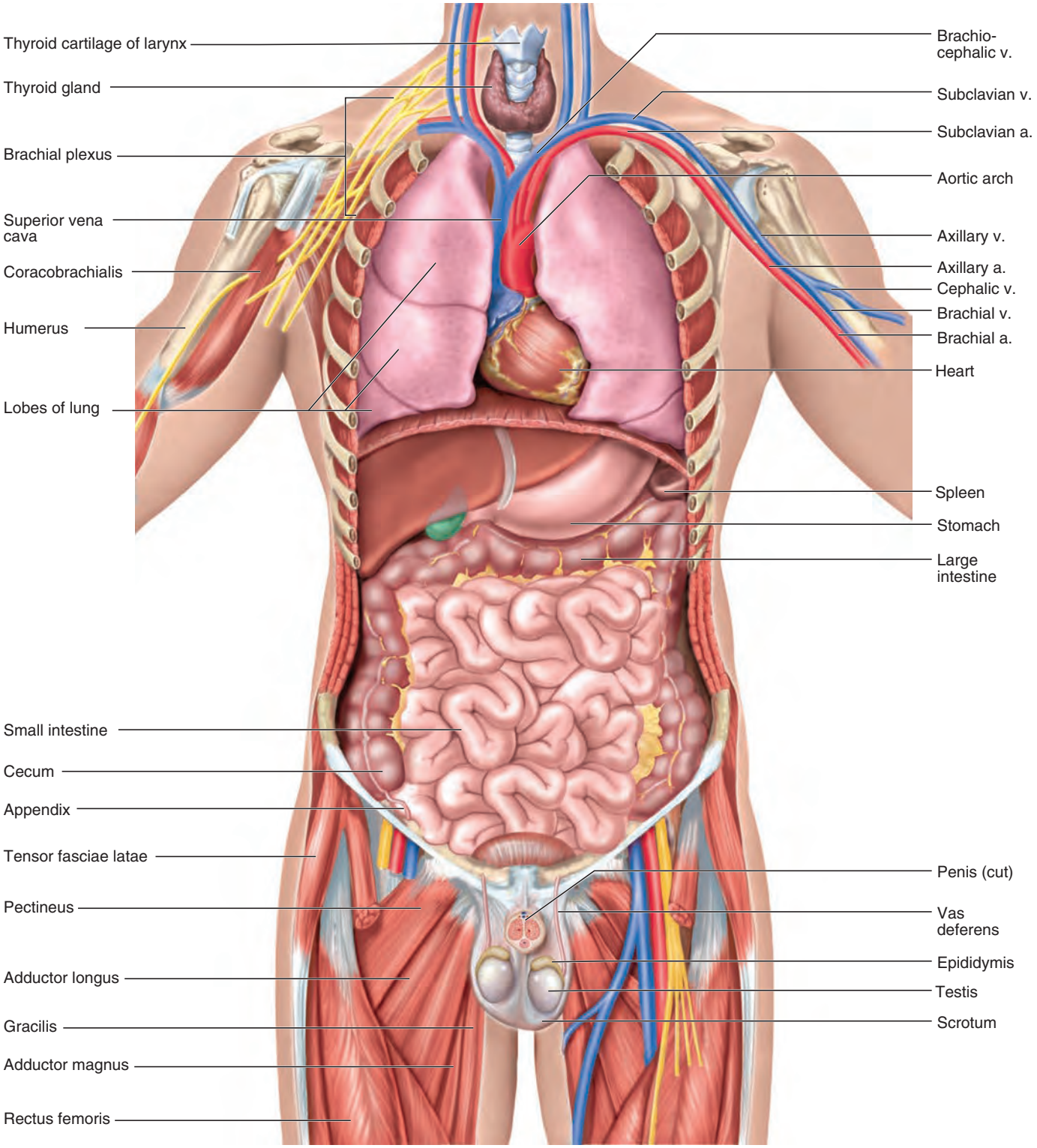


Plate 3 Anatomy at the Level of the Lungs and Intestines (Male).
The sternum, ribs, and greater omentum are removed (a. = artery; v. = vein).

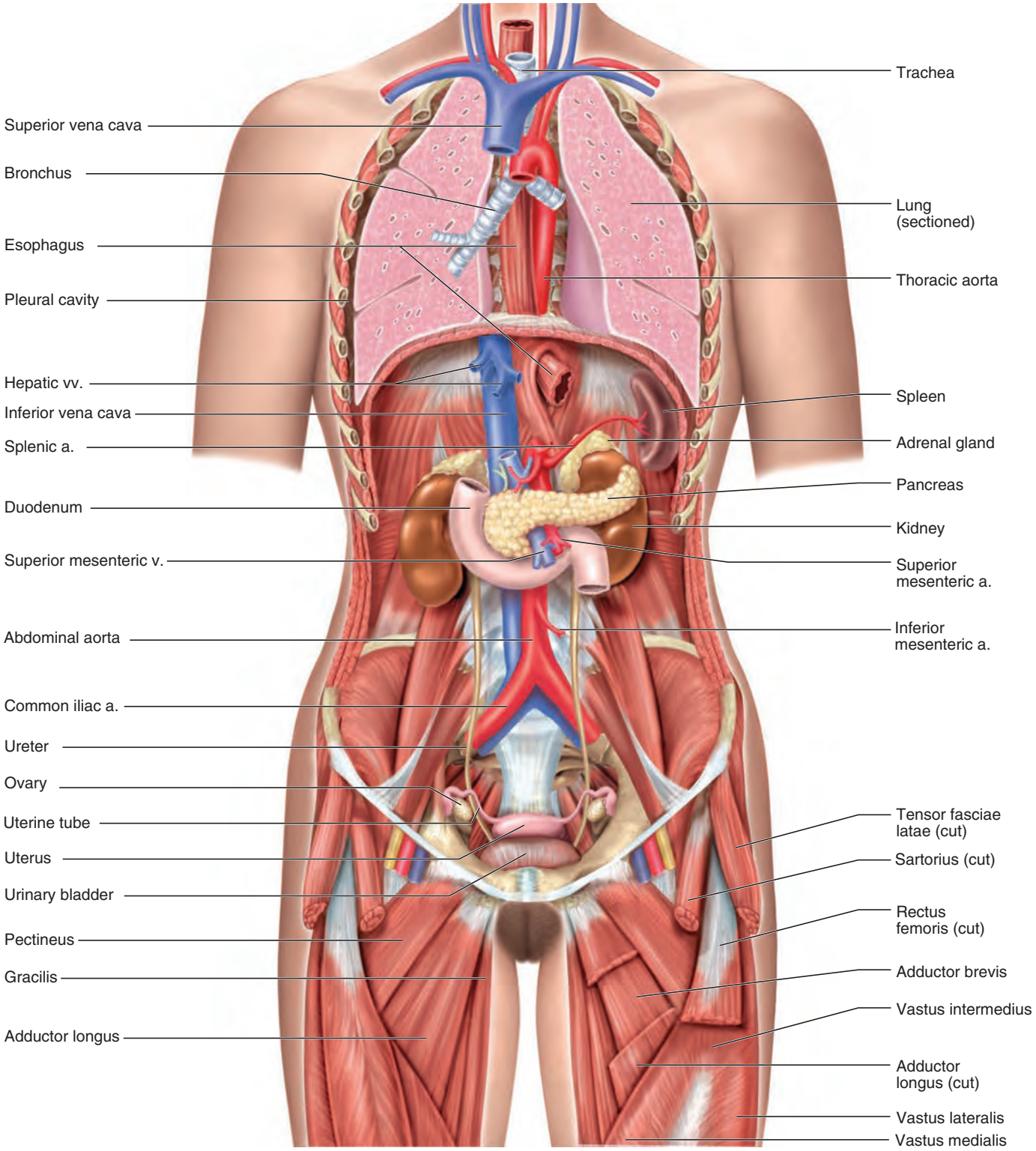


Plate 4 Anatomy at the Level of the Retroperitoneal Viscera (Female).
The heart is removed, the lungs are frontally sectioned, and the viscera of the peritoneal cavity and the peritoneum itself are removed (a. = artery; v. = vein; vv. = veins).

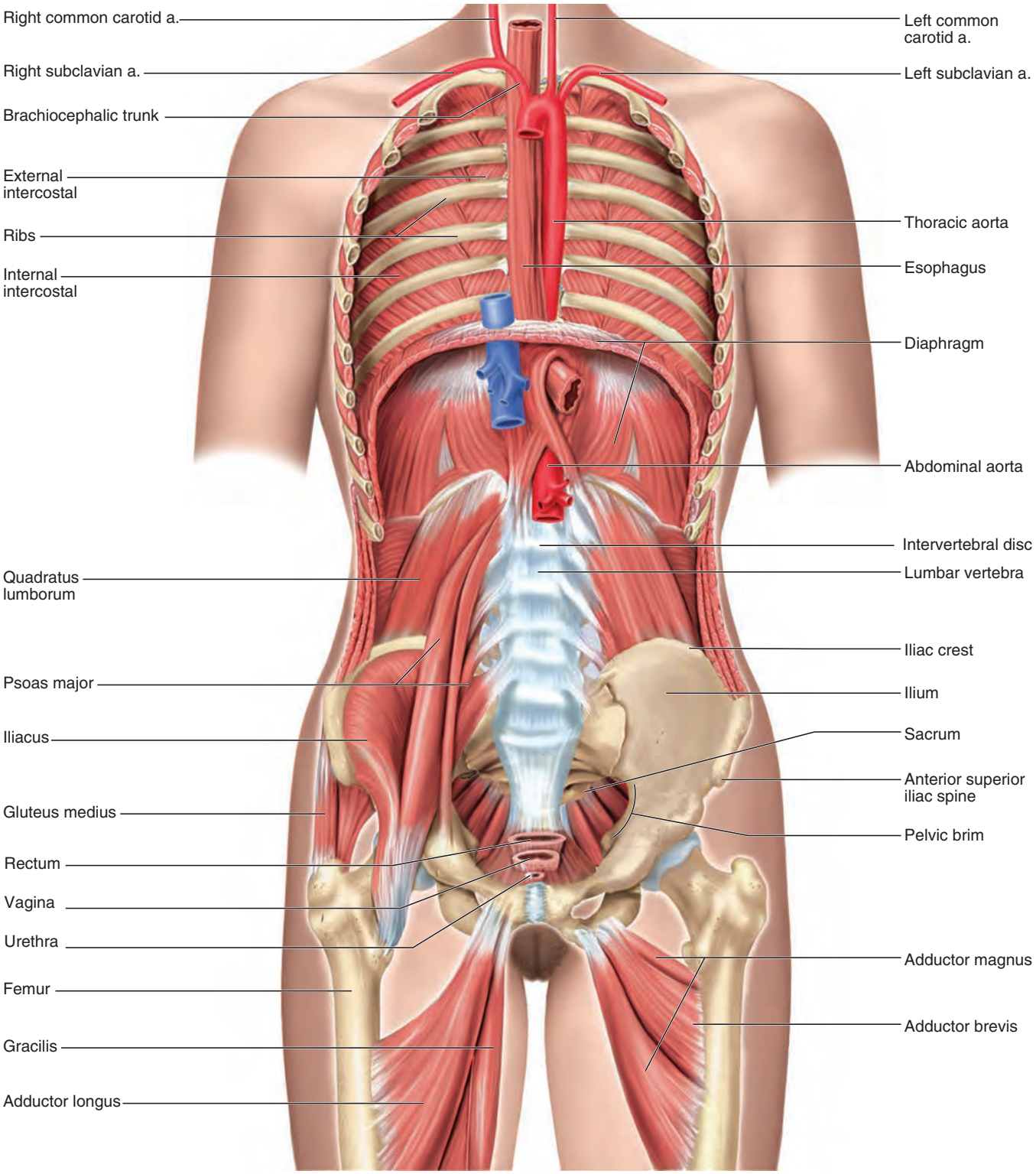


Plate 5 Anatomy at the Level of the Posterior Body Wall (Female).
The lungs and retroperitoneal viscera are removed (a. = artery).

2
CHAPTER

Cell

As a living structure, a cell possesses numerous organelles that carry out the chemical processes necessary to maintain homeostasis. Learning the relationships between organelle structure and function can be quite challenging for students owing to their microscopic nature and the complexity of the chemical processes involved. So for a moment, imagine that you are a cell, a small living unit within the body. Every day, numerous challenges must be overcome to survive but, within you, there are structures that do just that. For example, if you need to obtain nutrients or remove wastes, you have an outer boundary that controls the movement of chemicals. If energy is needed to carry out a chemical process, you have structures that make the energy in your nutrients accessible. In order to respond to changes in your surroundings, you have the ability to communicate with other cells by detecting or producing chemical and electrical signals. By making cellular structures and functions relate to you and your real-world experiences, you will create a way to better "visualize" and understand the microscopic world within your body.

CHAPTER OUTLINE

SELECTED KEY TERMS

Active transport Movement of substances across a plasma membrane, requiring the expenditure of energy by the cell.
Cell (cella = room, cell) The simplest structural and functional living unit of organisms.
Cellular respiration Breakdown of organic nutrients in cells, to release energy and form ATP.
Centrioles (centr = center) Paired cylindrical organelles that form the spindle during cell division.
Chromosome (chrom = color; soma = body) A threadlike or rodlike structure in the nucleus that is composed of DNA and protein.
Cytoplasm (cyt = cell; plasma = molded) The semifluid substance located between the nucleus and the plasma membrane.
Cytosol (sol = soluble) The gel-like fluid of the cytoplasm.
Diffusion Passive movement of substances from an area of higher concentration to an area of lower concentration.
Endocytosis (end = inside; cyt = cell; sis = condition) The process by which a cell engulfs substances by invagination of the plasma membrane.
Exocytosis (exo = outside) The process by which a cell releases substances by fusion of a vesicle with the plasma membrane.
Mitosis (mit = thread; sis = condition) Separation and distribution of chromosomes to daughter cells during mitotic cell division.
Nucleus (nucle = kernel) Spherical organelle containing chromosomes and controlling cellular functions.
Organelle (elle = little) A specific structure within a cell that performs a specific function.
Osmosis The passive movement of water across a selectively permeable membrane.
Passive transport Movement of substances across a plasma membrane without expenditure of energy by the cell.
Plasma membrane Outer boundary of a cell.
Selectively permeable membrane A membrane that allows some, but not all, substances to pass across it.

THE HUMAN BODY is composed of about 75 trillion **cells,** the smallest living units that exist. Body cells can be classified into about 300 types, such as neurons, epithelial cells, muscle cells, and red blood cells. Each type of cell has a unique structure for performing specific functions. Although these cells vary in size, shape, and function, they exhibit many structural and functional similarities.

Human cells are very small and are visible only with a microscope. Knowledge of cell structure is based largely on the examination of cells with an electron microscope, a type of microscope that provides magnifications up to 200,000× or more.

3.1 Cell Structure

Learning Objective

1. Describe the structure and function(s) of each part of a generalized cell.

Although human cells are small, they are amazingly complex with many specialized parts. The composite cell in figure 3.1 illustrates the major structures known to compose human cells. These structures are shown as they appear in electron microscope images. Most, but not all, of these structures are found in each human cell. The three common parts found in all the cells are the plasma membrane, cytoplasm, and nucleus. The other structures may or may not be present, depending on cell type. As each part of a cell is discussed, note its structure and relationship to other structures in figure 3.1.

The Plasma Membrane

The **plasma membrane** forms the outer boundary of a cell. It maintains the integrity of the cell and separates the intracellular fluid from the extracellular fluid surrounding the cell. The plasma membrane consists of two layers of phospholipid molecules, aligned back-to-back, with their fatty acid tails forming the internal layer of the membrane and their polar heads facing the extracellular and intracellular fluids (figure 3.2). Cholesterol molecules are scattered among the phospholipids, where they serve to increase the stability of the plasma membrane. The fatty acid tails of the plasma membrane allow lipid-soluble substances to pass across the membrane but prevent the passage of water-soluble substances. Thus, the plasma membrane serves as a barrier between water-soluble substances in the intracellular and extracellular fluids.

Many different types of protein molecules are embedded in the plasma membrane, and each type has specific functions. Some proteins form channels or pores through which water and water-soluble substances move across the membrane. Some of these proteins allow a variety of substances to pass across; others permit only specific molecules or ions to enter or exit a cell. Some proteins serve as receptors for substances, such as hormones,

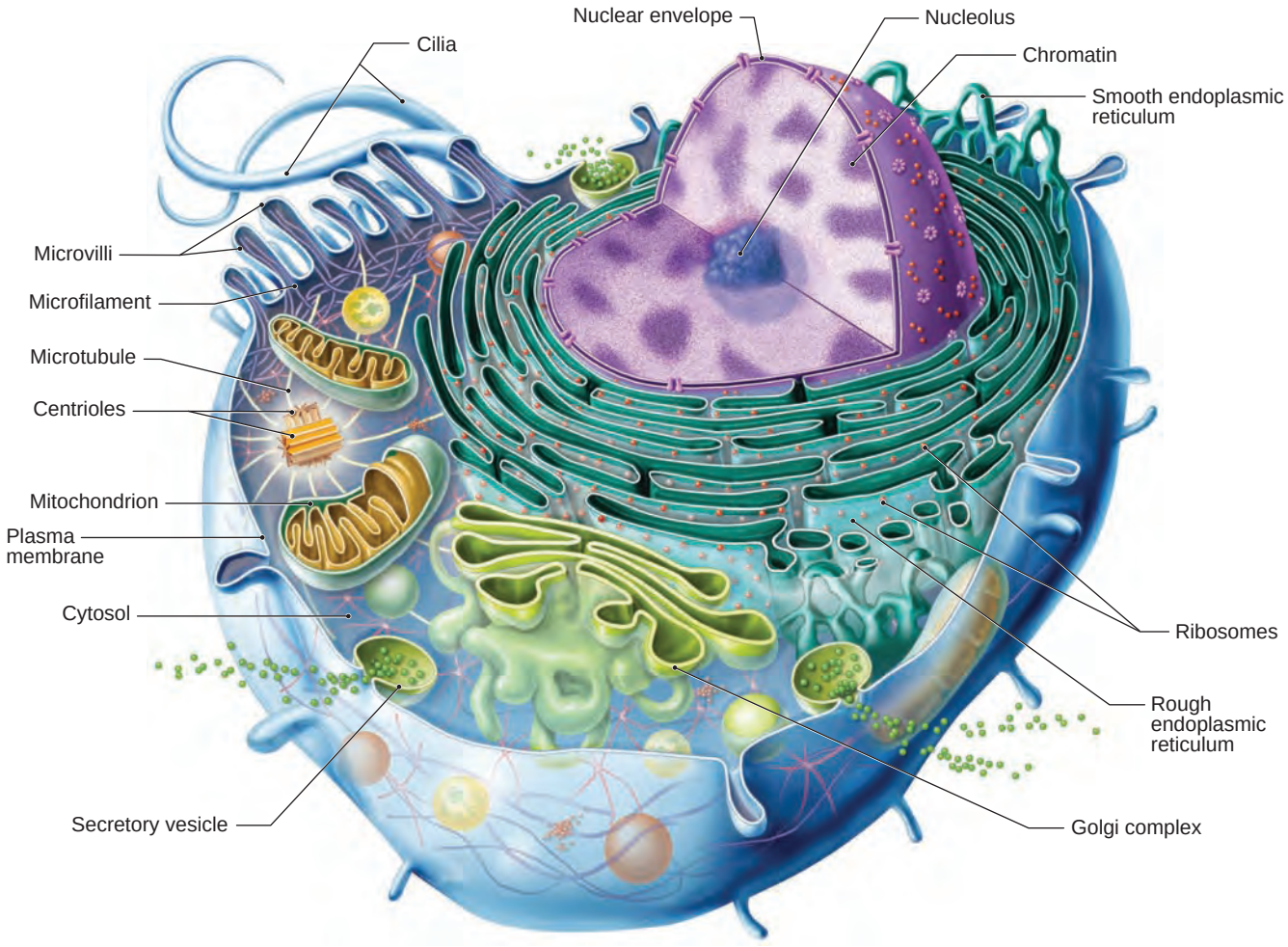


Figure 3.1 A composite human cell showing the major organelles. No cell contains all of the organelles shown.

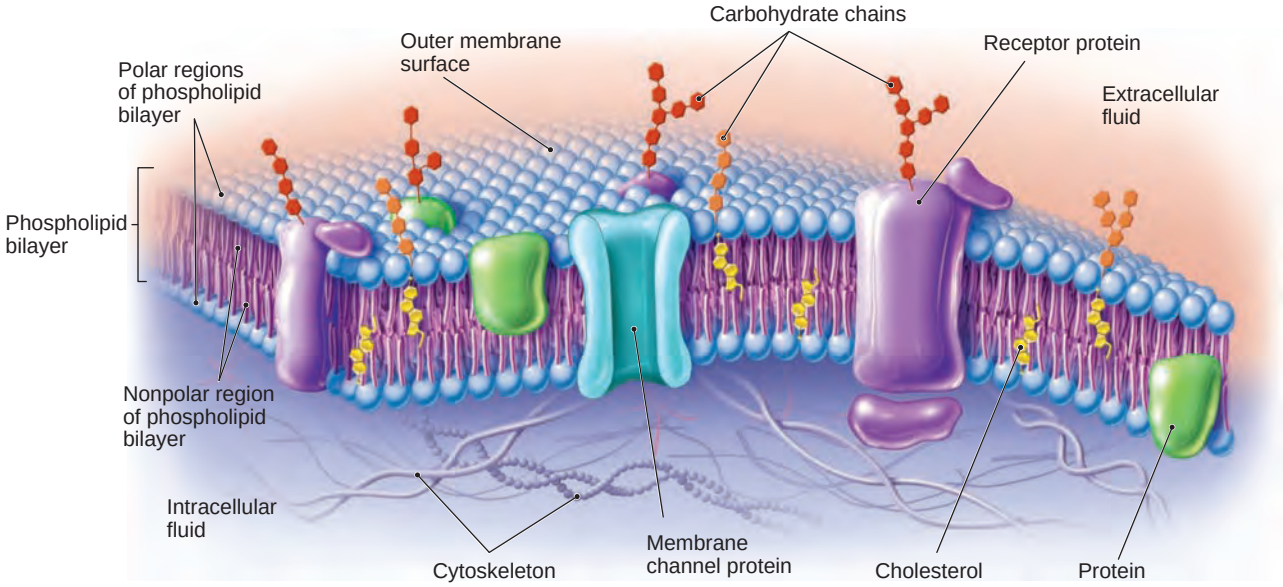


Figure 3.2 The plasma membrane is composed of two layers of phospholipid molecules with scattered embedded protein and cholesterol molecules. The hydrophilic heads of the phospholipids face the extracellular and intracellular fluids, and the hydrophobic tails form the internal layer of the membrane.

that influence the function of a cell. Other proteins are enzymes that catalyze metabolic reactions. Certain proteins, in combination with carbohydrate molecules, serve as identification markers allowing cells to recognize each other. These identification markers allow the lymphoid system to recognize "self" cells from "nonself" (foreign) cells, a distinction essential in fighting pathogens.

All materials that enter or exit a cell must pass across the plasma membrane. The plasma membrane is a **selectively permeable membrane** because it allows only certain substances to enter or exit the cell. Whether or not a substance can pass across the membrane is determined by a number of factors that include the substance's size, solubility, electrical charges, and attachment to carrier proteins (discussed later in the chapter).

Cytoplasm

The interior of a cell between the plasma membrane and the nucleus is filled with a semifluid material called **cytoplasm** (sī′-tō-plasm). It is composed of a gel-like fluid called **cytosol,** which is 75–90% of water and contains organic and inorganic substances, and small subcellular structures known as organelles.

Organelles

A variety of **organelles** (or-gah-nel′z), or little organs, are surrounded by cytosol. Organelles are distinguished by size, shape, structure, and specific function. Table 3.1 summarizes the structure and functions of the major parts of a cell.

Nucleus

The largest organelle is the **nucleus** (nū′klē-us), a spherical or egg-shaped structure that is slightly more dense than the surrounding cytoplasm. It is separated from the cytoplasm by a double-layered **nuclear envelope** containing numerous pores that allow the movement of materials between the nucleus and cytoplasm.

Table 3.1 Summary of Cell Parts

Component	Structure	Function
Plasma membrane	Phospholipid bilayer with proteins and cholesterol molecules embedded in it	Selectively controls movement of materials into and out of the cell; maintains integrity of the cell; has receptors for hormones
Cytosol	Gel-like fluid surrounding organelles	Site of numerous chemical reactions
Organelles		
Nucleus	Largest organelle; contains chromosomes and nucleoli	Controls cellular functions
Endoplasmic reticulum (ER)	System of membranes extending through the cytoplasm; RER has ribosomes on the membrane; SER does not	Serves as sites of chemical reactions; channels for material transport within cell
Ribosomes	Tiny granules of rRNA and protein either associated with RER or free in cytoplasm	Sites of protein synthesis
Golgi complex	Series of stacked membranes near nucleus; associated with ER	Sorts and packages substances in vesicles for export from cell or use within cell; forms lysosomes
Mitochondria	Contain a folded internal membrane within a smaller external membrane	Sites of aerobic respiration that form ATP from breakdown of nutrients
Lysosomes	Small vesicles containing strong digestive enzymes	Digest foreign substances or worn-out parts of cells
Microfilaments	Thin rods of protein dispersed in cytoplasm	Provide support for cell; contraction causes cell movement
Microtubules	Thin tubules dispersed in cytoplasm	Provide support for cell, cilia, and flagella; form spindle during cell division
Microvilli	Numerous, tiny extensions of the plasma membrane on certain cells	Increase the surface area, which aids absorption
Centrioles	Two short cylinders formed of microtubules; located near nucleus	Form spindle fibers during cell division
Cilia	Numerous short, hairlike projections from certain cells	Move materials along the free surface of cells
Flagella	Long, whiplike projections from sperm	Enable movement of sperm
Vesicles	Tiny membranous sacs containing substances	Transport or store substances

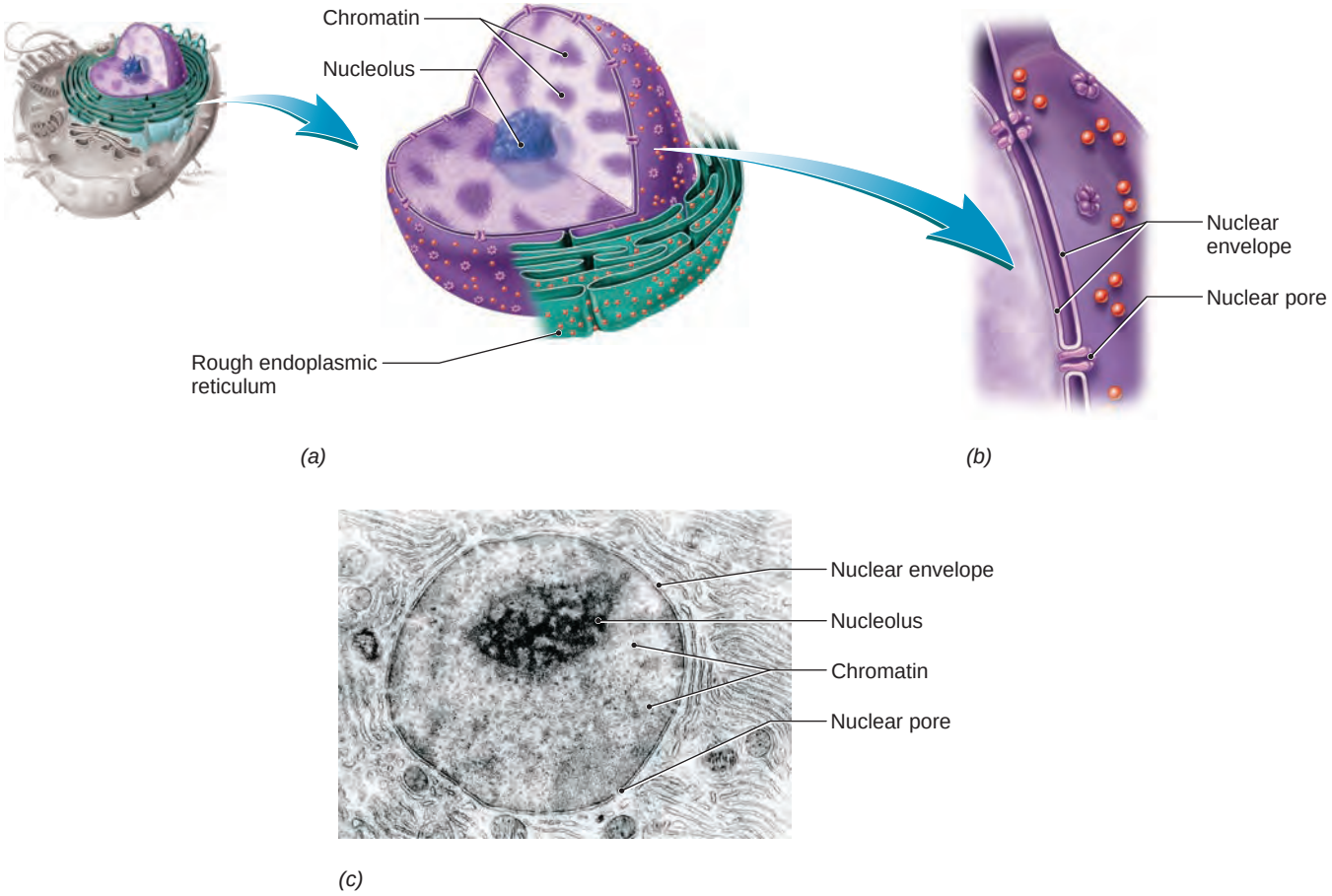


Figure 3.3 *(a)* The nuclear envelope is selectively permeable and allows certain substances to pass. *(b)* Details of the nuclear envelope. *(c)* Transmission electron photomicrograph of a cell nucleus (8,000×).

Chromosomes (krō′-mō-sōms), the most important structures within the nucleus, consist of DNA and proteins. The DNA of chromosomes contains coded instructions, called genes, that determine the functions of the cell (see chapter 18 for the details). When a cell is not dividing, chromosomes are extended to form thin threads that appear as *chromatin* (krō′-mah-tin) *granules* when viewed microscopically, as in figure 3.3. During cell division, the chromosomes coil, shorten, and become rod-shaped (see figure 3.19). Each human body cell contains 23 pairs of chromosomes, with a total of 46 in all.

One or more dense spherical bodies, called the **nucleolus** (nū-klē-ō-lus) or **nucleoli** (nū-klē-ō-lē), are also present in the nucleus. A nucleolus consists of RNA and protein and is the site of ribosome production.

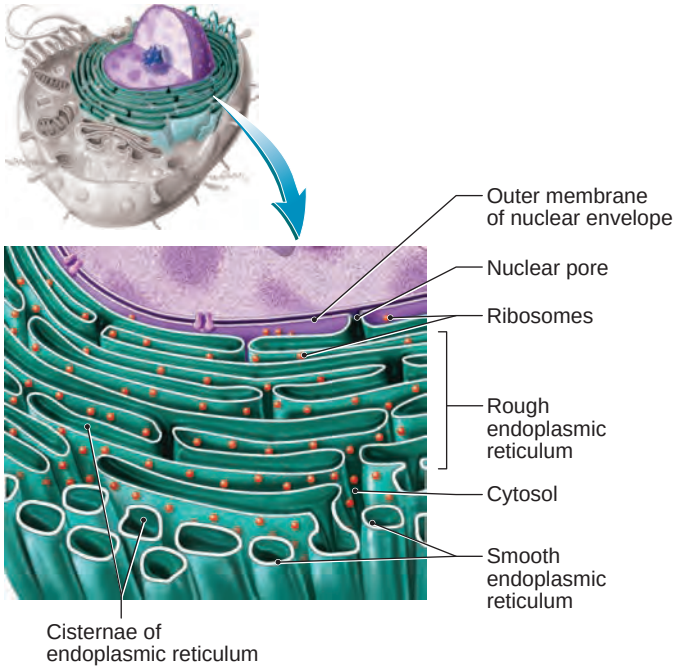
Ribosomes

Ribosomes are tiny organelles that appear as granules within the cytoplasm even in electron photomicrographs. They are composed of ribosomal RNA (rRNA) and proteins, which are preformed in a nucleolus before migrating from the nucleus into the cytoplasm. Ribosomes are the sites of protein synthesis in cells. They may occur singly or in small clusters and are located either on the endoplasmic reticulum (figure 3.4) or as free ribosomes in the cytoplasm.

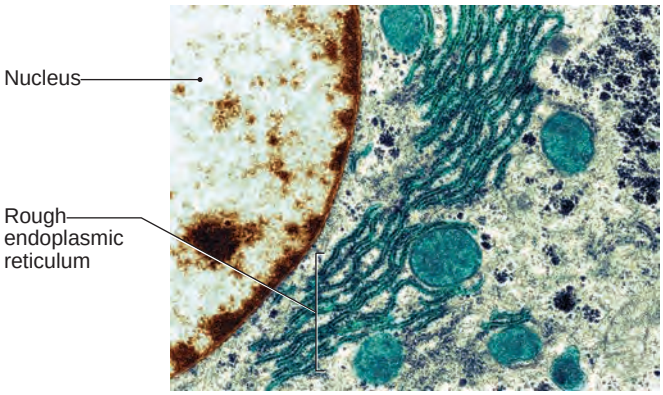
Endoplasmic Reticulum

The numerous membranes that extend from the nucleus throughout the cytoplasm are collectively called the **endoplasmic reticulum** (en″-dō-plas′-mik rē-tik′-ū-lum), or **ER** for short. These membranes provide some support for the cytoplasm and form a network of channels that facilitate the movement of materials within the cell.

There are two types of ER: rough ER and smooth ER. *Rough endoplasmic reticulum (RER)* is characterized by the presence of numerous ribosomes located on the outer surface of the membranes. *Smooth endoplasmic reticulum (SER)* lacks ribosomes and serves as a site for the synthesis of lipids (see figure 3.4).

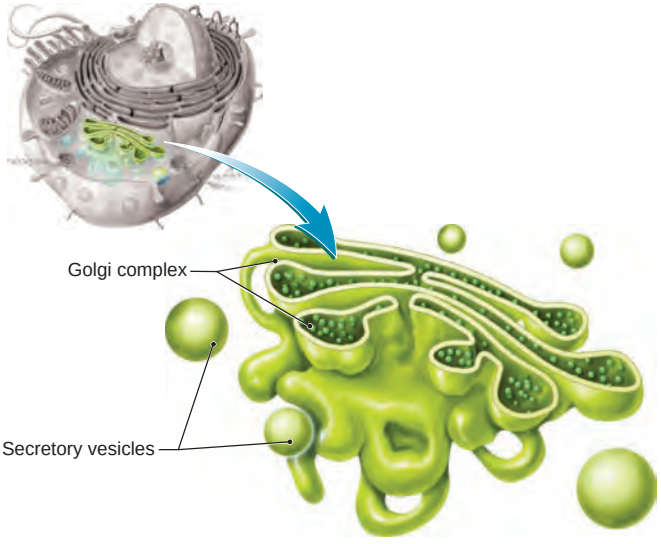


(a)



(b)

Figure 3.4 *(a)* Rough ER is dotted with ribosomes, and smooth ER lacks ribosomes. *(b)* Transmission electron photomicrograph of ER (100,000×).



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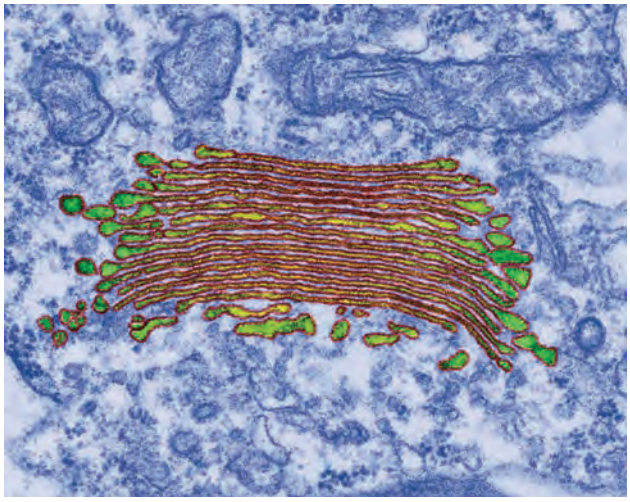


(b)

Figure 3.5 *(a)* The Golgi complex packages substances in vesicles that move within the cell or to the plasma membrane to release the substances outside the cell. *(b)* Transmission electron photomicrograph of Golgi complex (100,000×).

Golgi Complex

This organelle appears as a stack of flattened membranous sacs that are usually located near the nucleus and in close association with the nucleus and ER. The **Golgi** (Gol′-jē) **complex** processes and sorts synthesized substances, such as proteins, into vesicles. **Vesicles,** or "little bladders," are tiny membranous sacs that carry substances from place to place within a cell. *Secretory vesicles* transport substances to the plasma membrane and release them outside the cell (figure 3.5).

Mitochondria

The **mitochondria** (mī″-to-kon′-drē-ah, singular, *mitochondrion*) are relatively large organelles that are characterized by having a folded *internal membrane* surrounded by a smooth *external membrane*. The internal membrane folds, called *cristae* (singular, crista), possess the enzymes involved in aerobic respiration.

The release of energy from nutrients and the formation of ATP by aerobic respiration occur within mitochondria. For this reason, mitochondria are sometimes

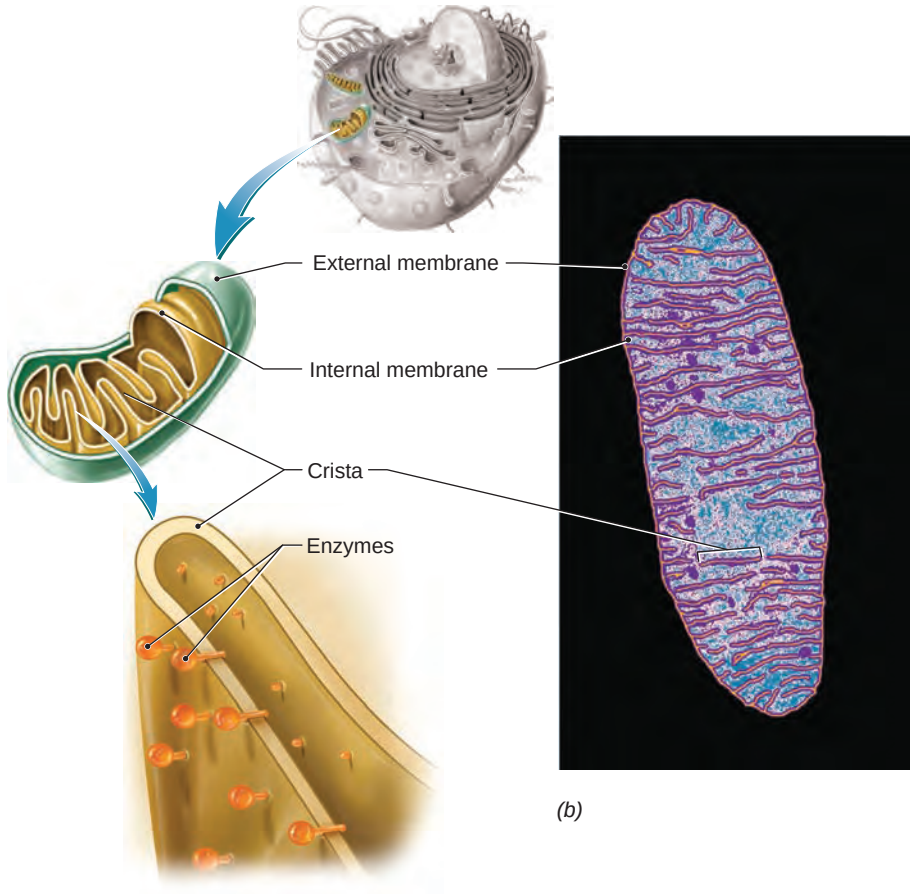


Figure 3.6 *(a)* A mitochondrion and its internal membrane. *(b)* Transmission electron photomicrograph of a mitochondrion (40,000×).

called the "powerhouses" of the cell. Mitochondria can replicate themselves if the need for additional ATP production increases (figure 3.6).

In addition to the nucleus, mitochondria also contain a small amount of DNA, known as mitochondrial DNA. The genes carried by this DNA account for less than 0.2% of the total genes in the human body, and are responsible only for the functions of the mitochondria. Mitochondrial DNA cannot be used to establish paternity as with nuclear DNA, because only maternal mitochondrial DNA is passed on to offspring.

Lysosomes

Lysosomes (lī′-sō-sōms) are formed by the Golgi complex. They are small vesicles that contain powerful digestive enzymes (see figure 3.1). These enzymes are used to digest (1) bacteria that may have entered the cell, (2) cell parts that need replacement, and (3) entire cells that have become damaged or worn out. Thus, they play an important role in cleaning up the cellular environment. (figure 3.7*a*).

The Cytoskeleton

Microtubules and microfilaments compose the cytoskeleton. **Microtubules** are long, thin protein tubules that provide support for the cell and are involved in the movement of organelles. The thinner **microfilaments** are tiny rods of contractile protein that not only support the cell but also play a role in cell movement and cell division. (figure 3.7).

Centrioles

The **centrioles** (sen′-trē-olz) are two short cylinders that are located near the nucleus and are oriented at right angles to each other. Nine triplets of microtubules are arranged in a circular pattern to form the wall of each cylinder (see figure 3.1). Centrioles form and organize the *spindle fibers* during cell division (see figure 3.19), and they are involved in the formation of microtubules found in cilia and flagella.

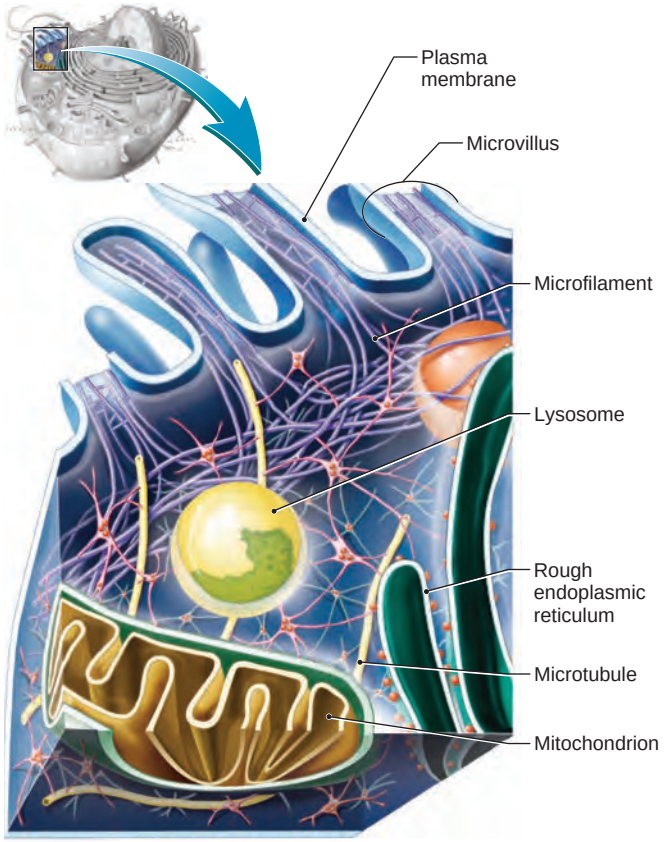
Cilia, Flagella, and Microvilli

Cilia and flagella (singular, flagellum) are small, hairlike projections from cells that are capable of wavelike movement. **Cilia** (sil′-ē-ah) are numerous, short, hairlike projections from cells that, in humans, are used to move substances along the free cell surfaces in areas such as the respiratory and reproductive tracts (figure 3.8). **Flagella** (flah-jel′-ah) are long, whiplike projections from cells. In humans, only sperm possess flagella, and each sperm has a single flagellum that enables movement. Both cilia and flagella contain microtubules that originate from centrioles positioned at the base of these flexible structures.

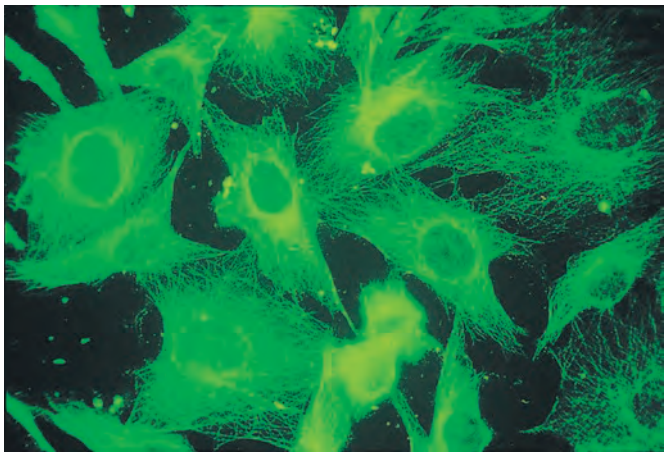
Microvilli are extensions of the plasma membrane that are smaller and more numerous than cilia. They do not move like cilia or flagella, but they increase the surface area of the plasma membrane and, therefore, aid absorption of substances. Microvilli are abundant on the free surface of the cells lining the intestines (see figure 3.7*a*).

Check My Understanding

1. What are the distinguishing features and functions of a mitochondrion, a nucleus, the Golgi complex, and rough endoplasmic reticulum?
2. What organelles enable cell movement or movement of substances along the free surface of the cells?

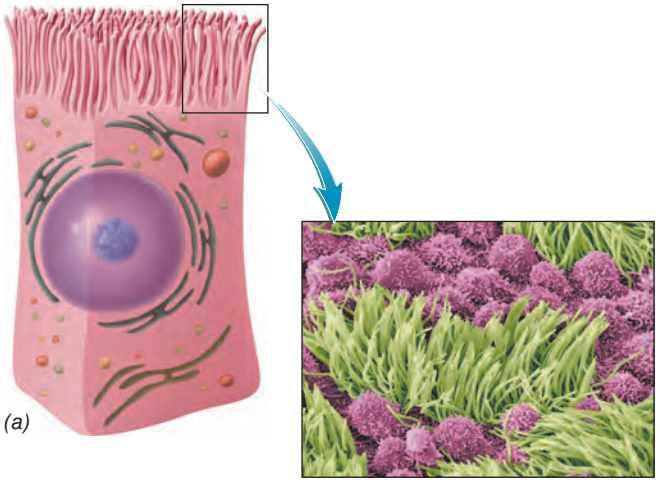


(a)

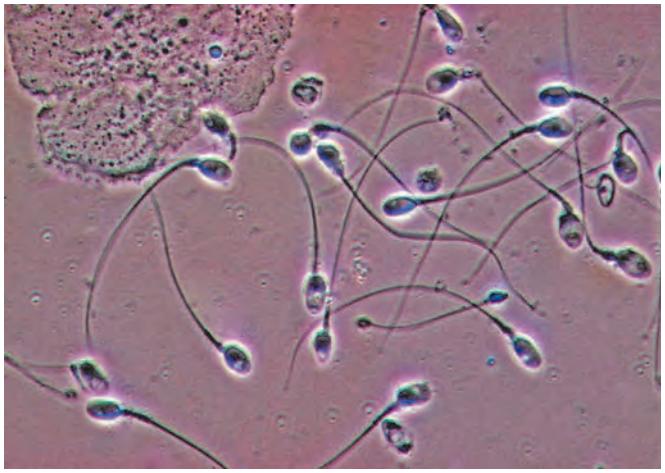


(b)

Figure 3.7 *(a)* Microtubules and microfilaments. *(b)* A false-color electron photomicrograph (750×) shows the microtubules and microfilaments of the cytoskeleton in green.



(a) (b)



(c)

Figure 3.8 *(a)* Cilia are located on the free surface of certain cells. Because these cells are stationary, beating cilia move substances along the free surface of the cells. *(b)* An electron photomicrograph of cilia (10,000×). *(c)* A light photomicrograph of human sperm (1,000×).

3.2 Transport Across Plasma Membranes

Learning Objectives

2. Compare the mechanisms of passive and active transport of substances across the plasma membrane.
3. Describe osmosis and tonicity, and the effect of tonicity on the cells.

A cell maintains its homeostasis primarily by controlling the movement of substances across the selectively permeable plasma membrane. Some substances pass across the plasma membrane by **passive transport,** which requires

no expenditure of ATP by the cell. Other substances move across the plasma membrane by **active transport,** which requires the cell to expend ATP.

Passive Transport

There are three major types of passive transport: diffusion, osmosis, and filtration. Filtration is described in chapters 12 and 16.

Diffusion

Diffusion (di-fū′-zhun) is the net movement of substances from an area of higher concentration to an area of lower concentration. Thus, the movement of substances is along a **concentration gradient,** the difference between the concentration of the specific substances in the two areas.

Diffusion occurs in both gases and liquids and results from the constant, random motion of substances. Diffusion is not a living process; it occurs in both living and nonliving systems. For example, if a pellet of a water-soluble dye is placed in a beaker of water, the dye molecules will slowly diffuse from the pellet (the area of higher concentration) throughout the water (the area of lower concentration) until the dye molecules are equally distributed, that is, at equilibrium (figure 3.9). In a similar way, the molecules of cologne, on the skin of a student sitting in the corner of a classroom, will spread throughout the room.

Lipid-soluble molecules, such as lipids, oxygen, carbon dioxide, and lipid-soluble vitamins, are able to diffuse across a plasma membrane along concentration gradients because they can dissolve in the phospholipid molecules of the plasma membrane. This type of diffusion is called **simple diffusion** (figure 3.10*a*) because it does not require the help of the membrane proteins. For example,

Figure 3.9 An example of diffusion. As a drop of ink gradually dissolves in a beaker of water, the ink molecules diffuse from the region of their higher concentration to a region of their lower concentration.

the exchange of respiratory gases occurs by simple diffusion. Air in the lungs has a greater concentration of oxygen and a lower concentration of carbon dioxide than the blood does (figure 3.10*a*). Therefore, oxygen diffuses from air in the lungs into the blood, and carbon dioxide diffuses from the blood into the air in the lungs.

Water-soluble molecules, such as glucose, amino acids, water-soluble vitamins, and ions, cannot be transported by simple diffusion because they cannot dissolve in the phospholipids. Some water-soluble substances are transported through channel proteins. **Channel proteins** are tunnel-shaped membrane proteins that create pores or openings, which allow for specific substances to pass across the plasma membrane along their concentration

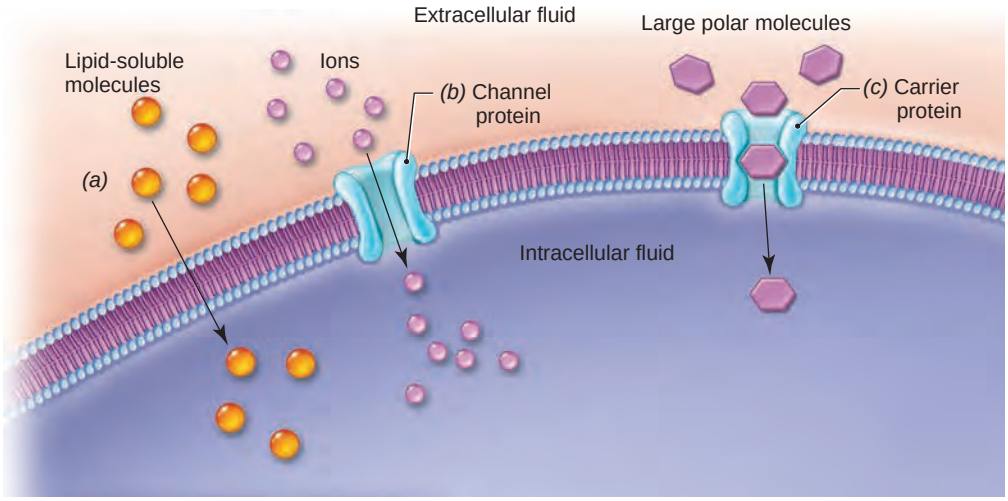


Figure 3.10 Diffusion.
(a) Simple diffusion. *(b)* Channel-mediated diffusion. *(c)* Carrier-mediated diffusion.

Clinical Insight

Dialysis involves the application of diffusion to remove small solute molecules across a selectively permeable membrane from a solution containing both small and large molecules. Dialysis is the process that is used in artificial kidney machines. As blood is passed through a chamber with a selectively permeable membrane, small waste molecules diffuse from the blood across the membrane into an aqueous solution that has a low concentration of these waste molecules. In this way, waste products in the blood are reduced to normal levels.

gradient. Channel proteins are generally selective; this means they tend to allow limited substances to pass across based mostly on size and charge. This type of transport is called *channel-mediated diffusion* (figure 3.10*b*). Other water-soluble substances use carrier proteins. **Carrier proteins** are membrane proteins that physically bind to and transport specific substances across the plasma membrane; this means that one type of carrier protein binds only one type of substance. This type of transport is called *carrier-mediated diffusion* (figure 3.10*c*). Carrier-mediated diffusion is a type of **facilitated transport,** which uses carrier proteins to facilitate the movement of substances across the plasma membrane. Carrier-mediated active transport, another type of facilitated transport, will be discussed later.

Osmosis

The passive movement of water across a selectively permeable membrane is called **osmosis** (os-mo′-sis). Water molecules move across the plasma membrane from an area of higher water concentration (lower solute concentration) into an area of lower water concentration (higher solute concentration), either by crossing the plasma membrane directly or by moving through a channel protein. Osmosis plays a very important role in the functions of the cells and the whole body. Water molecules are the dominant components of cells and serve as the solvent of the other chemicals. Also, the movement of water molecules into and out of the cells has the ability to significantly affect the volume of cells and the concentration of the chemicals within them.

Figure 3.11 illustrates the process of osmosis. The beaker is divided into two compartments (A and B) by a selectively permeable membrane that allows water molecules but not sugar molecules to pass across it. Because the higher concentration of water is in compartment A, water moves from compartment A into compartment B. Sugar molecules cannot pass across the membrane, so

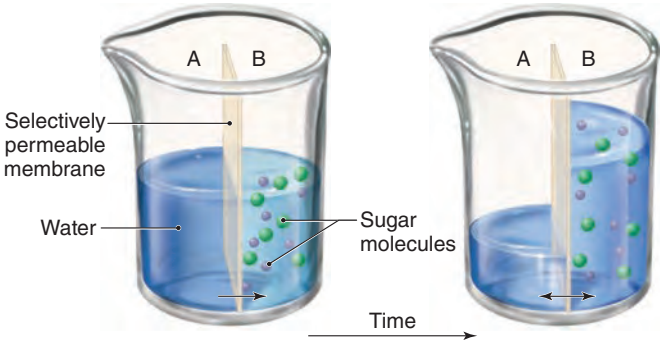


Figure 3.11 Osmosis.

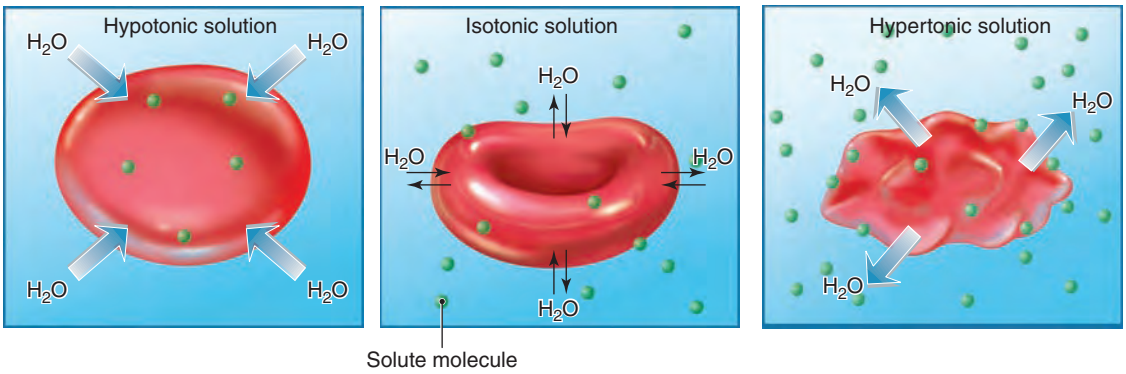
water molecules from compartment A continue to move into compartment B, causing the volume of the solution in compartment B to increase as the volume of water in compartment A decreases.

Like compartment B in figure 3.11, living cells also contain many substances to which the plasma membrane is impermeable. Therefore, any change in the concentration of water across the plasma membrane will result in net gain or loss of water by the cell and a change in cell volume and shape.

The ability of a solution to affect the tone or shape of living cells by altering the cells' water content is called *tonicity*. A solution with a lower concentration of solutes (higher concentration of water) than the cell is called a **hypotonic solution.** A cell placed in this solution will gain water and increase in size, which may eventually lead to rupture of the cell (figure 3.12*a*). A solution with a higher concentration of solutes (lower concentration of water) than the cell is known as a **hypertonic solution.** A cell placed in this solution will lose water and shrink, which may lead to cell death (figure 3.12*c*).

Clinical Insight

Solutions that are administered to patients intravenously usually are isotonic. Sometimes hypertonic solutions are given intravenously to patients with severe edema, or an accumulation of excess fluid in body tissues. The hypertonic solution will help to draw the excess fluid out of the body tissue and into the blood, where it can be removed by the kidneys and excreted in urine. Severely dehydrated patients may be given a hypotonic solution orally or intravenously to increase the water concentration of blood and tissue fluid, by increasing water movement from the digestive tract into the blood and from the blood into body tissues.



(a) In a hypotonic solution, there is a net gain of water by the cell, causing it to swell. Ultimately, the cell may burst.

(b) In an isotonic solution, there is no net gain or loss of water by the cell; the shape of the cell remains unchanged.

(c) In a hypertonic solution, there is a net loss of water from the cell, causing it to shrink.

Figure 3.12 The effect of tonicity on human red blood cells.

A solution that has the same concentration of solutes (same concentration of water) as the cell is an **isotonic solution.** When surrounded by this solution, a cell exhibits no net gain or loss of water and no change in volume (figure 3.12*b*).

Active Transport

Unlike passive transport, active transport requires the cell to expend energy (ATP) to move substances across a plasma membrane. There are three basic active transport mechanisms: carrier-mediated active transport, endocytosis, and exocytosis.

Carrier-Mediated Active Transport

Carrier-mediated active transport uses carrier proteins to move substances across the plasma membrane, usually opposite to (against) their concentration gradient, using energy provided by ATP. Figure 3.13 shows how a carrier protein, called the *sodium-potassium pump* (Na^+/K^+ pump), moves three sodium ions and two potassium ions against their concentration gradients. The action of this pump causes a sodium gradient from outside to inside the cell and a potassium gradient from the inside of the cell to the outside. The gradients established are highly important in the overall functioning of the entire human body.

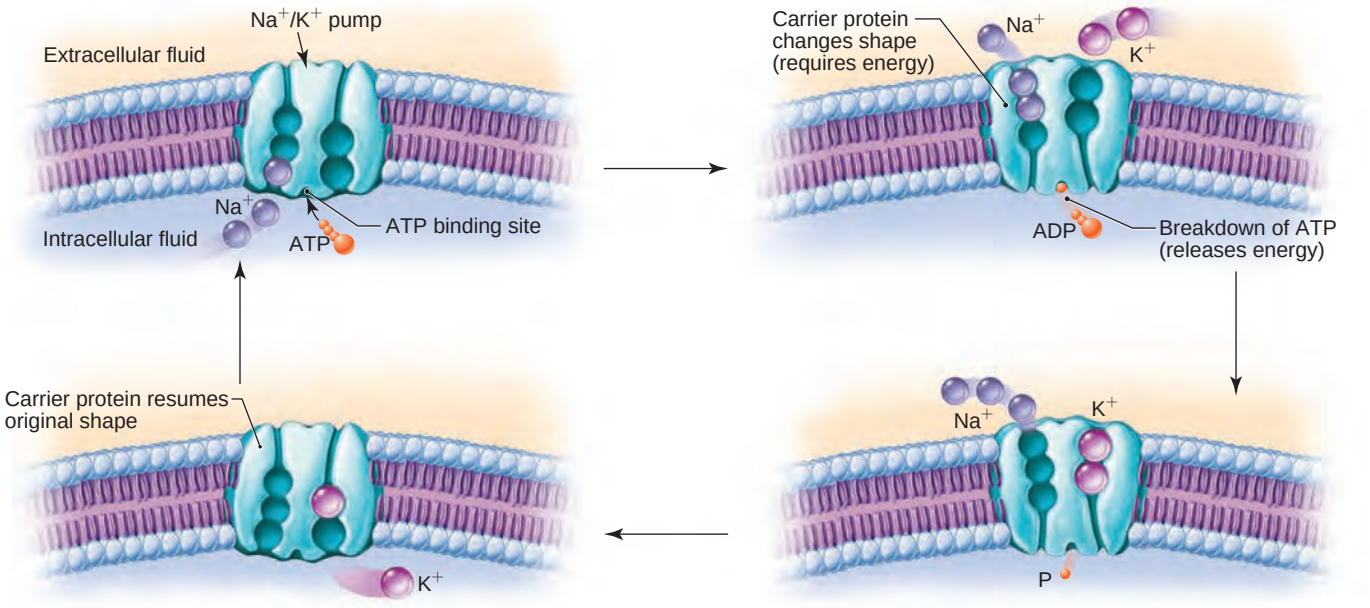


Figure 3.13 Carrier-mediated active transport. Sodium and potassium ions are moved across the plasma membrane against the concentration gradient by carrier-mediated active transport.

Endocytosis and Exocytosis

Materials that are too large to be transported by channel or carrier proteins must enter and exit a cell by totally different mechanisms. **Endocytosis** (en″-dō-sī-tō′-sis) is a process that uses the plasma membrane to engulf, or internalize, solid particles and droplets of liquid.

During endocytosis, the plasma membrane flows around the substance to be engulfed, forms an enveloping vesicle around the substance, and re-forms the plasma membrane exterior to the vesicle so that the vesicle and substance are brought inside the cell (figure 3.14*a*). There are two types of endocytosis: pinocytosis and phagocytosis. **Pinocytosis** (pī″-nō-sī-tō′-sis) is the engulfment of small droplets of extracellular fluid. **Phagocytosis** (fag″-ō-sī-tō′-sis) is the engulfment of solid particles. Many types of cells use these processes, but phagocytosis is especially important for certain white blood cells that engulf and destroy bacteria as a defense against disease.

Exocytosis is the reverse of endocytosis, in that it is used to remove large substances from cells. A secretory vesicle containing the substance forms within the cell. It then moves to the plasma membrane, fuses with it, and empties its contents outside of the cell (figure 3.14*b*). The secretion, or release, of enzymes and hormones from cells involves exocytosis. Table 3.2 summarizes the types of transport across the plasma membrane.

Check My Understanding

3. By what means do substances enter and exit living cells?

3.3 Cellular Respiration

Learning Objectives

4. Describe cellular respiration and its importance.
5. Compare aerobic respiration and anaerobic respiration.

Cells require a constant supply of energy to power the chemical reactions of life. This energy is directly supplied by ATP molecules, as noted in chapter 2. Because cells have a limited supply, ATP molecules must constantly be produced by cellular respiration in order to sustain life.

Cellular respiration is the process that breaks down nutrients in the cells to release energy held in their chemical bonds and transfers some of this energy into the high-energy phosphate bonds of ATP. About 40% of the energy in a nutrient molecule is "captured" in this way; the remainder is lost as heat. Glucose, a carbohydrate molecule, is the primary nutrient used in cellular respiration; however, the building units of proteins and lipids are also used (see chapter 15 for the details).

The actual process of cellular respiration of glucose is complex, but may be simplified as the equation below. Note that the breakdown of glucose ($C_6H_{12}O_6$) requires oxygen (O_2) and yields carbon dioxide (CO_2) and water (H_2O). The energy released is used to form ATP from ADP and Pi (phosphate group). Some of the energy is released as heat.

$$C_6H_{12}O_6 + 6O_2 \xrightarrow{\text{36–38 ADP, 36–38 Pi} \;\rightarrow\; \text{36–38 ATP}} 6CO_2 + 6H_2O + \text{Heat}$$

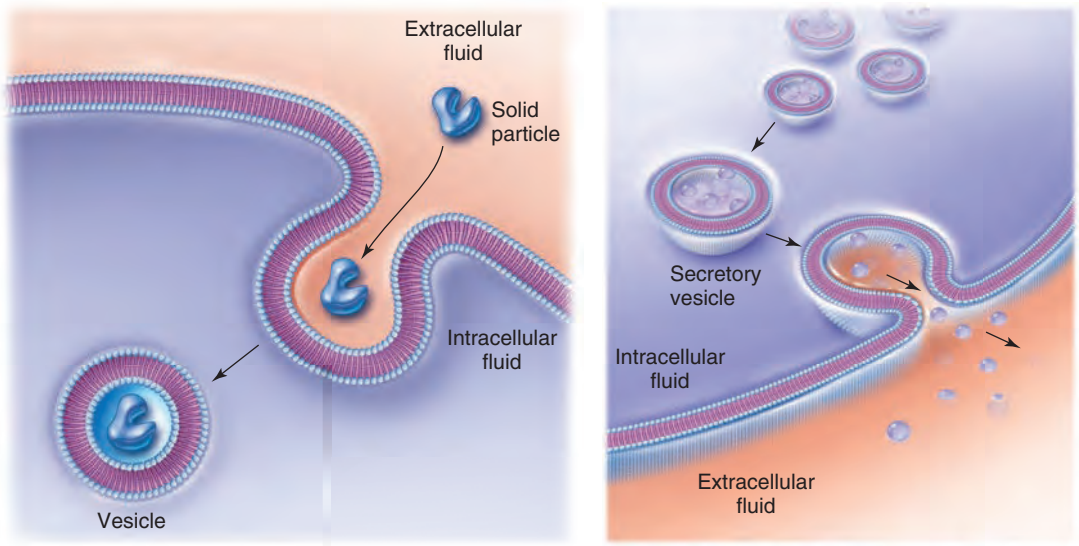


Figure 3.14 *(a)* A particle is engulfed by plasma membrane and brought into the cell by endocytosis. *(b)* Particles are enclosed in a secretory vesicle and are expelled from the cell by exocytosis.

Table 3.2 Types of Transport Across the Plasma Membrane

Type	Mechanism
Passive Transport	The transport that requires no expenditure of ATP by the cell
Simple diffusion	Transport of lipid-soluble substances across plasma membrane along their concentration gradient without the help of membrane proteins
Channel-mediated diffusion	Transport of water-soluble substances across the plasma membrane along their concentration gradient through channel proteins
Carrier-mediated diffusion	Movement of water-soluble substances across the plasma membrane along their concentration gradient by using carrier proteins that facilitate transport by changing their shape
Osmosis	Movement of water across the plasma membrane in the direction of the more highly concentrated impermeable solutes, either by crossing the plasma membrane directly or by moving through a channel protein
Active Transport	The transport that requires the expenditure of ATP by the cell
Carrier-mediated active transport	Movement of small substances across the plasma membrane, by carrier proteins (pumps), usually opposite to the concentration gradient
Exocytosis	Movement of solid particles out of the cell, by merging the secretory vesicle with the plasma membrane and emptying its contents into extracellular space
Endocytosis	Movement of solid particles and droplets of liquid into the cell, by engulfing the substances with the plasma membrane and forming a vesicle containing the transported substance in the intracellular space
Pinocytosis	The process by which cells engulf droplets of extracellular fluid
Phagocytosis	The process by which cells engulf solid particles

Cellular respiration involves two sequential processes: anaerobic respiration and aerobic respiration. Each chemical process involves many steps, with each step requiring a special enzyme. However, the processes can be simplified as shown in figure 3.15. **Anaerobic** (an-a-rō′-bik) **respiration** (1) does not require oxygen and (2) occurs in the cytosol. It breaks down a six-carbon glucose molecule into two three-carbon pyruvic acid molecules to yield a net of two ATP molecules. The low level of ATP production by anaerobic respiration is insufficient to keep a person alive. A person deprived of oxygen or of the ability to use oxygen in cellular respiration (as in cyanide poisoning) quickly dies because anaerobic respiration does not provide sufficient ATP to sustain life.

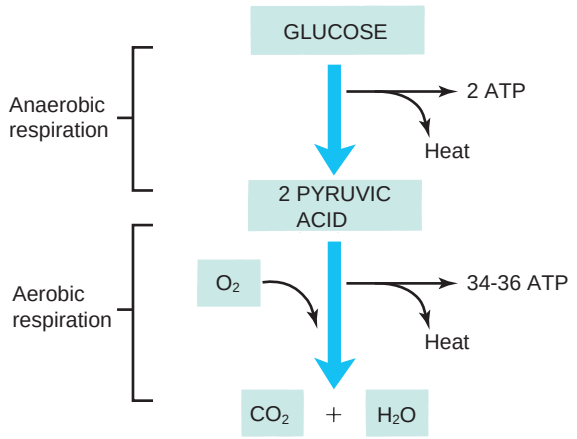


Figure 3.15 Cellular respiration of a glucose molecule occurs in two major steps. Anaerobic respiration occurs in the cytosol, does not require oxygen, and yields a net of 2 ATP. Aerobic respiration occurs in mitochondria, requires oxygen, and yields a net of 34–36 ATP. About 40% of the energy in the chemical bonds of glucose is captured to form ATP molecules.

Aerobic respiration, the second part of cellular respiration, (1) requires oxygen, (2) occurs only within mitochondria, and (3) is essential for human life. Aerobic respiration releases the energy in the high-energy electrons produced by anaerobic respiration, breaks down the two pyruvic acid molecules produced by anaerobic respiration into carbon dioxide and water, and yields a net of 34–36 ATP molecules. Thus, the respiration of a molecule of glucose yields a net total of 36–38 ATP.

Check My Understanding

4. What is cellular respiration and why is it important?

3.4 Protein Synthesis

Learning Objectives

6. Describe the process of protein synthesis.
7. Explain the roles of DNA and RNA in protein synthesis.

Proteins play a vital role in the body. Structural proteins compose significant portions of all cells, and functional proteins, such as enzymes and hormones, directly regulate cellular activities. Remember that a protein is formed of a long chain of amino acids joined together by peptide bonds. Protein synthesis involves placing a specific amino acid in the correct position in the amino acid chain.

DNA and RNA are intimately involved in the synthesis of proteins.

The Role of DNA

Recall the structure of DNA described in chapter 2. The two coiled strands of nucleotides are joined by hydrogen bonds between the nucleotide bases in each strand by *complementary base pairing*. Adenine (A) pairs with thymine (T), and cytosine (C) pairs with guanine (G).

The sequence of bases in a DNA molecule encodes information that determines the sequence of amino acids in a protein. More specifically, a sequence of three nucleotide bases (a triplet) in DNA encodes for a specific amino acid. For example, a sequence of ACA encodes for the amino acid cysteine, while AGG encodes for serine. In this way, inherited information that determines the structure of proteins is encoded in DNA.

The Role of RNA

In contrast to DNA, RNA consists of a single strand of nucleotides. Each nucleotide contains one of four nitrogenous bases: adenine, cytosine, guanine, or *uracil* (U). Note that uracil is present in RNA instead of thymine, which occurs in DNA. RNA is synthesized in a cell's nucleus by using a strand of DNA as a template. Complementary pairing of RNA bases with DNA bases produces a strand of RNA nucleotides whose bases are complementary to those in the DNA molecule. Uracil (U) in RNA pairs with adenine (A) in DNA; adenine (A) in RNA pairs with thymine (T) in DNA.

There are three types of RNA, and each plays a vital role in protein synthesis.

Messenger RNA (mRNA) carries the genetic information from DNA into the cytoplasm to the ribosomes, the sites of protein synthesis. This information is carried by the sequence of bases in mRNA, which is complementary to the sequence of bases in the DNA template.

Ribosomal RNA (rRNA) and protein compose ribosomes, the sites of protein synthesis. Ribosomes contain the enzymes required for protein synthesis.

Transfer RNA (tRNA) carries amino acids to the ribosomes, where the amino acids are joined like a string of beads to form a protein. There is a different tRNA for transporting each of the 20 kinds of amino acids used to build proteins.

Table 3.3 summarizes the characteristics of DNA and RNA.

Table 3.3 Distinguishing Characteristics of DNA and RNA

	DNA	RNA
Strands	Two strands joined by the complementary pairing of their nitrogenous bases	One strand
Sugar	Deoxyribose	Ribose
Bases	Adenine	Adenine
	Thymine	Uracil
	Cytosine	Cytosine
	Guanine	Guanine
Shape	Helix	Straight

Transcription and Translation

The process of protein synthesis involves two successive events: **transcription,** which occurs in the nucleus, and **translation,** which takes place in the cytoplasm.

In *transcription,* the sequence of bases in DNA determines the sequence of bases in mRNA due to complementary base pairing. Thus, transcription transfers the encoded information of DNA into the sequence of bases in mRNA. For example, if a triplet of DNA bases is AGG, which encodes for the amino acid serine, the complementary paired triplet of bases in mRNA is UCC. A triplet of bases in mRNA is known as a **codon,** and there is a codon for each of the 20 amino acids composing proteins. Messenger RNA consists of a chain of codons. Once it is synthesized, mRNA moves out of the nucleus into the cytoplasm where it combines with a ribosome, the site of protein synthesis.

In *translation,* the encoded information in mRNA is used to produce a specific sequence of amino acids to form the protein. As the ribosome moves along the mRNA strand, tRNA molecules bring amino acids to the ribosome and place them in the correct sequence in the forming polypeptide chain (protein) as specified by the mRNA codons.

Each tRNA molecule has a triplet of RNA bases called an **anticodon** at one end of the molecule. Because there are 20 different kinds of amino acids composing proteins, there are at least 20 kinds of tRNA whose anticodons can bind with codons of mRNA. A tRNA molecule can only transport the specific amino acid that is encoded by the codon to which its anticodon can bond. For example, a tRNA transporting the amino acid serine has the anticodon AGG that can bond with the mRNA codon UCC to place serine in the correct position in the forming amino acid chain. See figure 3.16.

By transcription and translation, DNA determines the structure of proteins, which, in turn, determines the functions of proteins. Transcription and translation may be summarized as follows:

$$\text{DNA} \xrightarrow[\text{Transcription}]{} \text{mRNA} \xrightarrow[\text{Translation}]{} \text{Protein}$$

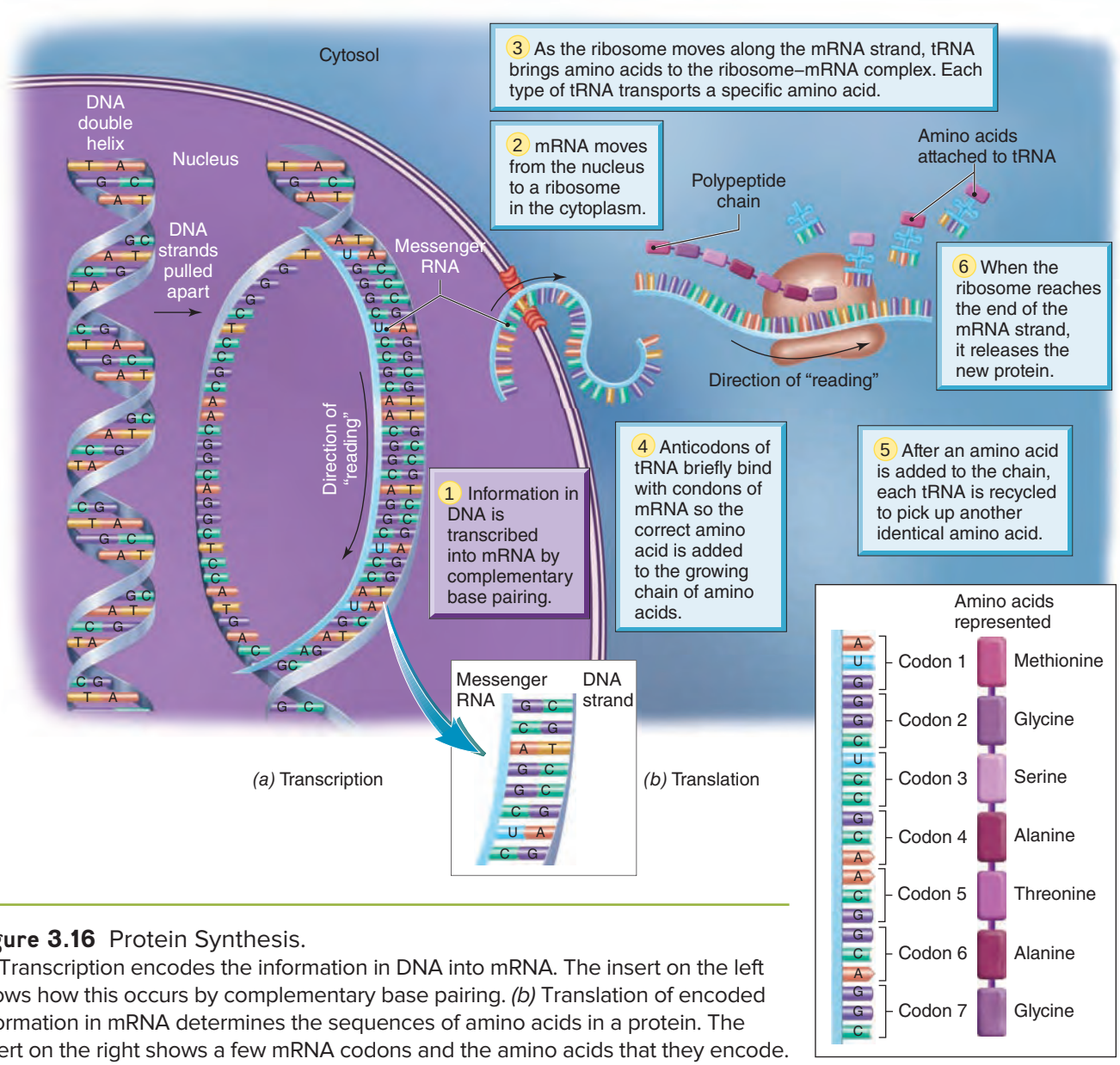


Figure 3.16 Protein Synthesis.
(a) Transcription encodes the information in DNA into mRNA. The insert on the left shows how this occurs by complementary base pairing. *(b)* Translation of encoded information in mRNA determines the sequences of amino acids in a protein. The insert on the right shows a few mRNA codons and the amino acids that they encode.

Check My Understanding

5. How does chromosomal DNA determine the structure of proteins?

3.5 Cell Division

Learning Objectives

8. Describe the two types of cell division and their roles.
9. Describe each phase of mitosis.

Cells replicate themselves through a process called **cell division.** Two types of cell division occur in the body: mitotic cell division and meiotic cell division. Somatic cells (cells other than sex cells) divide by **mitotic** (mī-tot′-ik) **cell division,** during which a parent cell divides to form two new daughter cells that have the same number (46) and composition of chromosomes as the parent cell. It enables growth and the repair of tissues. **Meiotic** (mī-ot′-ik) **cell division** occurs only in the production of ova and sperm. In meiosis, a single parent cell divides to form four daughter cells that contain only half the number of chromosomes (23) found in the parent cell. In this chapter, we consider mitotic cell division only. Meiotic cell division is studied in chapter 17.

Mitotic Cell Division

Starting with the first division of the fertilized egg, mitotic cell division is the process that produces new cells for

growth of the new individual and the replacement of worn or damaged cells. Mitotic cell division occurs at different rates in different kinds of cells. For example, epithelial cells undergo almost continuous division but muscle cells lose the ability to divide as they mature. Three processes are involved in mitotic cell division: (1) replication (production of exact copies) of chromosomes, (2) mitosis, and (3) division of the cytoplasm.

In dividing cells, the time period from the separation of daughter cells of one division to the separation of daughter cells of the next division is called the **cell cycle. Mitosis** constitutes only 5% to 10% of the cell cycle. Most of the time, a cell merely is carrying out its normal functions (figure 3.17).

Interphase is defined as the phase when the cell is not involved in mitosis. When viewed with a microscope, a cell in interphase is identified by its intact nucleus containing chromatin granules. In cells that are destined to divide, both the centrioles and chromosomes replicate during interphase, while other organelles are synthesized and assembled. There is a growth period before and after replication of the 46 chromosomes.

A chromosome consists of a very long DNA molecule coated with proteins. During interphase, chromosomes are uncoiled and resemble very thin threads within the cell nucleus. Chromosomes replicate during interphase in order to provide one copy of each chromosome for each of the two daughter cells that will be formed by mitotic cell division. Chromosome replication is dependent upon the replication of the DNA molecule in each chromosome. Figure 3.18 illustrates the process of DNA replication.

The two original DNA strands "unzip," and new nucleotides are joined in a complementary manner by their bases to the bases of the separated DNA strands. When the new nucleotides are in place and joined together, each new DNA molecule consists of one "new" strand of nucleotides joined to one "old" strand of nucleotides. In this way, a DNA molecule is precisely replicated so that both new DNA molecules are identical.

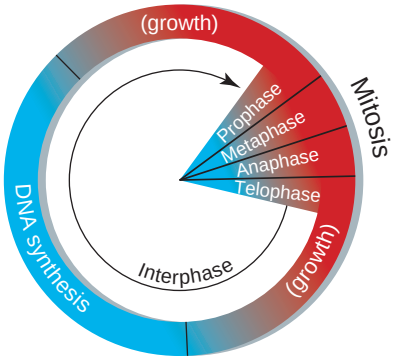


Figure 3.17 The Cell Cycle.
Interphase occupies most of the cell cycle. Only 5% to 10% of the time is used in mitosis. DNA and chromosome replication occur during interphase.

Mitotic Phases

Once it begins, mitosis is a continuous process that is arbitrarily divided into four sequential phases: prophase, metaphase, anaphase, and telophase. Each phase is characterized by specific events that occur.

Prophase During **prophase,** the replicated chromosomes coil, appearing first as threadlike structures and finally shortening sufficiently to become rod-shaped. Each replicated chromosome consists of two **chromatids** joined at their **centromeres.** Simultaneously, the nuclear envelope gradually disappears, and each pair of centrioles migrate toward opposite ends of the cell. A **spindle** is formed between the migrating centrioles. The spindle consists of spindle fibers that are formed of microtubules (figure 3.19*a*).

Metaphase During the brief **metaphase,** the replicated chromosomes line up at the equator of the spindle. The centromeres are attached to spindle fibers (figure 3.19*b*).

Clinical Insight

Mitotic cell division is normally a controlled process that ceases when it is not necessary to produce additional cells. Occasionally, control is lost and cells undergo continuous division, which leads to the formation of tumors. Tumors may be benign or malignant. *Benign tumors* do not spread to other parts of the body and may be surgically removed if they cause health or cosmetic problems. *Malignant tumors,* or *cancers,* may spread to other parts of the body by a process called *metastasis* (me-tas′-ta-sis). Cells break away from the primary tumor and are often carried by blood or lymph to other areas, where continued cell divisions form secondary tumors.

Treatment of malignant tumors involves surgical removal of the tumor, if possible, and subsequent chemotherapy and/or radiation therapy. Both chemotherapy and radiation therapy tend to kill malignant cells because dividing cells are more sensitive to treatment, and malignant cells are constantly dividing.

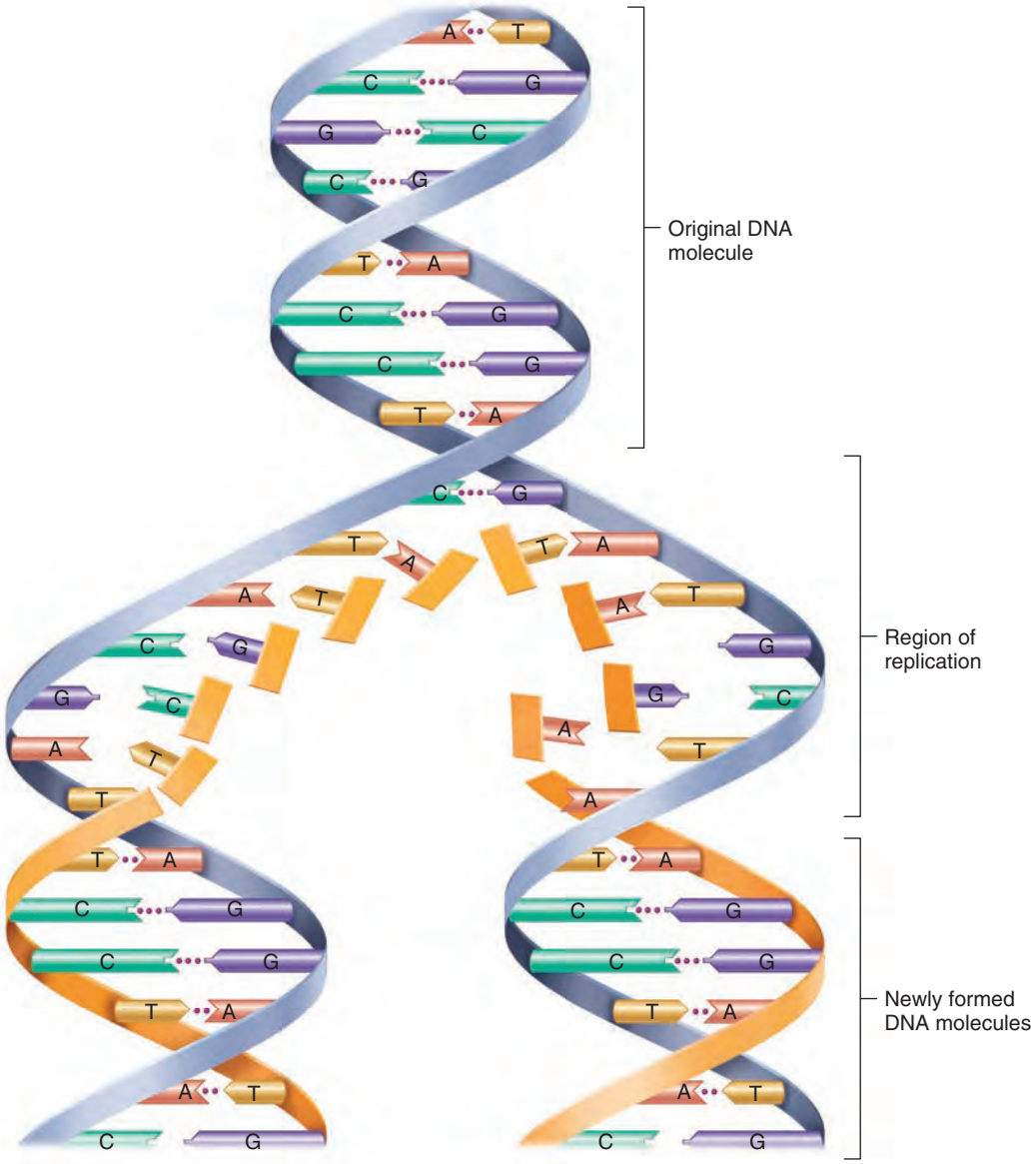


Figure 3.18 When a DNA molecule replicates, the two strands unzip. Then a new complementary strand of nucleotides forms along each "old" strand to produce two new DNA molecules.

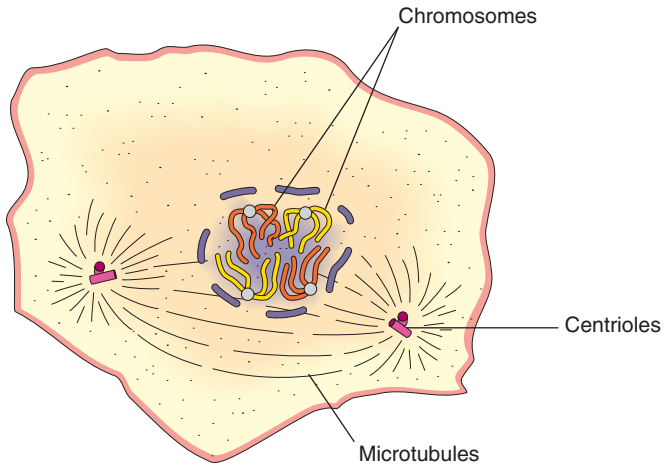
Anaphase During **anaphase,** separation of the centromeres results in the separation of the paired chromatids. The members of each pair are pulled by spindle fibers towards opposite sides of the cell. The separated chromatids are now called chromosomes, and each new set of chromosomes is identical (figure 3.19*c*).

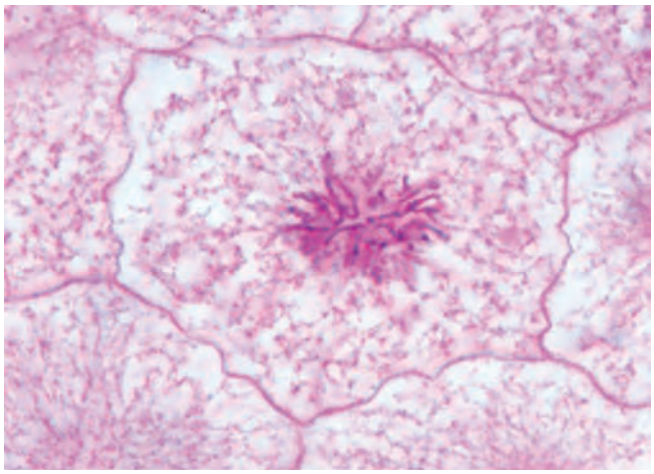
Telophase During **telophase,** the spindle fibers disassemble and a new nuclear envelope starts forming around each set of chromosomes as the new nuclei begin to take shape. The chromosomes start to uncoil, and they will ultimately become visible only as chromatin granules. The new daughter nuclei are completely formed by the end of telophase.

Usually during late anaphase and telophase, the most obvious change is the division of the cytoplasm, which is called **cytokinesis** (si″-to-ki-nē′-sis). It is characterized by a furrow that forms in the plasma membrane across the equator of the spindle and deepens until the parent cell is separated into two daughter cells. The formation of two daughter cells, each having identical chromosomes in the nuclei, marks the end of mitotic cell division (figure 3.19*d*).

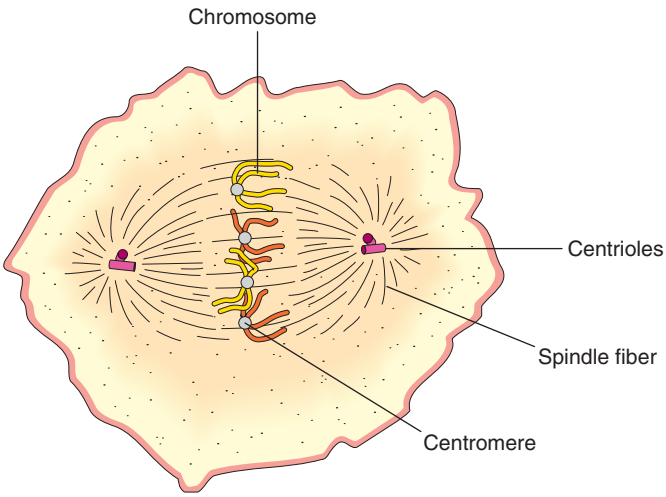
Check My Understanding

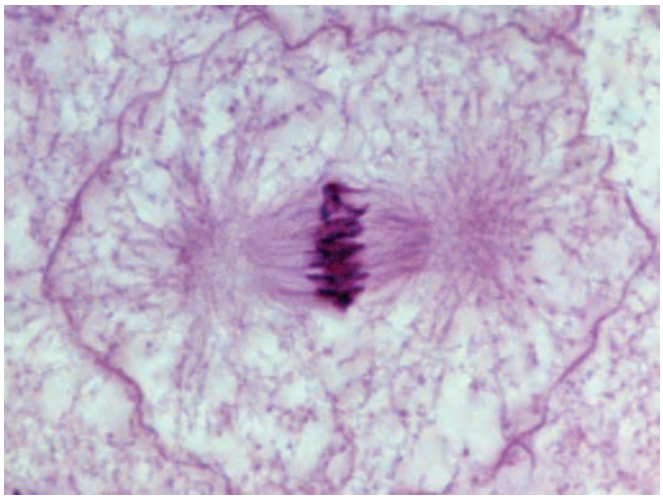
6. What are the phases of mitosis and how is each phase distinguished?





(a) Prophase
Replicated chromosomes coil and shorten; nuclear envelope disappears; centriole pairs move toward opposite sides of the cell, forming a spindle between them.





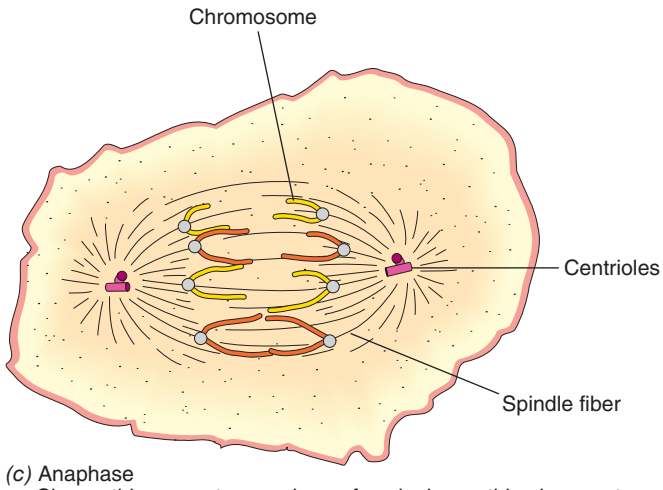
(b) Metaphase
Chromosomes line up at the equator of the spindle. Each replicated chromosome consists of a pair of chromatids joined by centromere.

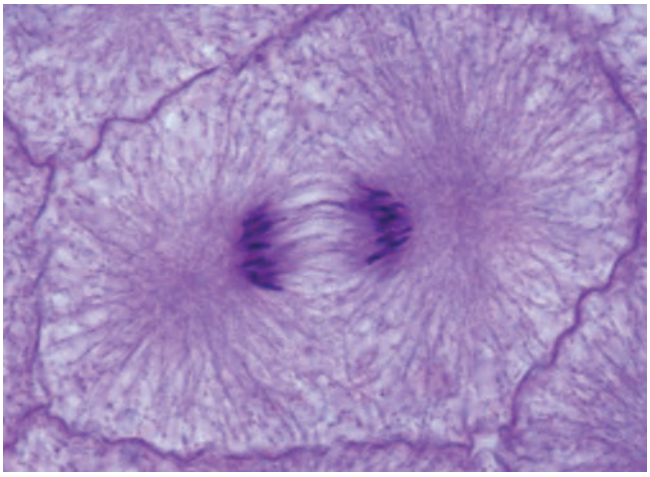
Figure 3.19 Drawings and photomicrographs (1,000×) of mitosis.

Chapter Summary

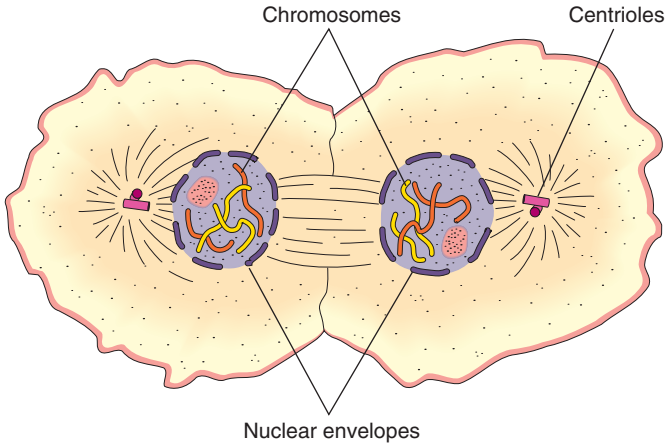
3.1 Cell Structure

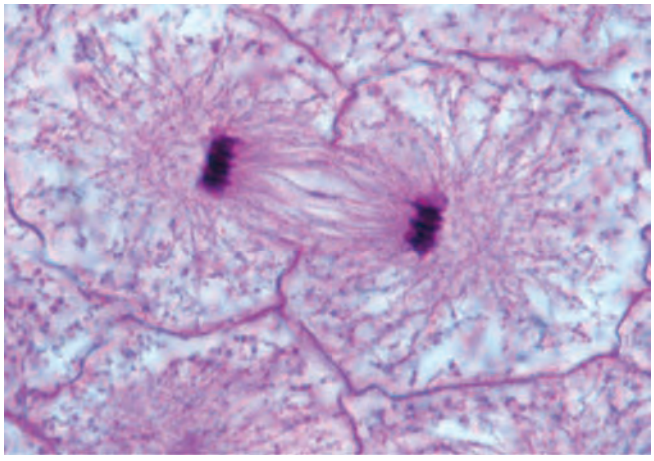
- The plasma membrane is composed of a double layer of phospholipid molecules along with associated cholesterol and protein molecules. It is selectively permeable and controls the movement of the materials into and out of cells.
- The cytoplasm, which is composed of cytosol and organelles, lies external to the nucleus and is enveloped by the plasma membrane.
- The nucleus is a large, spherical organelle surrounded by the nuclear envelope.
- Chromosomes, composed of DNA and protein, are found in the nucleus. The uncoiled chromosomes appear as chromatin granules in nondividing cells.
- The nucleolus is the site of ribosome synthesis.
- Ribosomes are tiny organelles formed of rRNA and protein. They are sites of protein synthesis.
- The endoplasmic reticulum (ER) consists of membranes that form channels for transport of materials within the cell. RER is studded with ribosomes that synthesize proteins for export from the cell. SER lacks ribosomes and is involved in lipid synthesis.





(c) Anaphase
Chromatids separate, members of each chromatid pair move toward opposite ends of the spindle.





(d) Telophase
Nuclear envelopes form around each set of chromosomes; spindle fibers disappear; chromosomes uncoil and extend; cytokinesis produces two daughter cells.

- The Golgi complex packages materials into vesicles for secretion from the cell or transport within the cell.
- Mitochondria are large, double-membraned organelles within which aerobic respiration occurs.
- Lysosomes are small vesicles that contain digestive enzymes used to digest foreign particles, worn-out parts of a cell, or an entire damaged cell.
- The cytoskeleton is formed by microtubules and microfilaments, and is used in maintaining cell structure and cell movement.
- A pair of centrioles, used in cell division, is present near the cell's nucleus. The wall of each centriole is composed of microtubules arranged in groups of three.
- Cilia are short, hairlike projections on the free surface of certain cells. The beating of cilia moves materials along the cell surface.
- Each sperm swims by the beating of a flagellum, a long, whiplike organelle.

3.2 Transport Across Plasma Membranes

- Passive transport does not require the expenditure of energy by the cell.
- Diffusion is the movement of substances from an area of higher concentration to an area of lower concentration. It is caused by the constant motion of substances in gases and liquids.
- Substances diffuse across plasma membrane by simple diffusion, channel-mediated diffusion, and carrier-mediated diffusion.
- Osmosis is the passive movement of water across a selectively permeable membrane.
- Hypotonic solutions have a higher water concentration than the cells. Hypertonic solutions have a lower water concentration than the cells. Isotonic solutions have the same water concentration as the cells.

- Cells in hypotonic solutions have a net gain of water. Cells in hypertonic solutions have a net loss of water. Cells in isotonic solutions have no net change of water content.
- Active transport requires the cell to expend energy.
- Active transport mechanisms include carrier-mediated active transport, endocytosis, and exocytosis.

3.3 Cellular Respiration

- Cellular respiration is the breakdown of nutrients in cells to release energy and form ATP molecules, which power cellular processes.
- Cellular respiration of glucose involves anaerobic respiration and aerobic respiration.
- Cellular respiration of a glucose molecule yields a net of 36–38 ATP. A net of 2 ATP is produced during anaerobic respiration, which occurs in the cytosol. A net of 34–36 ATP is produced during aerobic respiration, which occurs in mitochondria.

3.4 Protein Synthesis

- Protein synthesis involves the interaction of DNA, mRNA, rRNA, and tRNA.
- The sequence of bases in DNA determines the sequence of codons in mRNA, which, in turn, determines the sequence of amino acids in a protein.

$$\text{DNA} \xrightarrow[\text{Transcription}]{} \text{mRNA} \xrightarrow[\text{Translation}]{} \text{Protein}$$

3.5 Cell Division

- Mitotic cell division produces two daughter cells that have the same number and composition of chromosomes. It enables growth and tissue repair.
- Meiotic cell division results in production of ova and sperm. Four daughter cells are formed that have half the number of chromosomes as the parent cell.
- Most of a cell cycle is spent in interphase, where cells carry out normal metabolic functions. In cells destined to divide, chromosomes and centrioles are replicated in interphase.
- After chromosome replication, mitosis is the orderly process of separating and distributing chromosomes equally to the daughter cells.
- Mitosis consists of four phases: prophase, metaphase, anaphase, and telophase.

Self-Review

Answers are located in Appendix B.

1. Movement of materials in and out of cells is controlled by the _____.
2. Molecules of _____ located in chromosomes control the activities of cells.
3. Aerobic respiration occurs within _____.
4. The sites of protein synthesis are _____.
5. The _____ assembles protein and RNA to form ribosomes.
6. The _____ consists of intracellular membranous channels for material transport.
7. Movement of molecules from an area of their higher concentration to an area of their lower concentration is known as _____.
8. Movement of molecules across a membrane by carrier proteins without the expenditure of energy is a form of _____.
9. Breakdown of organic nutrients in cells to release energy and form ATP is called _____.
10. Instructions for synthesizing a protein are carried from DNA to ribosomes by _____.
11. The equal distribution of chromosomes to daughter nuclei occurs by _____.

Critical Thinking

1. How do the characteristics of a substance determine the transport mechanism that will be used to move it across the plasma membrane?
2. How is the correct sequence of amino acids in proteins determined?
3. How are glucose, pyruvic acid, mitochondria, oxygen, ADP, and ATP involved in cellular respiration?
4. How does mitotic cell division yield daughter cells with the same DNA content?

3
CHAPTER

Tissues and Membranes

Your body's ability to maintain homeostasis depends upon on the normal structure and function of body tissues. Consider your ability to move your hand off an environmental hazard, such as a hot surface. The bones of the body are physically hardened due to mineralized bone. Attached to these bones are muscles containing skeletal muscle tissue, which has the ability to contract and create force. When the muscles of the arm contract with force, they pull on the bones in the forearm to create movement at the elbow. As a result, the hand is moved away from the hazard. Nervous tissue detects and processes the pain stimuli from the hand when it contacts the hazard. It then acts to control and coordinate the contraction of the skeletal muscle tissue in response. As you can see, many types of body tissues are involved in all of the body's physiological processes. Gaining an understanding of your body's various tissues and their capabilities will facilitate a better understanding of how your organ systems work to maintain homeostasis within the body in upcoming chapters.

CHAPTER OUTLINE

SELECTED KEY TERMS

Adipose tissue (adip = fat) A connective tissue that stores fat.
Bone A hard connective tissue with a rigid matrix of calcium salts and fibers.
Cartilage A connective tissue with a relatively rigid, semisolid matrix.
Connective tissue (connect = to join) A tissue that binds other tissues together.
Epithelial tissue (epi = upon, over; thel = delicate) A thin tissue that covers body and organ surfaces and lines body cavities, and forms secretory portions of glands; epithelium.
Fibroblast (fibro = fiber; blast = germ) A cell that produces fibers and ground substance in connective tissue.
Matrix The extracellular substance in connective tissue.
Mucous membrane Epithelial membrane that lines tubes and cavities that have openings to the external environment.
Muscle tissue (mus = mouse) A tissue whose cells are specialized for contraction.
Nervous tissue A tissue that forms the brain, spinal cord, and nerves.
Serous membrane Epithelial membrane that lines the external surfaces of organs and the body wall in the ventral cavity.
Tissue (tissu = woven) A group of similar cells performing similar functions.

THE DIFFERENT KINDS OF CELLS COMPOSING the human body result from the specialization of cells during embryonic development. **Embryonic stem cells** of an early embryo are unspecialized cells containing encoded information in their DNA that enables them to form all types of specialized cells. As these cells divide repeatedly producing many generations of cells, the daughter cells become partially specialized. Such cells can produce daughter cells for only certain related types of specialized cells. This trend of decreasing potential (increasing specialization) continues through many generations of cells, ultimately producing the highly specialized cells of the human body plus a few partially specialized cells known as **adult stem cells.** Once fully specialized, cells may or may not divide. If they do, they can form only specialized cells like themselves; for example, skin cells divide to produce only skin cells. Because all of a person's cells (except red blood cells, which lack nuclei) contain the same DNA, the transition from unspecialized embryonic stem cells to fully specialized body cells results from cellular mechanisms that turn off specific portions of the encoded information in DNA.

A **tissue** is a group of fully specialized cells that perform similar functions. Most tissues contain a few adult stem cells, which play an important role in tissue repair. Each type of tissue is distinguished by the structure of its cells, its extracellular substance, and the function it performs. The structure of a tissue is a reflection of its function.

The different tissues of the body are classified into four basic types: epithelial, connective, muscle, and nervous tissues.

1. **Epithelial** (ep″-i-thē′-lē-al) **tissue** covers the surfaces of the body, lines body cavities and covers organs, and forms the secretory portions of glands.
2. **Connective tissue** binds organs together and provides protection and support for organs and the entire body.
3. **Muscle tissue** contracts to provide force for the movement of the whole body and many internal organs.
4. **Nervous tissue** detects changes, processes information, and coordinates body functions via the transmission of nerve impulses.

Clinical Insight

Adult stem cells from a variety of tissues are used in medical therapies. For example, stem cells in red bone marrow are used to treat leukemia. Medical scientists think that, with more research, stem cells may be used to treat cancer, brain and spinal cord injuries, multiple sclerosis, Parkinson disease, and other injuries and disorders.

4.1 Epithelial Tissues

Learning Objectives

1. Describe the distinguishing characteristics of epithelial tissues.
2. Identify the common locations and general functions of each type of epithelial tissue.

Epithelial tissues, or epithelia (singular, epithelium), may be composed of one or more layers of cells. The number of cell layers and the shape of the cells provide the basis for classifying epithelial tissues (figures 4.1 and 4.2). Epithelial tissues are distinguished by the following five characteristics:

1. Epithelial cells are packed closely together with very little extracellular material between them.
2. The sheetlike tissue is firmly attached to the deeper connective tissue by a thin layer of

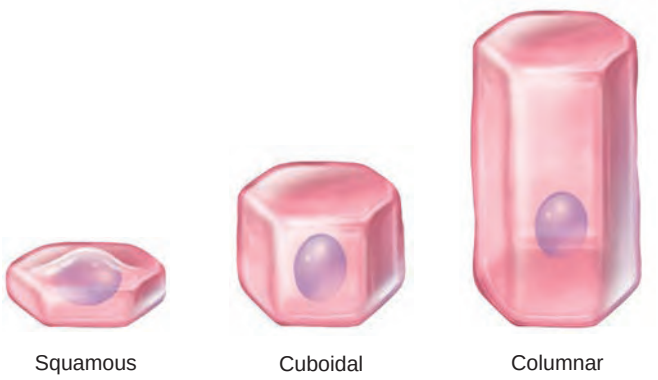


Figure 4.1 Classes of epithelium based on cell shape.

proteins and carbohydrates called the **basement membrane.**

3. The surface of the tissue (free surface) opposite the basement membrane is not attached to any other type of tissue and is located on a surface or next to an opening.
4. Blood vessels are absent, so epithelial cells must rely on diffusion to receive nourishment from blood vessels in the deeper connective tissue. Because these tissues are on surfaces, they are prone to damage. The lack of blood vessels prevents unnecessary bleeding.
5. Epithelial tissues regenerate rapidly by mitotic cell division of the cells. Large numbers of epithelial cells are destroyed and replaced each day.

The functions of epithelial tissues vary with the specific location and type of tissue, but generally they include *protection, diffusion, osmosis, absorption, filtration,* and *secretion.* Certain epithelial cells form *glandular epithelium,* the cells in glands that produce secretions. Two basic types of glands are contained in the body: exocrine and endocrine glands. **Exocrine glands** (exo = outside of; crin = to secrete) have ducts (small tubes) that carry their secretions to specific areas; sweat glands and salivary glands are examples. **Endocrine glands** (endo = within) lack ducts. Their secretions, called hormones, are carried by the blood supply to organs within the body to regulate their function. The thyroid gland and adrenal glands are examples of endocrine glands. Endocrine glands and their hormones will be discussed in more detail in chapter 10.

Simple Epithelium

Simple epithelium consists of a single layer of cells that may be flat (squamous), cube-like (cuboidal), and column-like (columnar) in shape (figures 4.1 and 4.2). These tissues are located where rapid diffusion, secretion, or filtration occur in the body.

Simple squamous (skwā′-mus) *epithelium* consists of thin, flat cells that have an irregular outline and a flat,

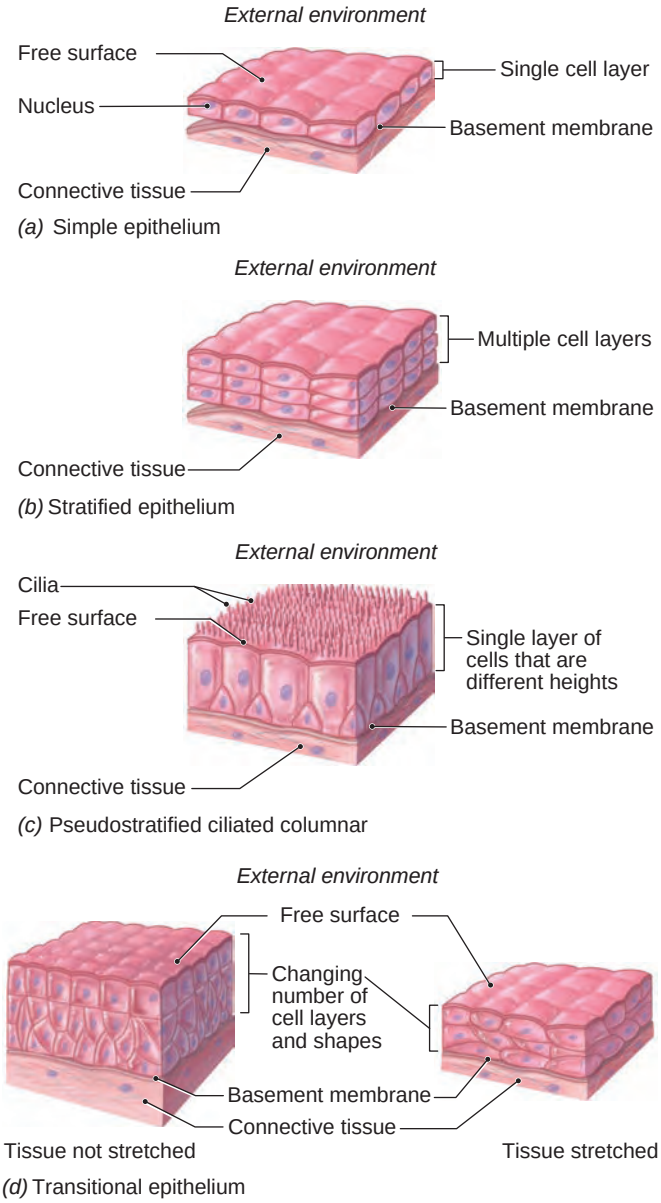


Figure 4.2 Classes of epithelium based on the number of cell layers.

centrally located nucleus. In a surface view, the cells somewhat resemble tiles arranged in a mosaic pattern. Simple squamous epithelium performs a diverse set of functions that include diffusion, osmosis, filtration, secretion, absorption, and friction reduction. Its locations in the body include (1) the air sacs in the lungs, where O_2 and CO_2 diffuse into and out of the blood, respectively; (2) special structures in the kidney called *glomeruli* (glo-mer′u-li), where blood is filtered during urine production (see chapter 16); (3) the **mesothelium,** which is part of the serous membranes lining the ventral cavity; (4) and the **endothelium,** which lines the internal surfaces of the heart, blood vessels, and lymphatic vessels (figure 4.3).

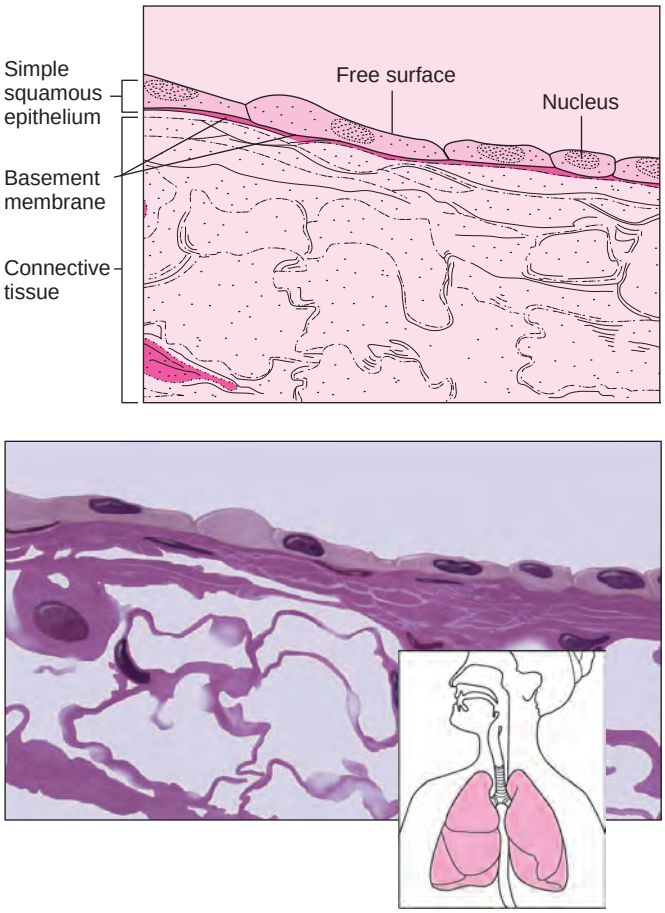


Figure 4.3 Simple Squamous Epithelium (250×).
Structure: A single layer of squamous cells.
Location: Endothelium, mesothelium, air sacs of the lungs, and glomeruli of the kidneys.
Function: Absorption, secretion, filtration, diffusion, osmosis, and friction reduction.

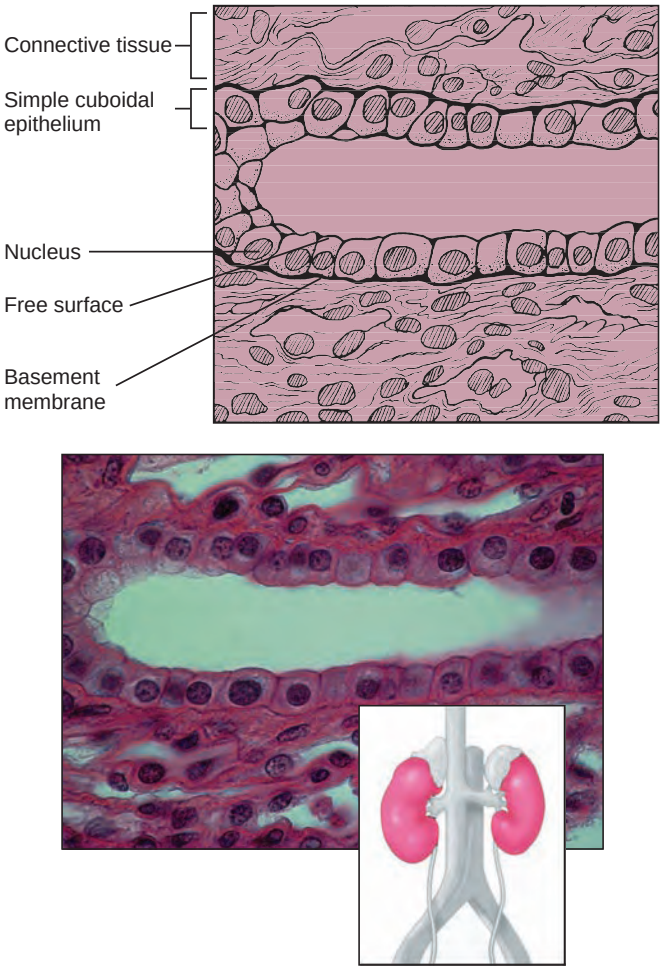


Figure 4.4 Simple Cuboidal Epithelium (250×).
Structure: A single layer of cuboidal cells.
Location: Forms kidney tubules, secretory portion of some glands, and the superficial layer of the ovaries.
Function: Absorption and secretion.

Simple cuboidal epithelium consists of a single layer of cube-shaped cells. The cells have a single, round, centrally located nucleus. Its basic functions are absorption and secretion. Locations for simple cuboidal epithelia include (1) the secretory portion of glands, such as the thyroid and salivary glands; (2) the kidney tubules where secretion and reabsorption of materials occur; and (3) the superficial layer of the ovaries (figure 4.4).

Simple columnar epithelium consists of a single layer of elongated, columnar cells with oval nuclei usually located near the basement membrane. Scattered among the columnar cells are **goblet cells,** specialized mucus-secreting cells with a goblet or wine glass shape. Their purpose is to secrete a protective layer of mucus on the free surface of the epithelium. Secretion and absorption are the major functions of this tissue in areas such as the stomach and intestines. The cells lining the intestine possess numerous microvilli on their free surface, often called a "brush border" because of its bristle-like appearance, which greatly increases their absorptive surface area. In areas such as uterine tubes, paranasal sinuses, and ventricles of the brain, this tissue possesses cilia that allow for movement of materials across the tissue surface (figure 4.5).

Pseudostratified ciliated columnar epithelium consists of a single layer of cells. It is said to be **pseudostratified** (pseudo = false) because its structure creates a visual illusion of being multilayered but it really is a simple epithelium. The layered effect results in part from the nuclei being located at various levels within the cells. Also, even though all of the cells are attached to the basement membrane, not all of them reach the free surface (see figure 4.2). Just as in simple columnar epithelium, goblet cells are scattered throughout the tissue. This epithelium lines the internal surfaces of many of the respiratory passageways, where it collects and removes airborne

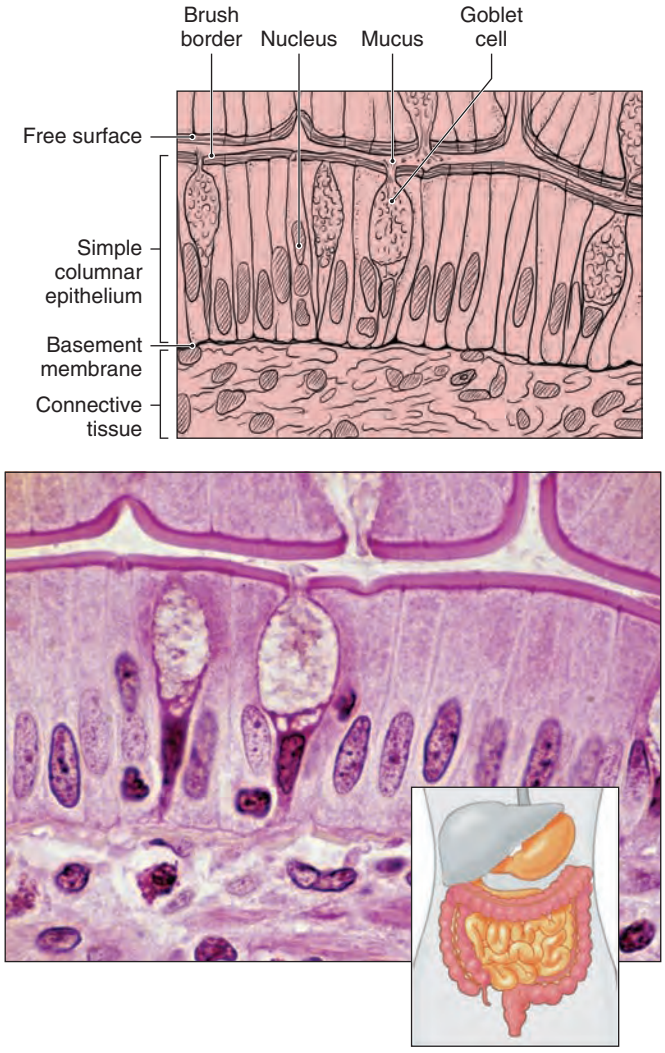


Figure 4.5 Simple Columnar Epithelium (400×).
Structure: A single layer of columnar cells; contains scattered goblet cells.
Location: Lines the internal surfaces of the stomach and intestines, the ducts of many glands, uterine tubes, paranasal sinuses, and ventricles in the brain.
Function: Absorption, secretion, and protection.

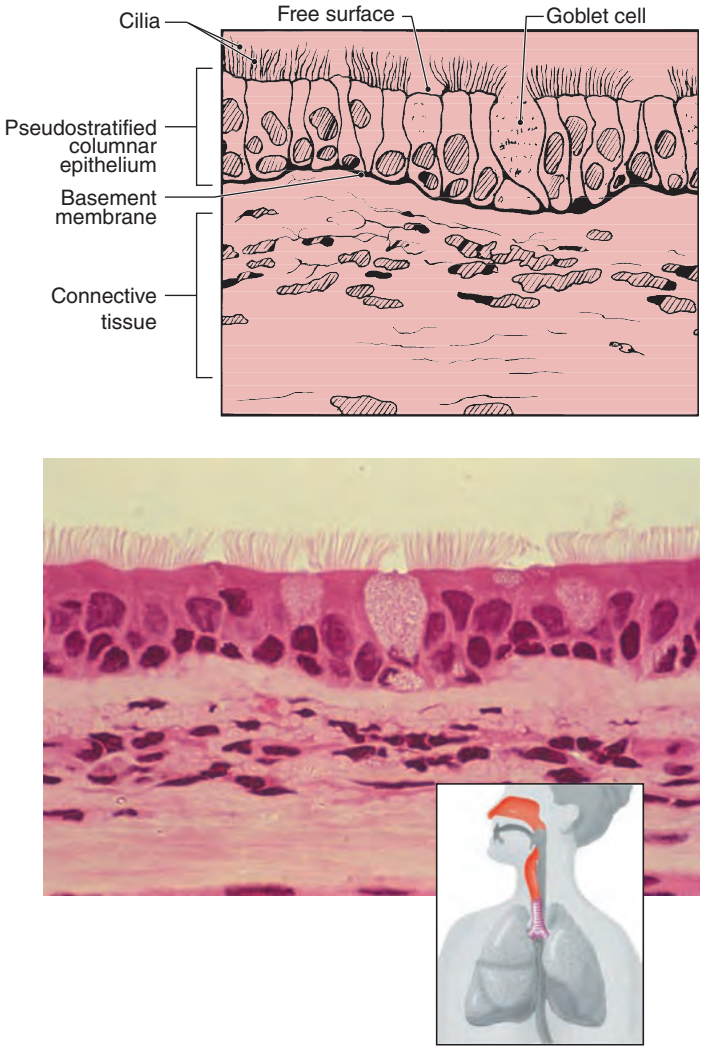


Figure 4.6 Pseudostratified Ciliated Columnar Epithelium (500×).
Structure: A single layer of ciliated columnar cells that appears to be more than one layer of cells; contains scattered goblet cells.
Location: Lines many respiratory passageways.
Function: Secretion of mucus; beating cilia remove secreted mucus and entrapped particles.

particles. The particles are trapped in the secreted mucus, which is moved by the beating cilia to the throat, where it is either swallowed or expectorated (figure 4.6).

Stratified Epithelium

Stratified epithelium consists of more than one layer of cells, which makes them more durable to abrasion (see figure 4.2). Only the deepest layer of cells produces new cells by mitotic cell division. The cells are pushed toward the free surface of the tissue as more new cells are formed deep to them. Cells in the superficial layer are continuously lost as they die and are rubbed off by abrasion. Protection of underlying tissues is an important function of stratified epithelia. These tissues are named according to the shape of cells on their free surfaces.

Stratified squamous epithelium occurs in two distinct forms: keratinized and nonkeratinized. The keratinized type forms the superficial layer (epidermis) of the skin. Its cells become impregnated with a waterproofing protein, **keratin** (ker′-ah-tin), as they migrate to the free surface of the tissue. This specific type of epithelium is discussed

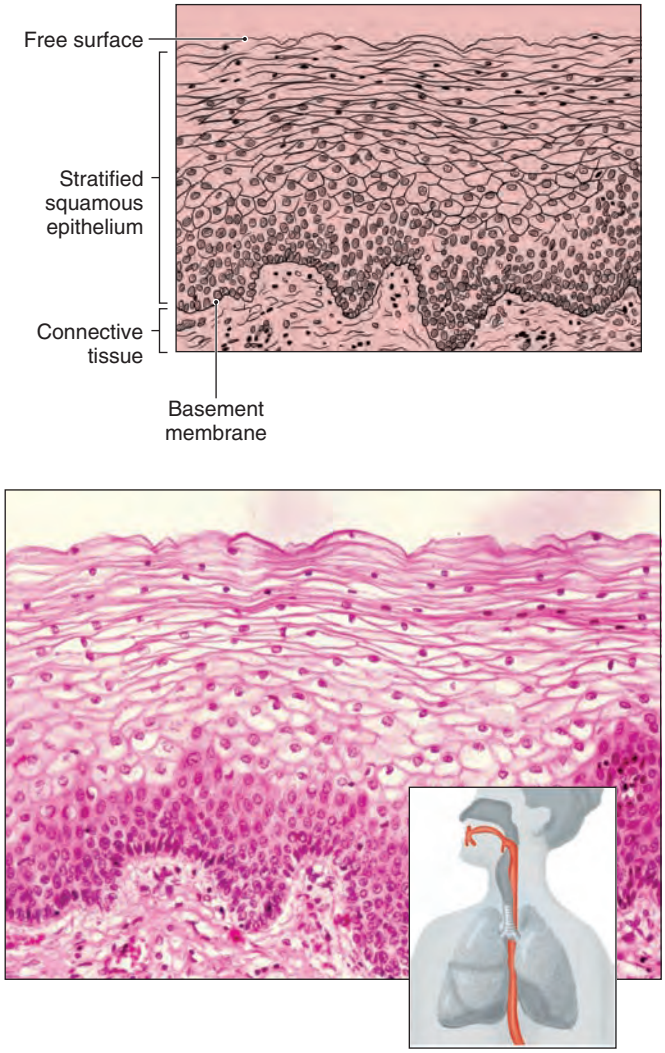


Figure 4.7 Stratified Squamous Epithelium (70×).
Structure: Several cell layers; cells in the deepest layer are cuboidal in shape but gradually become flattened as they migrate to the surface of the tissue.
Location: The keratinized type forms the epidermis of the skin; nonkeratinized type lines the mouth, esophagus, vagina, and rectum.
Function: Protection.

further in chapter 5. The nonkeratinized type lines the mouth, esophagus, vagina, and rectum. Both types provide resistance to abrasion (figure 4.7).

Transitional epithelium lines most of the urinary tract and stretches as these structures fill with urine. It consists of multiple layers of cells, with the free surface cells of the unstretched tissue possessing a large and rounded shape. When stretched, the free surface cells become thin, flat cells resembling squamous epithelial cells (figure 4.8, see figure 4.2).

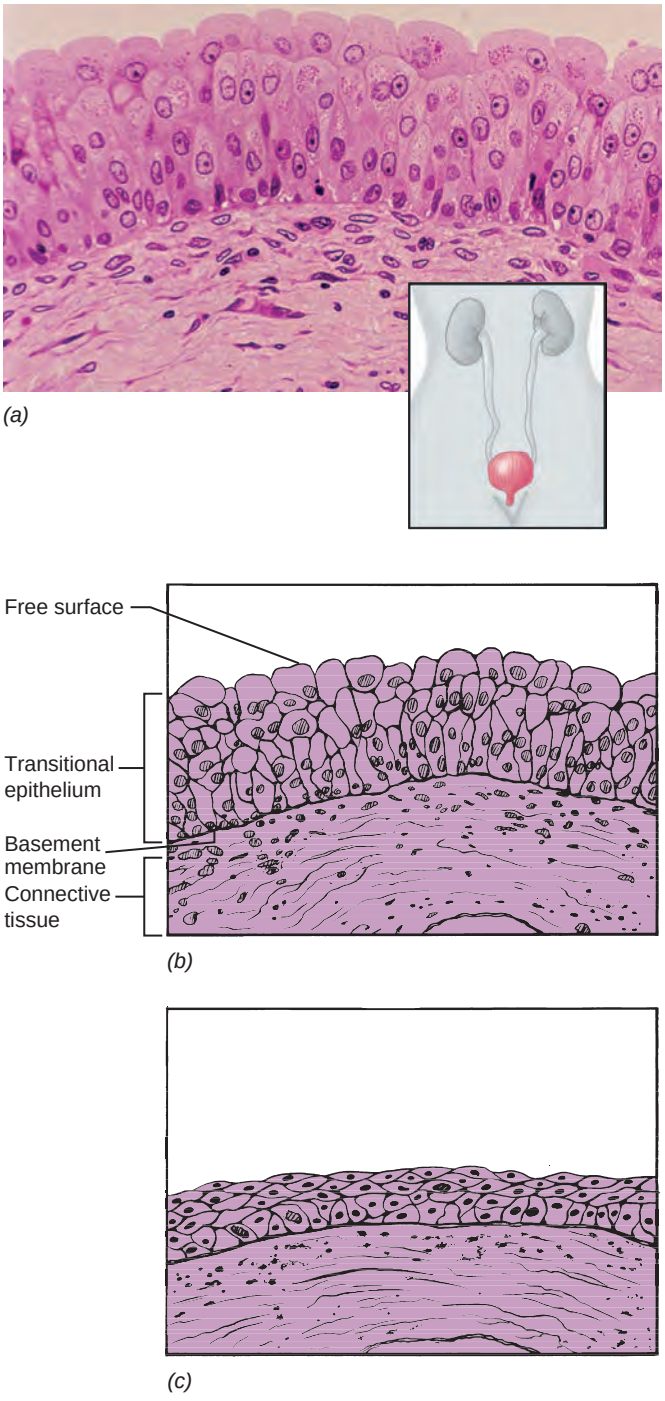


Figure 4.8 Transitional Epithelium.
(a) A photomicrograph (250×) and *(b)* drawing showing several layers of rounded cells when the urinary bladder wall is contracted. *(c)* When the bladder wall is stretched, the tissue and cells become flattened.
Structure: Several layers of large, rounded cells that become flattened when stretched.
Location: Lines the internal surface of the urinary tract.
Function: Protection; permits stretching of the wall of the urinary tract.

Two relatively rare types of stratified epithelial tissues are not shown. *Stratified cuboidal epithelium* lines larger ducts of certain glands (e.g., mammary and salivary glands). *Stratified columnar epithelium* lines parts of the pharynx and male urethra.

Check My Understanding

1. What are the general characteristics and functions of epithelial tissues?
2. How are the various epithelial tissues different in terms of structure, location, and function?

4.2 Connective Tissues

Learning Objectives

3. Describe the distinguishing characteristics of each type of connective tissue.
4. Identify the common locations and general functions of each type of connective tissue.

Connective tissues are the most widely distributed and abundant tissues in the body. As the name implies, connective tissues support and bind together other tissues so they are never found on exposed surfaces. Like epithelial cells, most connective tissue cells have retained the ability to reproduce by mitotic cell division.

Connective tissues consist of a diverse group of tissues that can be divided into three broad categories: (1) loose connective tissues, (2) dense connective tissues, and (3) connective tissues with specialized functions–cartilage, bone, blood, and lymph. Loose and dense connective tissues are sometimes referred to as "connective tissue proper" because they are common tissues that function to bind other tissues and organs together.

All connective tissues consist of relatively few, loosely arranged cells and a large amount of extracellular substance called **matrix** (ma'-triks). Matrix, which is produced by the cells, is used to classify connective tissues. It is composed of ground substance and protein fibers. **Ground substance,** which is composed of water and both inorganic and organic compounds, can be fluid, semifluid, gelatinous, or calcified.

Three types of protein fibers are found in the matrix of connective tissues. **Collagen fibers,** composed of collagen protein, are relatively large fibers resembling cords of a rope. They provide strength and flexibility but not elasticity. **Reticular fibers,** also made of collagen, are very thin and form highly branched, delicate, supporting frameworks for tissues. **Elastic fibers** are made of elastin protein and possess great elasticity, which means they can stretch up to 150% their resting length without damage and then recoil back to their resting length.

Clinical Insight

Because epithelial and connective tissue cells are active in cell division, they are prone to the formation of tumors when normal control of cell division is lost. The most common types of cancer arise from epithelial cells, possibly because these cells have the most direct contact with *carcinogens,* cancer-causing agents in the environment. A cancer derived from epithelial cells is called a *carcinoma.* Malignant tumors that originate in connective tissue are also common types of cancer. A cancer of connective tissue is called a *sarcoma.*

Loose Connective Tissue

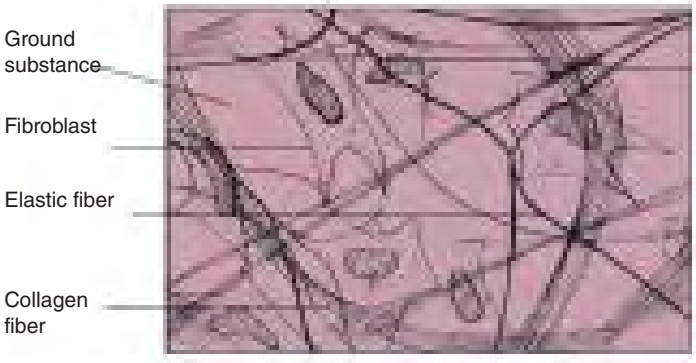
Loose connective tissues help to bind together other tissues and form the basic supporting framework for organs. Their matrix consists of a semifluid or jelly-like *ground substance* in which fibers and cells are embedded. The word "loose" describes how the fibers are widely spaced and intertwined between the cells. **Fibroblasts** are the most common cells and they are responsible for producing the ground substance and protein fibers. There are three types of loose connective tissue: areolar connective tissue, adipose tissue, and reticular tissue.

Areolar Connective Tissue

Areolar (ah-rē'-ō-lar) **connective tissue** is the most abundant connective tissue in the body. Fibroblasts are the most numerous cells, but macrophages are present to help protect against invading pathogens (see chapters 11 and 13). A semifluid ground substance fills the spaces between the cells and fibers. Areolar connective tissue (1) attaches the skin to underlying muscles and bones as part of the subcutaneous tissue (see chapter 5); (2) provides a supporting framework for internal organs, nerves, and blood vessels; (3) is a site for many immune reactions; and (4) forms the superficial region of the dermis, which is the deep layer of the skin (figure 4.9).

Adipose Tissue

Large accumulations of fat cells, or **adipocytes**, form **adipose** (ad'-i-pōs) **tissue,** a special type of loose connective tissue. It occurs throughout the body but is more common deep to the skin, within the subcutaneous tissue, and around internal organs. Adipocytes are filled with fat droplets that push the nucleus and cytoplasm to the edge of the cells. In addition to fat storage, adipose tissue serves as a protective cushion for internal organs, especially around the kidneys and posterior to the eyeballs. It also helps to insulate the body from abrupt temperature changes and, as part of the subcutaneous tissue, to attach skin to underlying bone and muscle (figure 4.10).



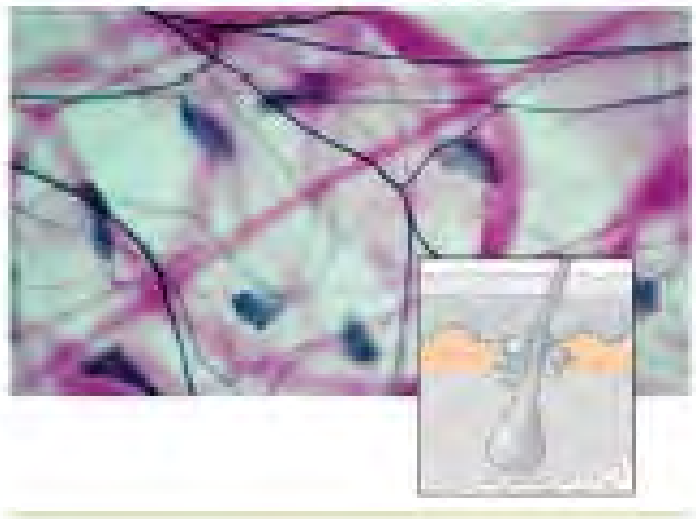


Figure 4.9 Areolar Connective Tissue (250×).
Structure: Formed of scattered fibroblasts and a loose network of collagen and elastic fibers embedded in a gel-like ground substance.
Location & Function: Attaches the skin to underlying muscles and bones as part of the subcutaneous tissue; supports internal organs, blood vessels, and nerves; site for immune reactions; forms the superficial dermis of the skin.

Figure 4.10 Adipose Tissue (250×).
Structure: Formed of closely packed adipocytes with little matrix. Large fat-containing droplet pushes the cytoplasm and nucleus to the edge of the cell.
Location & Function: Stores excess nutrients as fat; provides insulation and attaches skin to underlying bones and muscles as part of the subcutaneous tissue; provides a protective cushion to bones, muscles, and internal organs.

Reticular Tissue

Reticular tissue consists of a fine interlacing of reticular fibers and **reticular cells,** the main cell type in this tissue. Reticular tissue forms a supportive network called a *stroma* that assists in maintaining the structure of red bone marrow and organs such as the liver and spleen. Reticular fibers also act as filters in structures like lymph nodes, where they help to remove bacteria from an extracellular drainage fluid called lymph (figure 4.11).

Dense Connective Tissue

Like loose connective tissues, **dense connective tissues** aid in binding tissues together and providing support for organs. However, dense connective tissue has far fewer cells and ground substance and more numerous, thicker, and "denser" protein fibers. These tissues also contain far fewer blood vessels than loose connective tissues. There are three types of dense connective tissue: dense regular connective tissue, dense irregular connective tissue, and elastic connective tissue.

Dense Regular Connective Tissue

Dense regular connective tissue is characterized by an abundance of tightly packed collagen fibers and relatively few cells. The collagen fibers exist in large bundles that

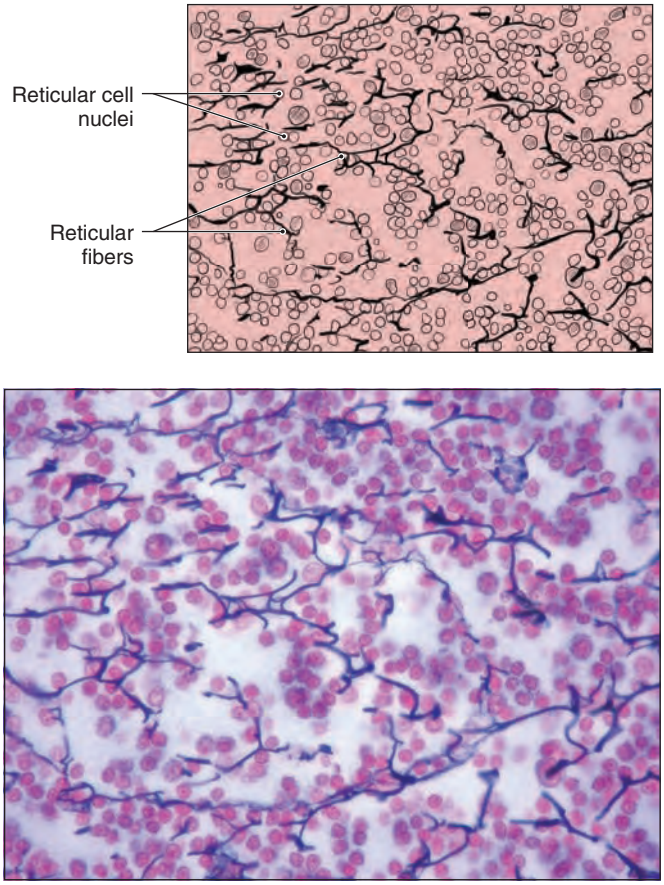


Figure 4.11 Reticular Tissue (400×).
Structure: Formed of reticular cells and a delicate, interwoven network of reticular fibers.
Location & Function: Forms a stroma to maintain the structure of red bone marrow and organs like the liver and spleen; acts as a biological filter in organs like lymph nodes.

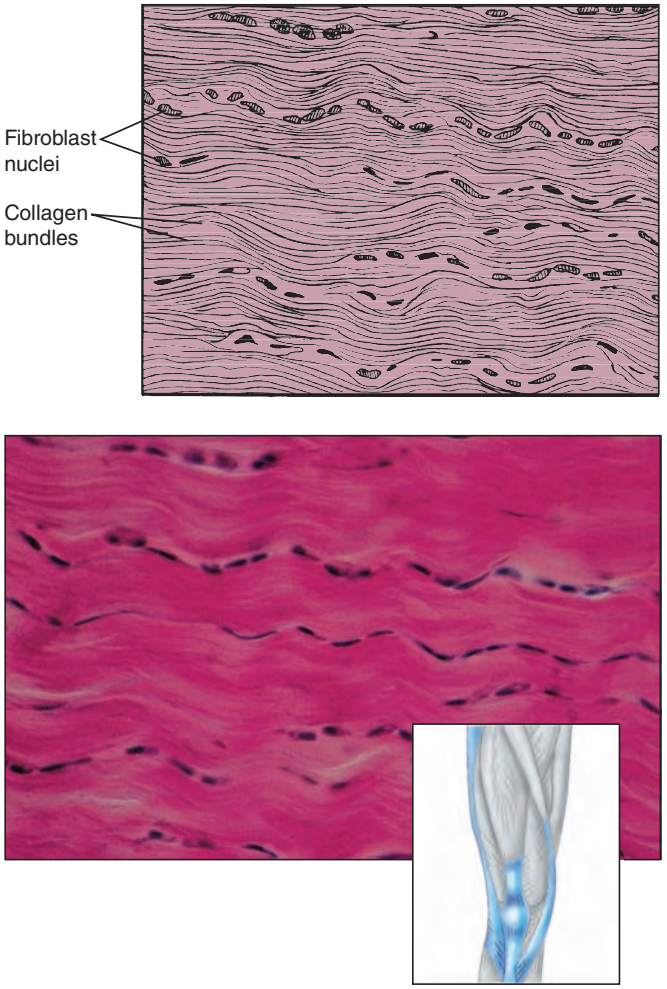


Figure 4.12 Dense Regular Connective Tissue (100×).
Structure: Consists of tightly packed collagen fibers that are separated by scattered rows of fibroblasts.
Location & Function: Strong attachment; forms ligaments attaching bones to bones at joints and tendons attaching muscles to bones.

are "regularly" arranged, meaning they are generally parallel to each other. Fibroblasts are located in rows between the collagen bundles. This tissue exhibits great strength when stress is applied in the same direction as the collagen bundles, meaning this tissue can withstand damage when stress is applied in one direction but not when stress is applied in multiple directions. Dense regular connective tissue is the main tissue in structures such as (1) ligaments, which attach bones to bones, and (2) tendons, which attach skeletal muscles to bones (figure 4.12).

Dense Irregular Connective Tissue

Dense irregular connective tissue is similar in structure to dense regular connective tissue, except for the organization of the collagen bundles. In this tissue, the collagen bundles are "irregularly" arranged, meaning they are oriented in multiple directions throughout the tissue. The irregular arrangement allows this tissue to resist tearing when stress arrives from multiple directions. Dense irregular connective tissue can be found in (1) the deep layer of the skin (dermis), (2) the joint capsules surrounding freely movable joints, (3) the membranes surrounding bone, cartilage, and the heart, (4) heart valves, and (5) membrane capsules surrounding some internal organs (figure 4.13).

Elastic Connective Tissue

An abundance of elastic fibers in the matrix distinguishes **elastic connective tissue.** Collagen fibers are also present,

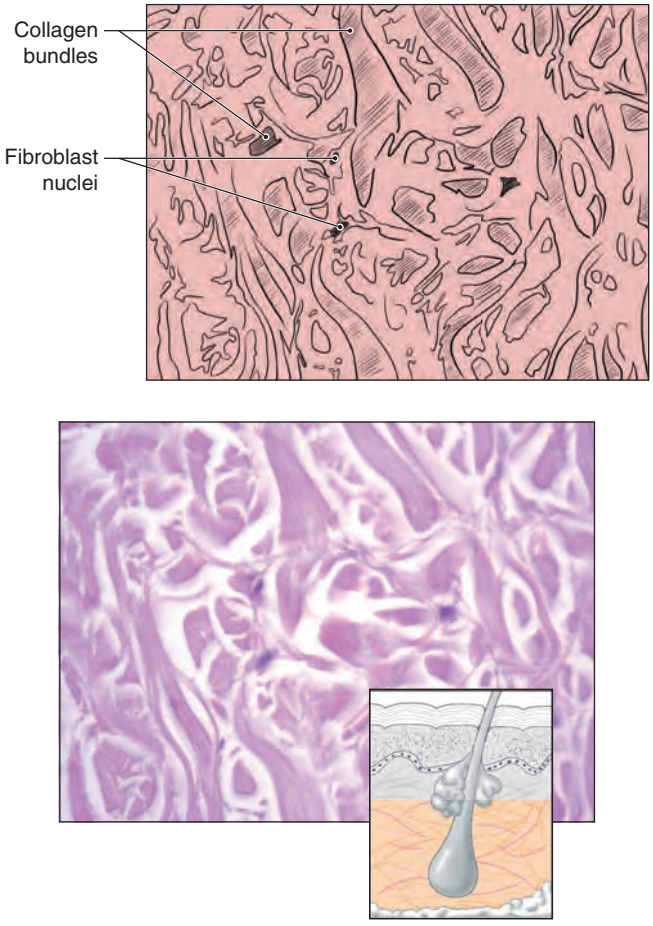


Figure 4.13 Dense Irregular Connective Tissue (400×).
Structure: Consists of tightly packed, irregularly arranged collagen fibers with scattered fibroblasts between the fibers.
Location & Function: Resists tearing with stress in the deep dermis; joint capsules of movable joints; membranes surrounding bone, cartilage, heart, and other internal organs; and heart valves.

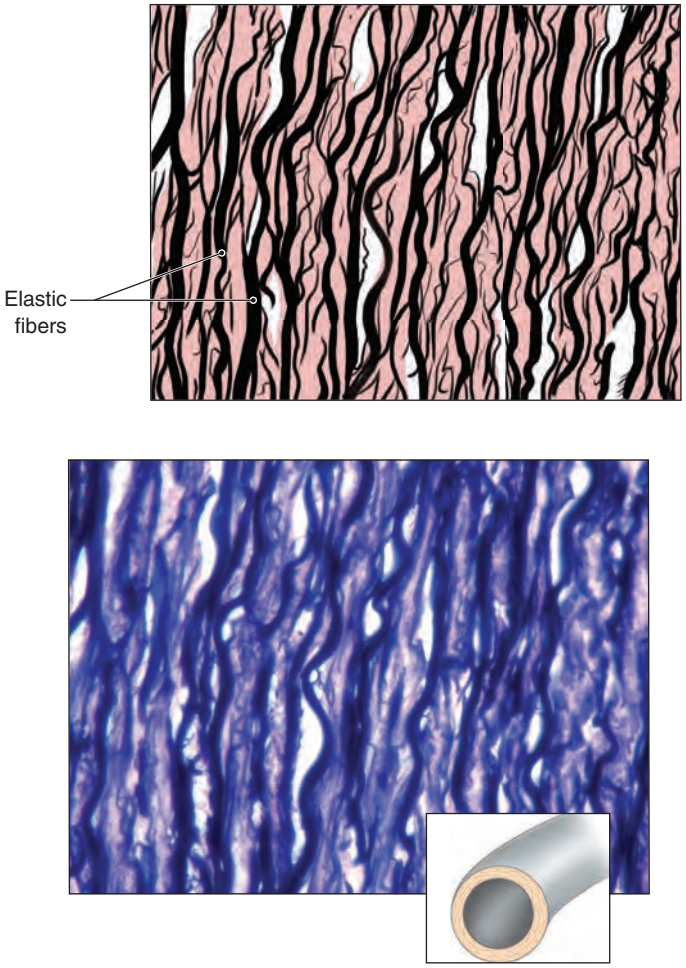


Figure 4.14 Elastic Connective Tissue (400×).
Structure: Consists of tightly packed, regularly arranged elastic fibers with scattered fibroblasts between the fibers.
Location & Function: Allows for elasticity in structures such as the lungs, air passageways, vocal cords, and arterial walls.

and fibroblasts are scattered between the fibers. Elastic connective tissue occurs where extensibility and elasticity are advantageous, such as in the lungs, air passages, vocal folds, and arterial walls. For example, elastic connective tissue enables the expansion of the lungs as air is inhaled and the recoil of the lungs as air is exhaled (figure 4.14).

Cartilage

Cartilage consists of a firm, gelatinous matrix in which cartilage cells, or **chondrocytes** (kon′-drō-sītz), are embedded. The fluid-filled spaces in the matrix that contain the chondrocytes are called **lacunae** (lah-kū′-nē; singular, *lacuna*) which means "little lakes". Cartilage usually lacks blood vessels; this means that these tissues rely on diffusion to obtain needed substances. Because diffusion is slow through cartilage matrix, cellular processes occur at much slower rates. The major functions of cartilage are support and protection. All types of cartilage act as a cushion to absorb shock, and their toughness allows them to be deformed by pressure and return to their original shape when the pressure is removed. Three types of cartilage are present in the body: hyaline cartilage, elastic cartilage, and fibrocartilage.

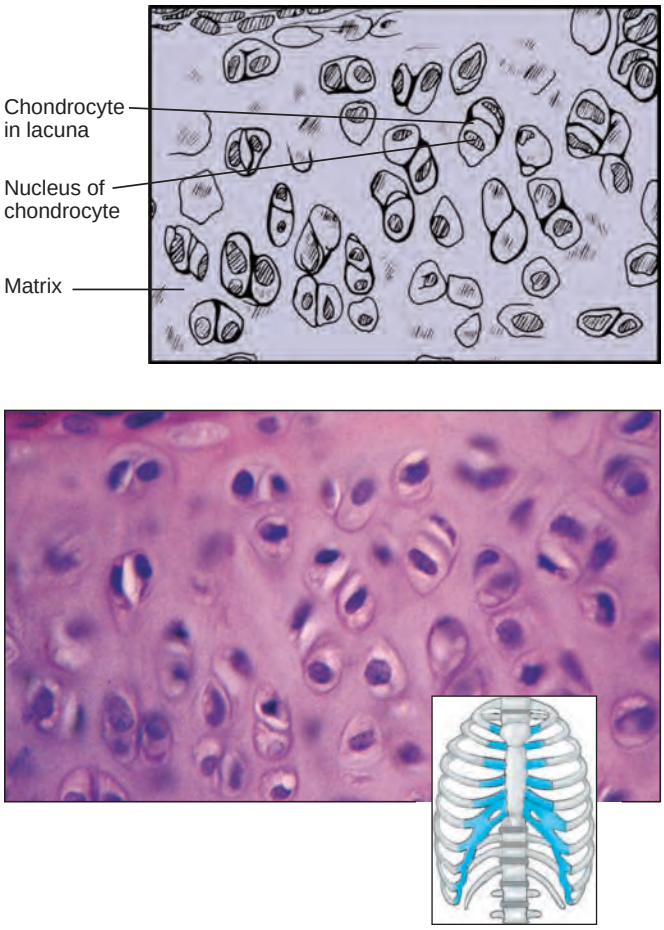


Figure 4.15 Hyaline Cartilage (250×).
Structure: Smooth glassy matrix with many chondrocytes in lacunae.
Location & Function: Forms protective covering of bones at freely movable joints; forms the larynx and part of the nose; attaches ribs to sternum, and supports walls of air passages.

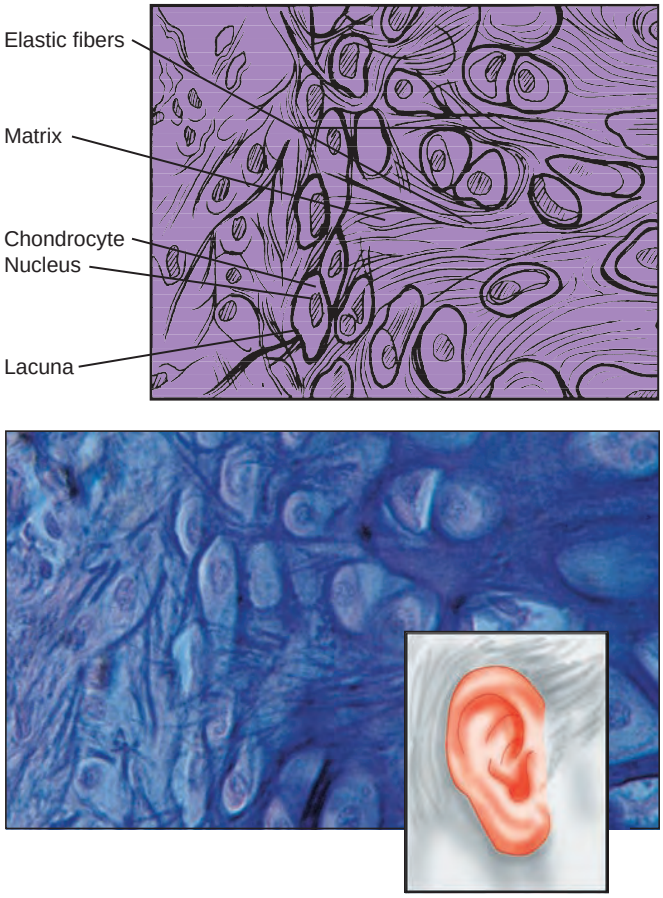


Figure 4.16 Elastic Cartilage (100×).
Structure: Consists of numerous chondrocytes occupying lacunae in a gel-like matrix containing numerous elastic fibers.
Location & Function: Provides the supporting framework for the external ears; forms the auditory tubes that connect the pharynx to the middle ear; forms the epiglottis, which closes the airway when swallowing.

Hyaline Cartilage

Under microscopic examination with standard stains, the matrix of **hyaline** (hī′-a-lin) **cartilage** has a smooth, glassy, bluish white or pinkish white appearance. It contains collagen fibers, but they are not easily visible. Numerous chondrocytes in lacunae are present. Hyaline cartilage is the most abundant cartilage in the body and its functions include (1) providing a protective covering on the bone surfaces forming freely movable joints, (2) forming the larynx, or voicebox, and part of the nose, (3) connecting the ribs to the sternum (breastbone), and (4) supporting the walls of air passages. During embryonic development, most bones of the body are initially formed of hyaline cartilage. Subsequently, the cartilage is gradually remodeled into bone (figure 4.15).

Elastic Cartilage

This tissue is similar to hyaline cartilage, but **elastic cartilage** contains an abundance of elastic fibers that impart greater elasticity and flexibility to the tissue. Elastic cartilage forms (1) the auditory tubes connecting the pharynx (throat) to the middle ear, (2) the epiglottis, a lid that closes the opening into the larynx when swallowing, and (3) the supportive framework for the external ear (figure 4.16).

Fibrocartilage

The matrix of **fibrocartilage** contains many tightly packed collagen fibers that lie between short rows or clumps of chondrocytes. This cartilage forms (1) the intervertebral discs that are located between vertebrae,

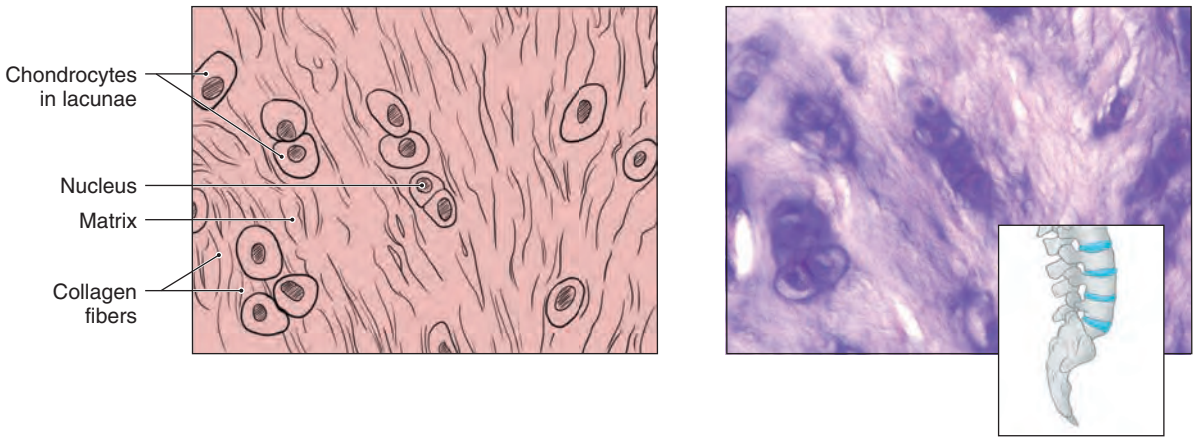


Figure 4.17 Fibrocartilage (250×).
Structure: Consists of rows or clusters of chondrocytes occupying lacunae in a matrix containing tightly packed collagen fibers.
Location & Function: Composes the intervertebral discs between vertebrae, the pubic symphysis, and cartilaginous pads in the knee joint where it serves as a protective shock absorber.

(2) the cartilaginous pads in the knee joints, and (3) the protective cushion of the pubic symphysis (anterior union of the pelvic bones). Fibrocartilage is especially tough, and the dense collagen fibers enable it to absorb greater shocks and pressure without permanent damage (figure 4.17).

Bone

Of all the supportive connective tissues, **bone,** also called *bone tissue* or *osseous tissue,* is the hardest and most rigid. This results from the minerals, mostly calcium salts, that compose the matrix along with some collagen fibers. Bone provides the rigidity and strength necessary for the skeletal system to support and protect the body. There are two types of bone: **compact bone** and **spongy bone** (figure 4.18).

In compact bone, bone matrix is deposited in concentric rings, called **lamellae** (lah-mel'-e), around microscopic tubes called **central** (or **osteonic**) **canals.** These canals contain blood vessels and nerves. A central canal and the lamellae surrounding it form an **osteon,** the structural unit of compact bone. Spongy bone does not possess osteons; rather, the lamellae are organized into thin, interconnected bony plates called **trabeculae.** The spaces between trabeculae are filled with highly vascular red or yellow bone marrow. Bone cells, or **osteocytes,** are located in lacunae that are located between lamellae in both types of bone. The tiny, fluid-filled canals that extend outward from the lacunae are called **canaliculi** (kan″-ah-lik′-u-li; singular, *canaliculus*) and they contain cell processes from osteocytes. Canaliculi serve as passageways for the movement of materials between osteocytes and the blood supply within the central canals and bone marrow. Bone will be discussed further in chapter 6.

Blood

Blood is a specialized type of connective tissue, called a fluid connective tissue. It consists of numerous **formed elements** that are suspended in the plasma, the liquid matrix of the blood. There are three basic types of formed elements: red blood cells, white blood cells, and platelets (figure 4.19).

Blood plays a vital role in carrying materials and gases throughout the body. For example, blood is used to carry nutrients absorbed by the digestive tract to cells throughout the body and wastes produced by body cells to the kidneys for elimination. The formed elements also perform crucial body functions. **Red blood cells** are used primarily to transport O_2 molecules and, to a lesser degree, CO_2 molecules. **White blood cells** carry out various defensive and immune functions throughout the body. **Platelets** play a crucial role in the process of blood clotting. Blood is discussed in more depth in chapter 11.

Check My Understanding

3. What are the general characteristics and functions of connective tissue?
4. What are the characteristics, locations, and functions of the different connective tissues?

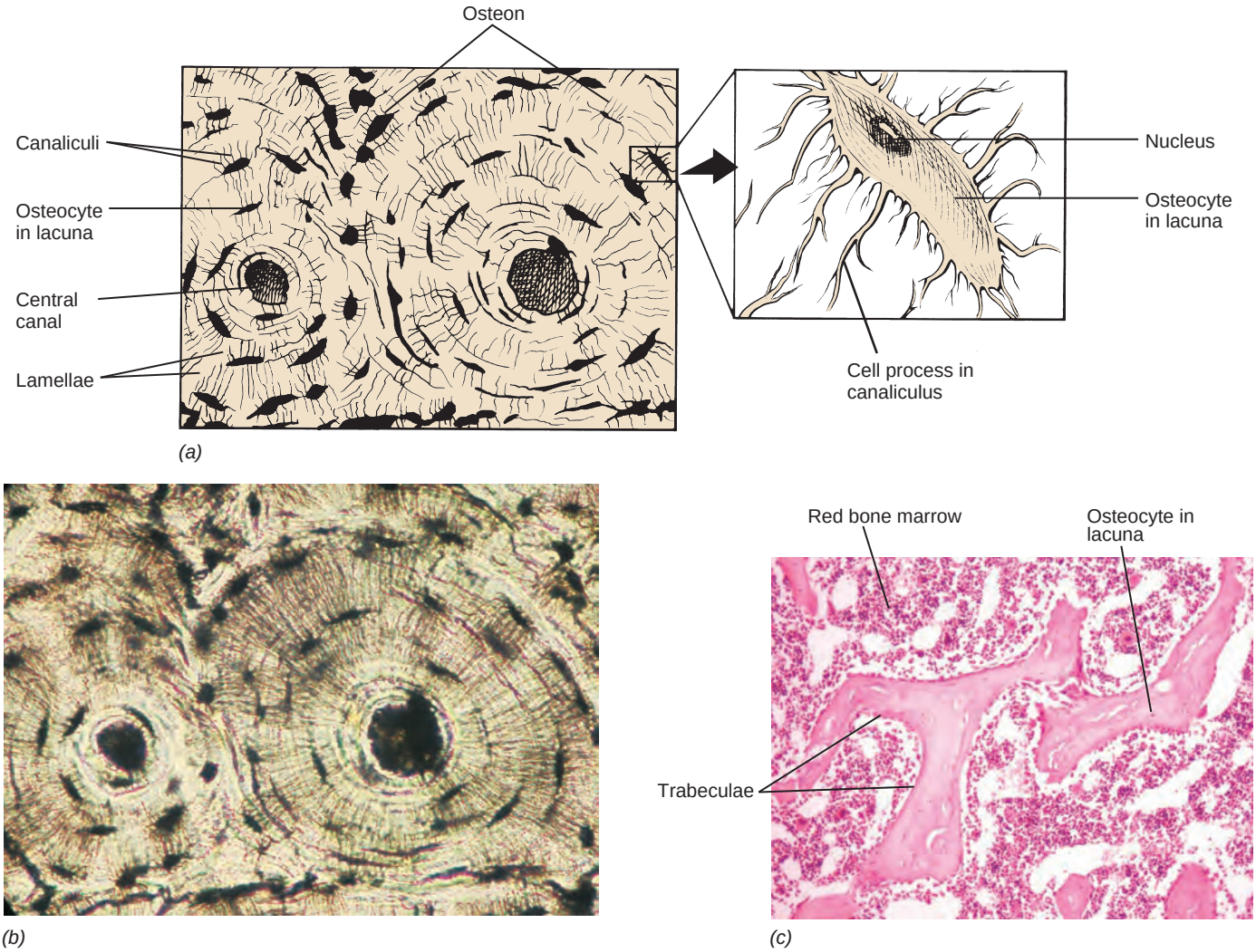


Figure 4.18 *(a) (b)* Compact bone (160×) *(c)* Spongy Bone (100×).
Structure: In compact bone, matrix is arranged in concentric layers around central canals. In spongy bone, the bone layers form thin, bony plates called trabeculae. Osteocytes are found within lacunae located between layers of matrix. Canaliculi, minute channels between lacunae, enable movement of materials between osteocytes in both compact and spongy bone.
Location & Function: Forms bones of the skeleton that provide support for the body and protection for vital organs.

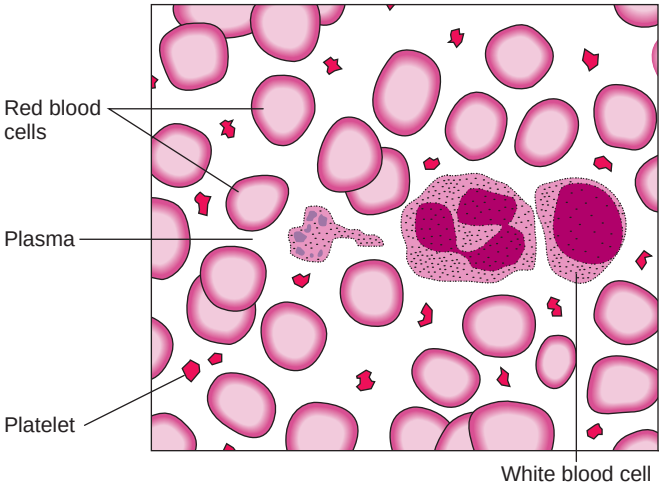
4.3 Muscle Tissues

Learning Objectives

5. Describe the distinguishing characteristics and locations of each type of muscle tissue.
6. Identify the general functions of each type of muscle tissue.

Muscle tissue consists of muscle cells. Muscle cells have lost the ability to divide, so destroyed muscle cells cannot be replaced. In skeletal muscle tissue, muscle cells are called **muscle fibers** owing to their long, cylindrical appearance. The cells in smooth and cardiac muscle tissue are not long and cylindrical, so they are referred to as muscle cells but not muscle fibers. The cells within all three types of muscle tissue are specialized for contraction (shortening). Contraction is enabled by the interaction of specialized protein fibers. The contraction of these tissues enables the movement of the whole body and many internal organs, in addition to producing heat energy.

Three types of muscle tissue–skeletal, cardiac, and smooth muscle tissue–are classified according to their (1) location in the body, (2) structural features, and (3) functional characteristics.



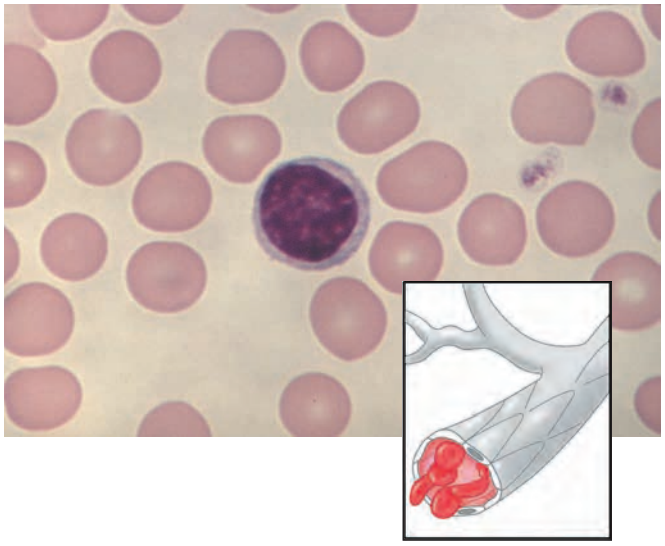


Figure 4.19 Blood (1,000×).
Structure: Consists of red blood cells, white blood cells, and platelets that are carried in a liquid matrix called plasma.
Location & Function: Located within blood vessels and the heart; transports materials and gases throughout the body, participates in blood clotting process, provides defense against disease.

Skeletal Muscle Tissue

Named for its location, **skeletal muscle tissue** is usually attached to bones and skin. Its contractions enable movement of the head, trunk, and limbs. The muscle fibers are wide, elongated, and cylindrical. Each skeletal muscle fiber contains multiple nuclei, which are located along the periphery of the fiber. *Striations,* alternating light and dark bands, extend across the width of the fibers.

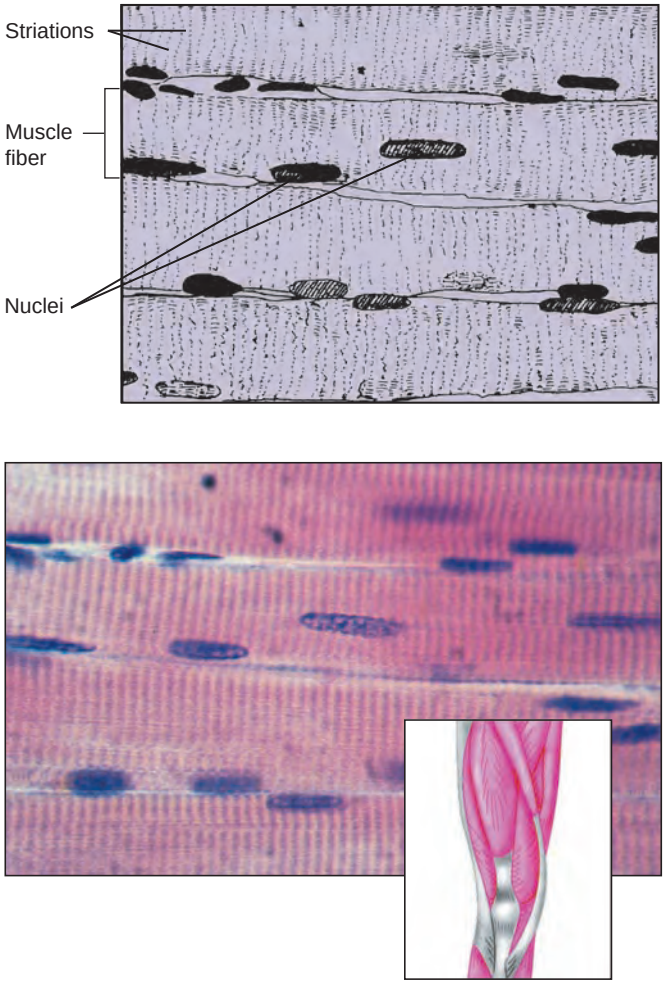


Figure 4.20 Skeletal Muscle Tissue (250×).
Structure: Consists of cylindrical muscle fibers that have striations and multiple, peripherally located nuclei.
Location & Function: Composes skeletal muscles that attach to bones and skin; voluntary, rapid contractions.

Functionally, skeletal muscle tissue is considered to be **voluntary** muscle because its rapid contractions can be consciously controlled (figure 4.20). Skeletal muscle tissue is discussed in greater detail in chapter 7.

Cardiac Muscle Tissue

The muscle tissue located in the walls of the heart is **cardiac** (kar′-dē-ak) **muscle tissue.** It consists of branching cells that interconnect in a netlike arrangement. **Intercalated** (in-ter-kah′-lā-ted) **discs** are present where the cells join together. Cardiac muscle cells are striated like skeletal muscle fibers but possess only one centrally located nucleus per cell. The rhythmic

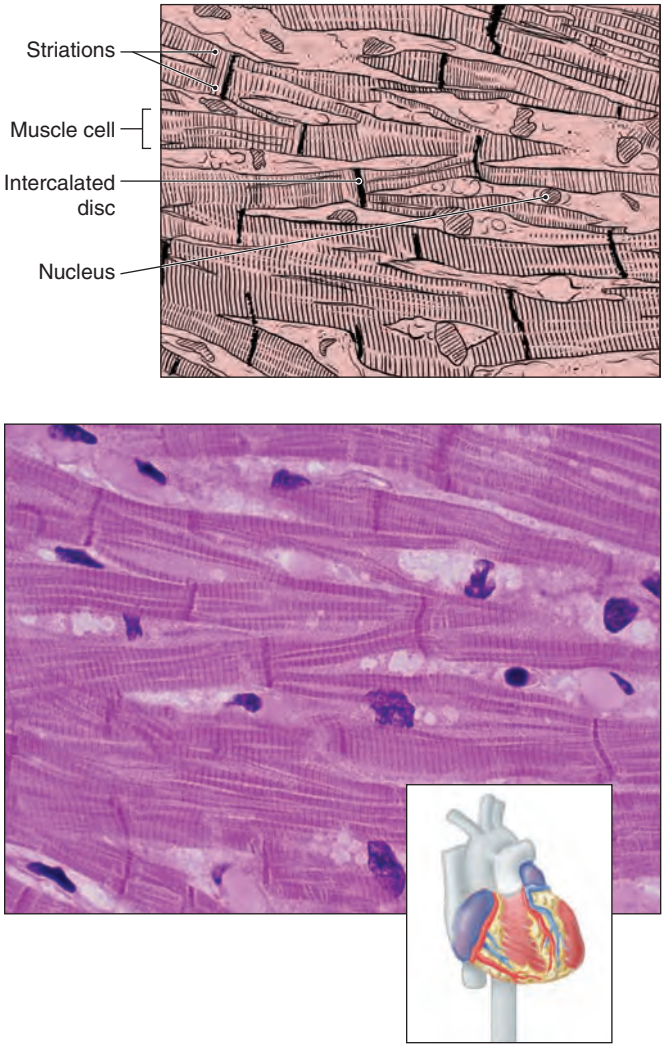


Figure 4.21 Cardiac Muscle Tissue (400×).
Structure: Consists of striated cells that are arranged in an interwoven network. Intercalated discs are present at the junctions between cells. A single, centrally located nucleus is present in each cell.
Location & Function: Forms the muscular walls of the heart; involuntary, rhythmic contractions.

contractions of cardiac muscle are **involuntary** because they cannot be consciously controlled (figure 4.21).

Smooth Muscle Tissue

Smooth muscle tissue derives its name from the absence of striations in its cells. It occurs in the walls of hollow internal organs, such as the stomach, intestines, urinary bladder, and blood vessels. The cells are long and spindle-shaped with a single, centrally located nucleus. The slow contractions of smooth muscle tissue are *involuntary* (figure 4.22).

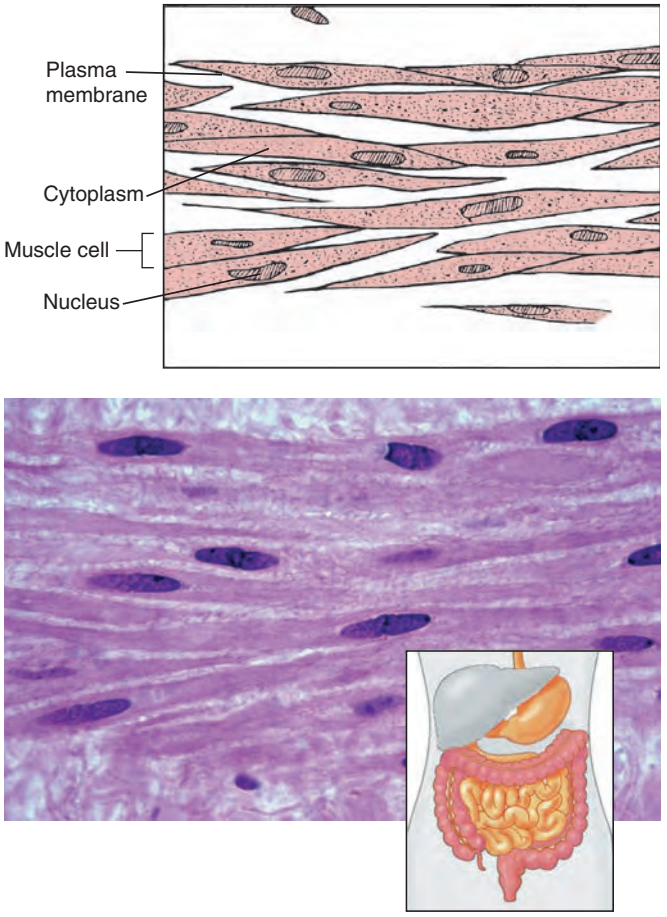


Figure 4.22 Smooth Muscle Tissue (250×).
Structure: Consists of elongate, tapered cells that lack striations and have a single, centrally located nucleus.
Location & Function: Forms muscle layers in the walls of hollow internal organs; involuntary, slow contractions.

4.4 Nervous Tissue

Learning Objectives

7. Describe the distinguishing characteristics and general functions of nervous tissue.
8. Identify the common locations of nervous tissue.

The brain, spinal cord, and nerves are composed of **nervous tissue,** which consists of **neurons** (nū′-ronz), or nerve cells, and numerous supporting cells that are collectively called **neuroglia** (nū-rog′-lē-ah). Neurons are the functional units of nervous tissue. They are specialized to detect and respond to environmental changes by generating and transmitting nerve impulses. Neuroglia nourish, insulate, and protect the neurons.

A neuron consists of a **cell body,** the portion of the cell containing the nucleus, and one or more *neuronal*

Figure 4.23 Nervous Tissue (50×).
Structure: Consists of neurons and neuroglia. Each neuron consists of a cell body, which houses the nucleus, and one or more neuronal processes extending from the cell body.
Location & Function: Forms the brain, spinal cord, and nerves; nerve impulse formation and transmission.

processes extending from the cell body (figure 4.23). There are two types of neuronal processes. **Dendrites** respond to stimuli by generating impulses and transmitting them toward the cell body. An **axon** transmits nerve impulses away from the cell body and dendrites. A neuron may have many dendrites but only one axon. The complex interconnecting network of neurons enables the nervous system to coordinate body functions. Nervous tissue is discussed in more detail in chapter 8.

Clinical Insight

Following minor injuries, tissues repair themselves by *regeneration*—the division of the remaining intact cells. The capacity to regenerate varies among different tissues. For example, epithelial tissues, loose connective tissues, and bone readily regenerate, but cartilage and skeletal muscle have little capacity for regeneration. Cardiac muscle never regenerates, and neurons in the brain and spinal cord usually do not regenerate.

After severe injuries, repair involves **fibrosis,** the formation of scar tissue. Scar tissue is formed by an excess production of collagen fibers by fibroblasts. Scar tissues that join together tissues or organs abnormally are called *adhesions,* which sometimes form following abdominal surgery.

Check My Understanding

5. What are the distinguishing characteristics, locations, and functions of the three types of muscle tissue?
6. What types of cells form nervous tissue and what are their functions?

4.5 Body Membranes

Learning Objectives

9. Compare epithelial and connective tissue membranes.
10. Describe the locations and functions of each type of epithelial membrane.
11. Identify examples of connective tissue membranes.

Membranes of the body are thin sheets of tissue that line cavities, cover surfaces, or separate tissues or organs. Some are composed of both epithelial and connective tissues; others consist of connective tissue only.

Epithelial Membranes

Sheets of epithelial tissue overlying a thin supporting framework of areolar connective tissue form the epithelial membranes in the body. Blood vessels in the connective tissue serve both connective and epithelial tissues. There are three types of epithelial membranes: serous, mucous, and cutaneous membranes (figure 4.24).

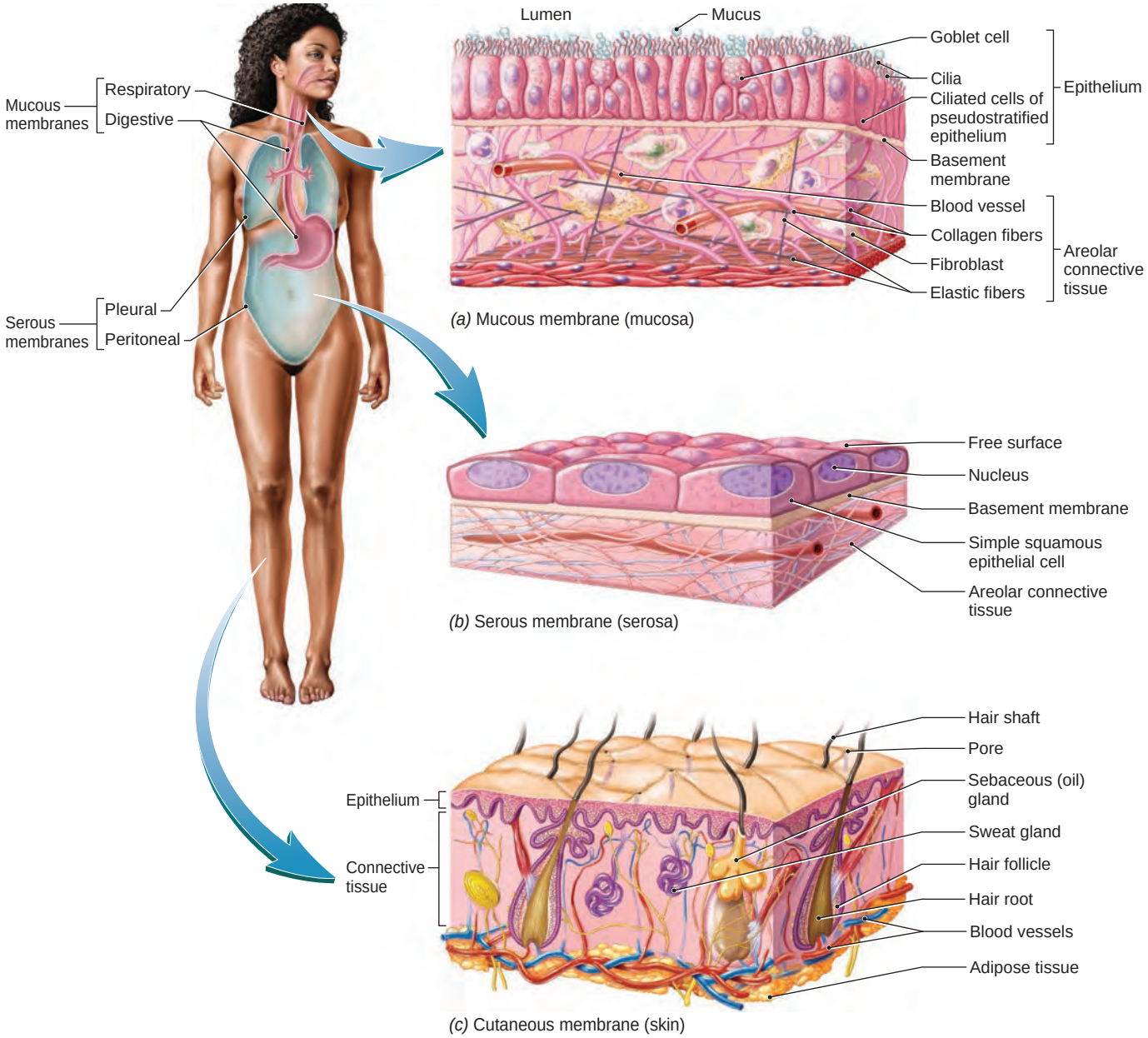


Figure 4.24 Epithelial Membranes.

Serous membranes, or *serosae,* line the ventral body cavity and cover most of the internal organs. They secrete **serous fluid,** a watery fluid, which reduces friction between the membranes. The pleurae, pericardium, and peritoneum are serous membranes. Recall that the epithelium of a serous membrane is a special tissue called mesothelium.

Mucous membranes, or *mucosae,* line tubes or cavities of organ systems, which have openings to the external environment. Their goblet cells secrete **mucus,** which coats the surface of the membranes to keep the cells moist and to lubricate their surfaces. The mucus also helps to trap foreign particles and pathogens, which limits their ability to enter the body. The digestive, respiratory, reproductive, and urinary tracts are lined with mucous membranes.

The **cutaneous membrane** is the skin that covers the body. Unlike other membranes, its free surface is dry, composed of nonliving cells, and exposed to the external environment. The skin is discussed in detail in chapter 5.

Connective Tissue Membranes

Some specialized membranes are formed only of connective tissue, usually dense irregular connective tissue. These

are considered in future chapters with their respective organ systems, but here are four examples:

1. The **meninges** are three connective tissue membranes that envelop the brain and spinal cord.
2. The **perichondrium** is a connective tissue membrane covering the surfaces of cartilage. It contains blood vessels, which supply cartilage through diffusion.
3. The **periosteum** is a connective tissue membrane that covers the surfaces of bones. It contains blood vessels that enter and supply the bone.
4. **Synovial membranes** line the cavities of freely movable joints, such as the knee joint. They secrete watery synovial fluid, which reduces friction in the joint.

Check My Understanding

7. What are the two kinds of body membranes?
8. How do the structures, locations, and functions of the epithelial membranes differ?

Chapter Summary

- As cells specialize during embryonic development, they form groups of similar cells called tissues.
- The body is formed of four basic types of tissues: epithelial, connective, muscle, and nervous tissues.

4.1 Epithelial Tissues

- Epithelial tissue covers surfaces of organs and of the body and lines the body cavities.
- Epithelial tissue is composed of closely packed cells with little extracellular material.
- Epithelial tissues are attached to underlying connective tissue by a noncellular basement membrane.
- Epithelial tissue lacks blood vessels.
- Epithelial tissues function in absorption, secretion, filtration, diffusion, osmosis, protection, and friction reduction.
- Epithelial tissues are classified according to the number of cell layers and the shape of the free surface cells. The epithelial tissues are

Simple Epithelium
- squamous
- cuboidal
- columnar
- pseudostratified ciliated columnar

Stratified Epithelium
- stratified squamous
- transitional

4.2 Connective Tissues

- Connective tissue is composed of relatively few cells located within a large amount of matrix.
- All but cartilage are supplied with blood vessels.
- Connective tissue binds other tissues together and provides support and protection for organs and the body.
- Connective tissue is classified according to the nature of the matrix. The connective tissues are

Loose Connective Tissue
- Areolar connective tissue
- Adipose tissue
- Reticular tissue

Dense Connective Tissue
- Dense regular connective tissue
- Dense irregular connective tissue
- Elastic connective tissue

Cartilage
- Hyaline
- Elastic
- Fibrocartilage

Bone

Blood

4.3 Muscle Tissues

- Muscle tissue is composed of muscle cells that are specialized for contraction.
- Contraction of muscle tissue enables movement of the body and internal organs.
- Muscle tissue is classified according to its location in the body, the characteristics of the muscle cells, and the type of contractions (voluntary or involuntary).
- Three types of muscle tissue are skeletal, cardiac, and smooth muscle tissue.

4.4 Nervous Tissue

- Nervous tissue consists of neurons and neuroglia.
- Neurons consist of a cell body and long, thin neuronal processes, and are adapted to form and conduct nerve impulses.
- Nervous tissue forms the brain, spinal cord, and nerves.

4.5 Body Membranes

- Membranes in the body are either epithelial membranes or connective tissue membranes.
- Epithelial membranes are composed of both epithelial and connective tissues, while connective tissue membranes are composed of connective tissue only.
- There are three types of epithelial membranes: serous, mucous, and cutaneous.
- Examples of connective tissue membranes are meninges, perichondrium, periosteum, and synovial membranes.

Self-Review

Answers are located in Appendix B.

1. Simple epithelial tissues consist of _____ layer(s) of cells.
2. Epithelial tissue contains _____ (little/much) extracellular material.
3. Many respiratory passageways are lined with _____ epithelium.
4. The stomach and intestines are lined with _____ epithelium.
5. Protection from abrasion is the function of _____ epithelium.
6. The extracellular substance in connective tissues is called _____.
7. _____ fibers provide tissues with great strength and flexibility.
8. Triglycerides are stored within the cells of _____ tissue.
9. Cushioning pads in the knee joint are composed of _____.
10. Muscle tissue in the wall of the heart is _____ muscle tissue.
11. Muscle tissue lacking striations and found in walls of the digestive tract is _____ muscle tissue.
12. Nervous tissue consists of neurons and supporting _____.
13. Membranes lining digestive, respiratory, and urinary tracts are classified as _____ membranes.

Critical Thinking

1. Explain why healing a torn ligament can be problematic.
2. Why is stratified squamous epithelium not found within the lungs?
3. Why is it important for homeostasis that cardiac and smooth muscle tissue are involuntary?
4. How are skeletal muscle tissue, dense regular connective tissue, and bone involved in movement of limbs?

4

CHAPTER

Skeletal System

Steven and his friends are amateur skateboarders hanging out at their city skate park. At the urging of his friends, Steven decides to try a 360° spin for the very first time even though he has forgotten his helmet and other safety gear. As he reaches the top of the ramp and begins his spin, his right foot slips off the skateboard, disturbing his balance. Steven throws his arms out to brace his fall but he is unable to keep his head from impacting the ramp as he rolls to the bottom. He sits up and rubs his head, stunned from the fall. His friends race down and begin to check Steven's limbs for fractures. Thankfully, the dense minerals in the bones of his arms and legs were able to resist fracturing. His skull was also hard enough to protect his brain from damage when it hit the ground. Covered in minor cuts and abrasions, Steven stands up and grabs his skateboard. Without even a thought, he fearlessly walks back to the top of the ramp, convinced that he will conquer the 360° spin today.

CHAPTER OUTLINE

SELECTED KEY TERMS

Amphiarthrosis (amphi = two-sided; arthrosis = joint) A slightly movable joint.
Articulation (articul = joint) A joint formed between two bones or between a bone and a tooth.
Compact bone Dense bone formed of numerous tightly packed osteons.
Diaphysis (dia = through, apart; physis = to grow) The shaft of a long bone.
Diarthrosis (dia = apart, through) A freely movable joint.
Endochondral ossification (endo = inside; chondr = cartilage; oss = bone) The formation of bone within cartilage.
Epiphysial (growth) plate The hyaline cartilage between the epiphysis and diaphysis of a growing long bone.
Epiphysis (epi = upon) The enlarged ends of a long bone.
Intramembranous ossification (intra = inside) The formation of bone within embryonic connective tissue.
Ligament A band or cord of dense regular connective tissue that joins bones together at joints.
Medullary cavity (medulla = marrow) The cavity within the shaft of a long bone that is filled with yellow bone marrow.
Spongy (trabecular) bone Bone composed of interconnected bony plates surrounded by red or yellow bone marrow.
Synarthrosis (syn = together) An immovable joint.
Synovial joint (syn = with; ov = egg) A freely movable joint containing a joint cavity filled with synovial fluid.

THE SKELETAL SYSTEM SERVES as the supporting framework of the body, and performs several other important functions as well. The body shape, mechanisms of movement, and erect posture observed in humans would be impossible without the skeletal system. Two very strong tissues, bone and cartilage, compose the skeletal system.

6.1 Functions of the Skeletal System

Learning Objective

1. Describe the basic functions of the skeletal system.

The skeletal system performs five major functions:

1. **Support.** The skeleton serves as a rigid supporting framework for the soft tissues of the body.
2. **Protection.** The arrangement of bones in the skeleton provides protection for many internal organs. The thoracic cage provides protection for the internal thoracic organs including the heart and lungs; the cranial bones form a protective case around the brain, ears, and all but the anterior portion of the eyes; vertebrae protect the spinal cord; and the pelvic girdle protects some reproductive, urinary, and digestive organs.
3. **Attachment sites for skeletal muscles.** Skeletal muscles are attached to bones and extend across articulations. Bones function as levers, enabling movement at joints when skeletal muscles contract.
4. **Blood cell production.** The red bone marrow in spongy bone produces formed elements.
5. **Mineral storage.** The matrix of bones serves as a storage area for large amounts of calcium salts, which may be removed for use in other parts of the body when needed.

6.2 Bone Structure

Learning Objectives

2. List the types of bones based on their shapes.
3. Describe the gross structure and microstructure of a long bone and a flat bone.

There are approximately 206 bones in an adult and each bone is an organ composed of a number of tissues. Bone tissue forms the bulk of each bone and consists of both living cells and a nonliving matrix formed primarily of calcium salts. Other tissues include cartilage, blood, nervous tissue, adipose tissue, and dense irregular connective tissue.

There are six basic types of bones based on their shapes (figure 6.1). *Short bones* are the bones within the wrist and ankle and they possess a small, boxy appearance. *Long bones* possess a long, skinny shape and are found in the upper and lower limbs, with the exception of the wrists, ankles, and patella (kneecap). *Sutural bones* are small bones that form within the sutures of the skull and they vary in number and location from person to person. Certain skull bones, the ribs, and the sternum (breastbone) are classified as *flat bones*, meaning they are thin, flat, and slightly curved. *Irregular bones*, such as the vertebrae (spinal column), coxal bones (hip bones), and some skull bones, possess irregular shapes with numerous projections. *Sesamoid bones* are unique because

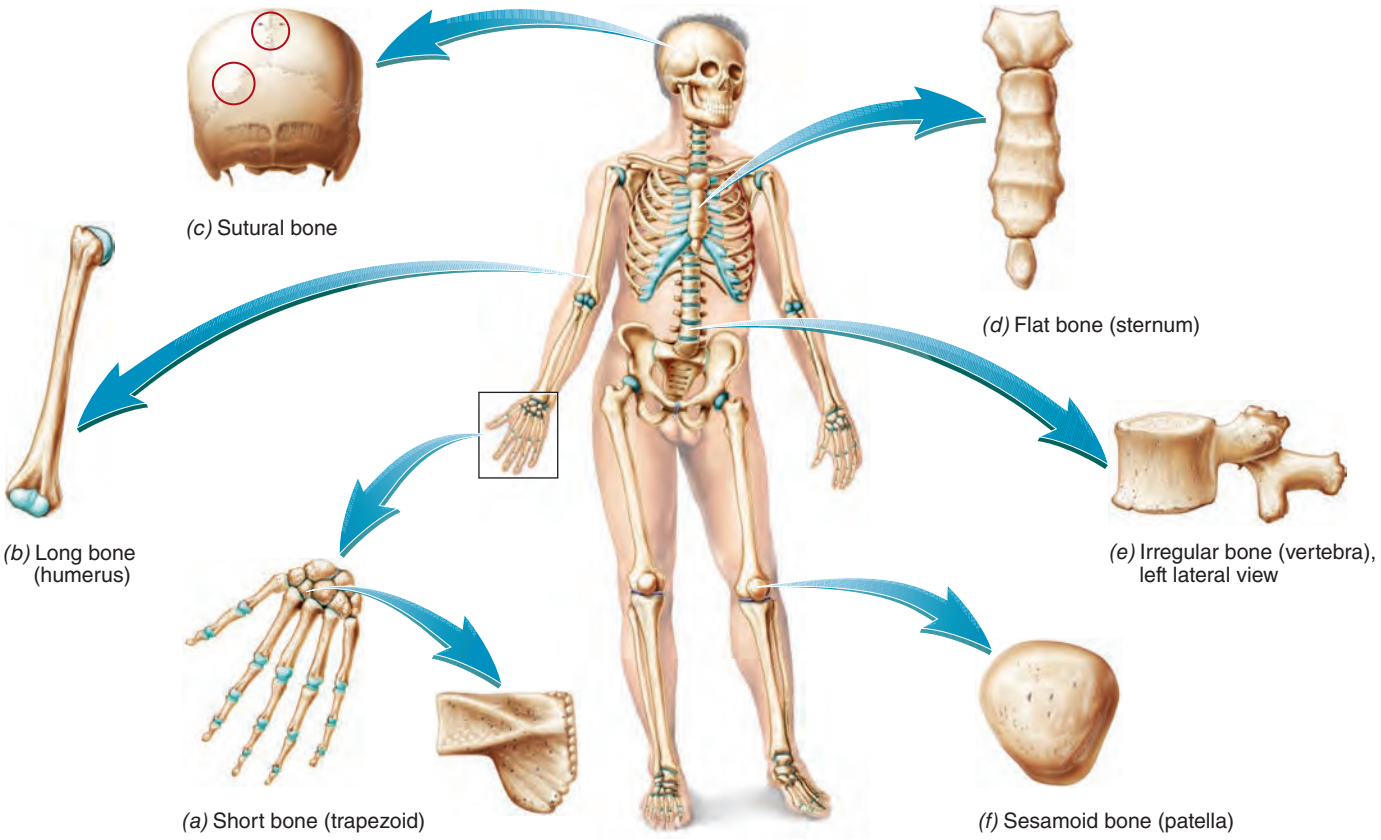


Figure 6.1 Basic Types of Bones.

of their sesame seed shape and the fact that they form inside muscle tendons. The patella is a sesamoid bone.

Gross Structure of a Long Bone

The femur, the bone of the thigh, will be used as an example in considering the structure of a long bone. Refer to figure 6.2 as you study the following section.

At each end of the bone, there is an enlarged portion called an **epiphysis** (ē-pif′-e-sis). The *epiphyses* (plural) articulate with adjacent bones to form joints. The **articular cartilage,** which is composed of hyaline cartilage, covers the articular surface of each epiphysis. Its purpose is to protect and cushion the end of the bone, in addition to providing a smooth surface for movement of joints. The long shaft of bone that extends between the two epiphyses is the **diaphysis** (dī-af′-e-sis). Each epiphysis is joined to the diaphysis by an **epiphysial (growth) plate** of hyaline cartilage in immature bones or by an **epiphysial line,** a line of fusion, in mature bones.

Except for the region covered by articular cartilages, the entire bone is covered by the **periosteum** (per-ē-os′-tē-um), a dense irregular connective tissue membrane that is firmly attached to the underlying bone. The periosteum provides protection and also is involved in the formation and repair of bone. Tiny blood vessels from the periosteum help to nourish the bone.

The internal structure of a long bone is revealed by a longitudinal section. **Spongy (trabecular) bone** forms the internal structure of the epiphyses and the internal surface of the diaphysis wall. It consists of thin rods or plates called *trabeculae* (trah-bek′-u-lē) that form a meshlike framework containing numerous spaces. The trabeculae are covered by a thin connective tissue membrane called **endosteum** (en-dos′-te-um) that is involved in forming and repairing bone. Spongy bone reduces the weight of a bone without reducing its supportive strength. In an adult's long bones, **red bone marrow** fills the spaces between trabeculae within the proximal epiphyses of the humerus and femur. In other epiphyses of the limbs, the spaces between trabeculae are filled with **yellow bone marrow,** which is composed of adipose tissue. The blood-forming properties of red bone marrow will be discussed in chapter 11.

Compact bone forms the wall of the diaphysis and a thin superficial layer over the epiphyses. As the name implies, compact bone is formed of tightly packed bone that lacks the spaces found in spongy bone. Compact bone is very strong, and it provides the supportive strength of long bones. The cavity that extends the length of the

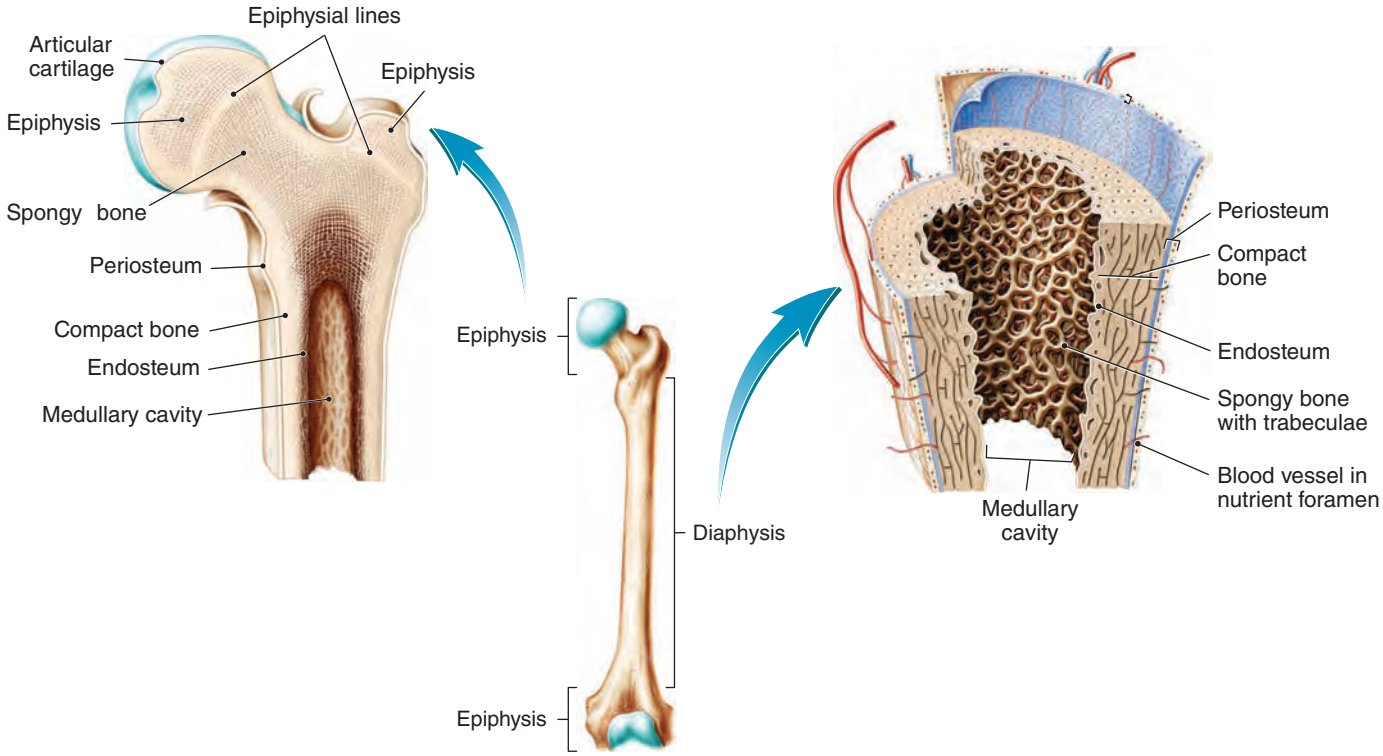


Figure 6.2 The Gross Structure of a Long Bone.

diaphysis is the **medullary cavity**. It is lined by the endosteum and is filled with yellow bone marrow.

Microscopic Structure of a Long Bone

As noted earlier, there are two types of bone: compact bone and spongy bone. When viewed microscopically, compact bone is formed of a number of subunits called osteons (figure 6.3). An **osteon** (os′-tē-on) is composed of a **central canal** containing blood vessels and nerves, surrounded by the **lamellae** (singular, *lamella*), concentric layers of bone matrix. Bone cells, the **osteocytes** (os′-tē-ō-sīẗz), are arranged in concentric rings between the lamellae and occupy tiny spaces in the bone matrix called **lacunae.**

Blood vessels and nerves enter a bone through a **nutrient foramen** (fō-rā′-men; plural, *foramina*), a channel entering or passing through a bone. The blood vessels form branches that pass through *perforating canals* and enter the central canals to supply nutrients to the osteocytes. **Canaliculi** the tiny tunnels radiating from the lacunae, interconnect osteocytes with each other and the blood supply.

The trabeculae of spongy bone lack osteons, so osteocytes receive nutrients by diffusion of materials through canaliculi from blood vessels in the bone marrow surrounding the trabeculae (figure 6.3).

The structure of the other bone types is like that of the epiphyses of long bones. Their external structure is a thin layer of compact bone covered with periosteum; the internal structure is spongy bone covered with endosteum. In most of these bones, red bone marrow fills in the spaces between the trabeculae.

Check My Understanding

1. What are the general functions of the skeletal system?
2. What are the major gross anatomical structures of a long bone?
3. How are compact and spongy bone histologically different?

6.3 Bone Formation

Learning Objectives

4. Compare intramembranous and endochondral ossification.
5. Compare the functions of osteoblasts and osteoclasts.

The process of bone formation is called **ossification** (os-i-fi-kā′-shun). It begins during the sixth or seventh week

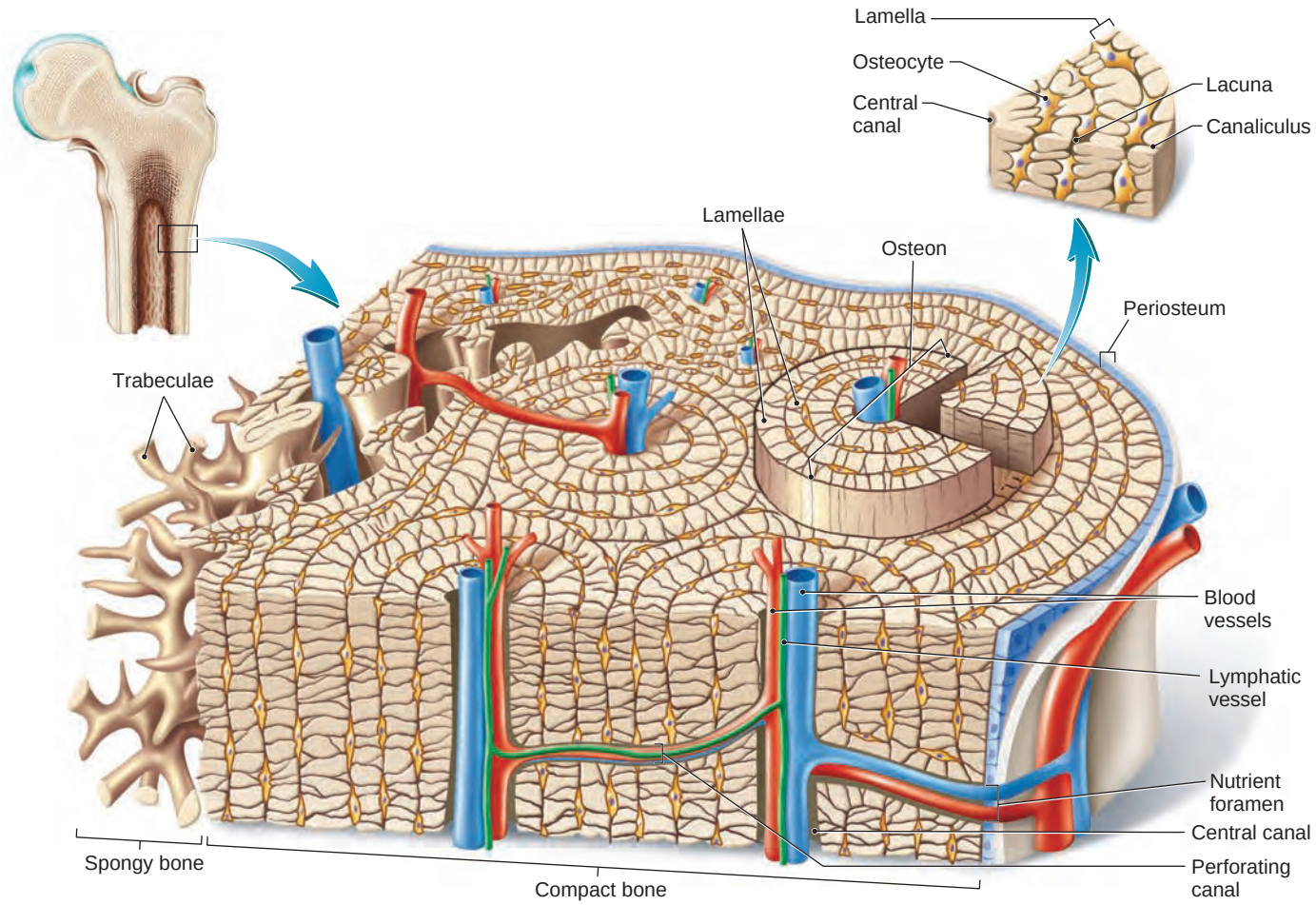


Figure 6.3 Microstructure of a Long Bone.

of embryonic development. Bones are formed by the replacement of existing connective tissues with bone (figure 6.4). There are two types of bone formation: intramembranous ossification and endochondral ossification. Table 6.1 summarizes these.

In both types of ossification, some primitive connective tissue cells are changed into bone-forming cells called **osteoblasts** (os′-tē-ō-blasts). Osteoblasts deposit bone matrix around themselves and soon become imprisoned in lacunae. Once this occurs, they are called osteocytes.

Intramembranous Ossification

Most skull bones are formed by **intramembranous ossification**. Connective tissue membranes form early in embryonic development at sites of future intramembranous bones. Later, some connective tissue cells become osteoblasts and deposit spongy bone within the membranes starting in the center of the future bone. Osteoblasts from the periosteum deposit a layer of compact bone over the spongy bone.

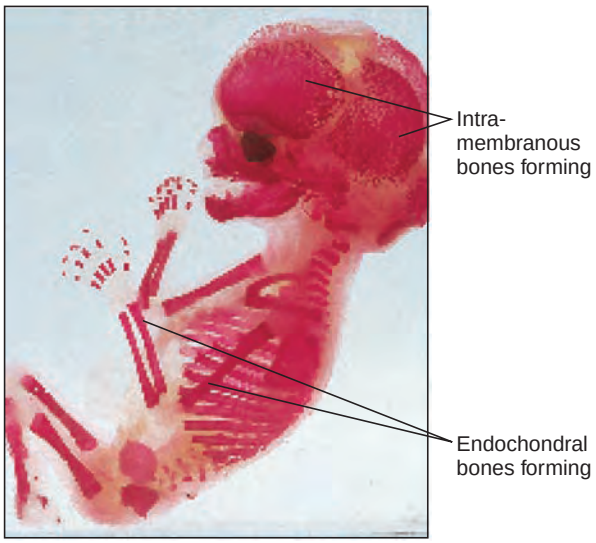


Figure 6.4 The stained developing bones of a 14-week fetus.

Table 6.1 Comparison of Intramembranous and Endochondral Ossification

Intramembranous	Endochondral
1. Membranes of embryonic connective tissue form at sites of future bones.	1. Bone is preformed in hyaline cartilage.
2. Some connective tissue cells become osteoblasts, which deposit spongy bone within the membrane.	2. Osteoblasts of periosteum form a collar of compact bone that thickens and grows toward each end of the bone.
3. Osteoblasts from the enclosing membrane, now called the periosteum, deposit a layer of compact bone over the spongy bone.	3. Cartilage is calcified, and osteoblasts derived from the periosteum form spongy bone, which replaces cartilage in ossification centers. The spongy bone is later removed in the diaphysis to form the medullary cavity.

Some bone must be removed and re-formed in order to produce the correct shape of the bone as it develops and grows. Cells that remove bone matrix are called **osteoclasts.** The opposing actions of osteoblasts and osteoclasts ultimately produce the shape of the mature bone.

Endochondral Ossification

Most bones of the body are formed by **endochondral** (en-dō-kon′-drul) **ossification**. Future endochondral bones are preformed in hyaline cartilage early in embryonic development. Figure 6.5 illustrates the ossification of a long bone.

In long bones, a new periosteum develops around the diaphysis of the hyaline cartilage template. Osteoblasts from the periosteum form a collar of compact bone around the diaphysis. A *primary ossification center* also forms in the middle of the cartilage shaft due to the enlargement of chondrocytes and a loss of cartilage matrix between lacunae. Calcification, which involves the depositing of calcium salts, occurs within the primary ossification center and leads to the death of chondrocytes. Blood vessels and nerves penetrate into the primary ossification center carrying along osteoblasts from the periosteum. As *secondary ossification centers* form in the epiphyses of the cartilage template, osteoclasts begin to remove spongy bone from the diaphysis to form the medullary cavity. The bone continues to grow as ossification progresses. As cartilage continues to be replaced, the cartilage between the primary and secondary ossification centers decreases until only a thin plate of cartilage, the *epiphysial plate,* separates the epiphyses from the diaphysis.

Subsequent growth in diameter results from continued formation of compact bone by osteoblasts from the periosteum. Growth in length occurs as bone replaces cartilage on the diaphysis side of each epiphysial plate while new cartilage is formed on the epiphysis side. The opposing actions of osteoblasts and osteoclasts continually reshape the bone as it grows.

Growth usually continues until about age 25, when the epiphysial plates are completely replaced by bone. After this, growth in the length of a bone is not possible. The visible lines of fusion between the epiphyses and the diaphysis are called *epiphysial lines.*

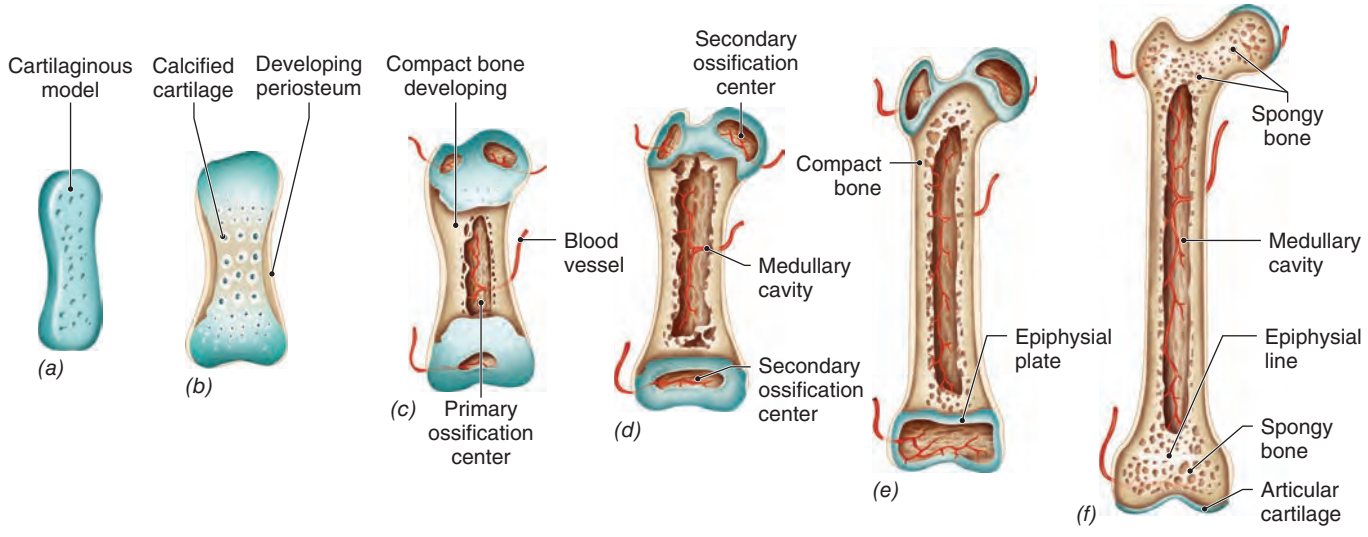


Figure 6.5 Major stages (*a–f*) in the development of an endochondral bone. (Bones are not shown to scale.)

Homeostasis of Bone

Bones are dynamic, living organs, and they are continually restructured throughout life. This occurs by the removal of bone matrix by osteoclasts and by the deposition of new bone matrix by osteoblasts. Physical activity causes the density and volume of bones to be maintained or increased, though inactivity results in a reduction in bone density and volume.

Calcium salts may be removed from bones to meet body needs anytime blood calcium levels are low, such as when dietary intake is inadequate. When dietary calcium intake increases blood calcium to a sufficient level, some calcium is used to form new bone matrix.

Children have a relatively large number of protein fibers in their bone matrix, which makes their bones somewhat flexible. But as people age, the amount of protein gradually decreases. This trend causes older people to have brittle bones that are prone to fractures. Older persons may also experience a gradual loss of bone matrix, which reduces the strength of the bones. A severe reduction in bone density, and therefore increased risk of fracture, is called *osteoporosis*.

Check My Understanding

4. How do intramembranous ossification and endochondral ossification differ?
5. How does physical activity affect the homeostasis of bones?

6.4 Divisions of the Skeleton

Learning Objectives

6. Name the two divisions of the skeleton.
7. Describe the major surface features of the bones and their importance.

The human adult skeleton is composed of two distinct divisions: the axial skeleton and the appendicular skeleton. The **axial** (ak′-sē-al) **skeleton** consists of the bones along the longitudinal axis of the body that support the head, neck, and trunk. The **appendicular** (ap-en-dik′-ū-lar) **skeleton** consists of the bones of the upper limbs and pectoral girdle and of the lower limbs and pelvic girdle (figure 6.6).

A study of the skeleton includes the various surface features of bones, such as projections, depressions, ridges, grooves, and holes. Specific names are given to each type of surface feature. Knowledge of surface bony features is essential for understanding the origins and insertions of skeletal muscles discussed in the muscular system, and is important in locating internal structures in clinical practice. The names of the major surface features are listed in table 6.2 and shown in figure 6.7 for easy reference as you study the bones of the skeleton.

6.5 Axial Skeleton

Learning Objectives

8. Identify the bones of the axial skeleton.
9. Compare the skulls of an infant and an adult.
10. Compare cervical, thoracic, lumbar, and sacral vertebrae.
11. Compare true, false, and floating ribs.

The major components of the axial skeleton are the skull, vertebral column, and thoracic cage. Bones of the axial skeleton are shown in figure 6.6.

Skull

The **skull** is subdivided into the *cranium*, which is formed of eight bones encasing the brain, and 14 *facial bones*. With the exception of the mandible, all the skull bones are joined by immovable joints, called **sutures** (sū′-churs) because they resemble stitches. The cranial cavity formed by the cranium protects the brain. The facial bones surround and support the openings of the digestive and respiratory systems. Several bones in the skull contain air-filled spaces called **paranasal sinuses** (figure 6.9) that are connected to the nasal cavity. These sinuses reduce the weight of the skull, add resonance to a person's voice, and produce mucus, which helps to moisten and purify the air within the sinuses and within the nasal cavity. The bones of the skull are shown in figures 6.8 to 6.12. Locate the bones on these figures as you study this section.

Cranium

The **cranium** is formed of one frontal bone, two parietal bones, one sphenoid, two temporal bones, one occipital bone, and one ethmoid.

The **frontal bone** forms the anterior part of the cranium, including the superior portion of the orbits (eye sockets), the forehead, and the roof of the nasal cavity. There are two large *frontal sinuses* in the frontal bone, one located superior to each eye.

The two **parietal** (pah-rī′-e-tal) **bones** form the sides and roof of the cranium. They are joined at the midline by the *sagittal suture* and to the frontal bone by the *coronal suture*.

The **occipital** (ok-sip′-i-tal) **bone** forms the posterior portion and floor of the cranium. It contains a large opening, the *foramen magnum*, through which the brainstem extends to join with the spinal cord. On each side of the foramen magnum are the *occipital condyles* (kon′-dīls), large knucklelike surfaces that articulate with the first vertebra of the vertebral column. The occipital bone is joined to the parietal bones by the *lambdoid* (lam′doyd) *suture*.

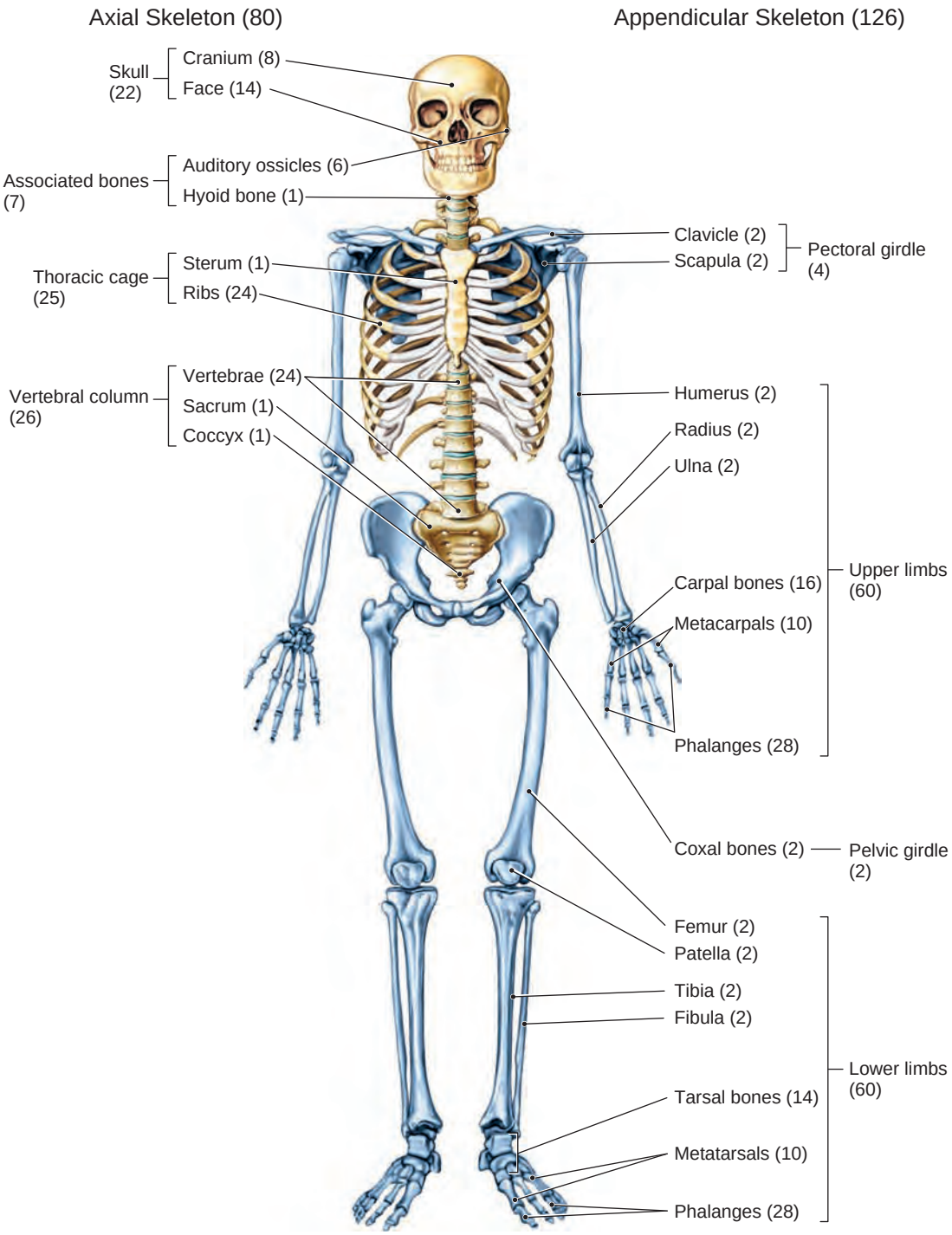


Figure 6.6 Bones of axial skeleton (colored gold) and appendicular skeleton (colored blue).

The **temporal bones** are located inferior to the parietal bones on each side of the cranium. They are joined to the parietal bones by *squamous* (skwā′mus) *sutures* and to the occipital bone by the lambdoid suture. In each temporal bone, an **external acoustic meatus** leads inward to the eardrum. Just anterior to the external acoustic meatus is the *mandibular fossa*, a depression that receives the mandibular condyle to form the *temporomandibular joint*.

Three processes are located on each temporal bone. The *zygomatic* (zī-gō-mat′-ic) *process* projects anteriorly to join with the zygomatic bone. The *mastoid* (mas′-toyd) *process* is a large, rounded projection that is located inferior

Table 6.2 Surface Features of Bones

Feature	Description
Processes Forming Joints	
Condyle	A rounded or knucklelike process
Head	An enlarged rounded end of a bone supported by a constricted neck
Facet	A smooth, nearly flat surface
Processes for Attachment of Ligaments and Tendons	
Crest	A prominent ridge or border
Epicondyle	A prominence superior to a condyle
Spine	A sharp or slender process
Trochanter	A very large process found on the femur
Tubercle	A small, rounded process
Tuberosity	A large, roughed process
Depressions and Openings	
Alveolus	A deep pit or socket
Canal, Meatus	A tubelike passageway into or through a bone
Foramen	An opening or passageway through a bone
Fossa	A small depression
Groove	A furrowlike depression
Sinus	An air-filled cavity within a bone

to the external acoustic meatus. It serves as an attachment site for some neck muscles. The *styloid process* lies just medial to the mastoid process. It is a long, spikelike process to which muscles and ligaments of the tongue and neck are attached.

The **sphenoid** (sfē′-noid) forms part of the floor of the cranium, the posterior portions of the orbits, and the lateral portions of the cranium just anterior to the temporal bones. Because it articulates with all other cranial bones, the sphenoid is referred to as the "keystone" of the cranium. On its superior surface at the midline is a saddle-shaped structure called the *sella turcica* (ter′-si-ka), or turkish saddle. It has a depression that contains the pituitary gland. Two *sphenoidal sinuses* are located just inferior to the sella turcica.

The **ethmoid** (eth′-moid) forms the anterior portion of the cranium, including part of the medial surface of each orbit and part of the roof of the nasal cavity. The lateral portions contain several air-filled sinuses called *ethmoidal cells*. The *perpendicular plate* extends inferiorly to form most of the nasal septum, which separates the right and left portions of the nasal cavity. It joins the sphenoid and vomer posteriorly and the nasal and frontal bones anteriorly.

The *superior* and *middle nasal conchae* (kong′-kē, singular, concha) extend from the lateral portions of the ethmoid toward the perpendicular plate. These delicate,

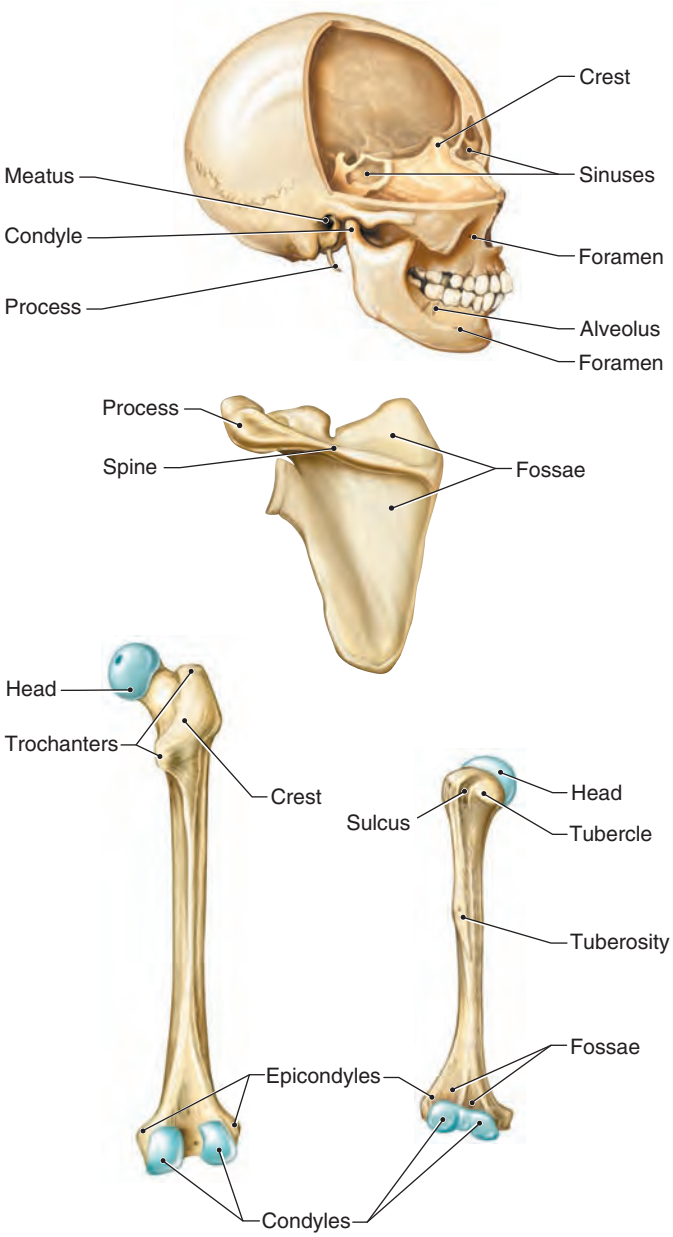


Figure 6.7 Surface Features of Bones.

scroll-like bones support the mucous membrane and increase the surface area of the nasal wall. The roof of the nasal cavity is formed by the *cribriform plate* of the ethmoid; the olfactory nerves enter the cranial cavity through foramina in the cribriform plate. On the superior surface where these plates join at the midline is a prominent projection called the *crista galli*, or cock's comb. The meninges that envelop the brain are attached to the crista galli.

Facial Bones

The paired bones of the face are the maxillae, palatine bones, zygomatic bones, lacrimal bones, nasal bones, and inferior nasal conchae. The single bones are the vomer and mandible.

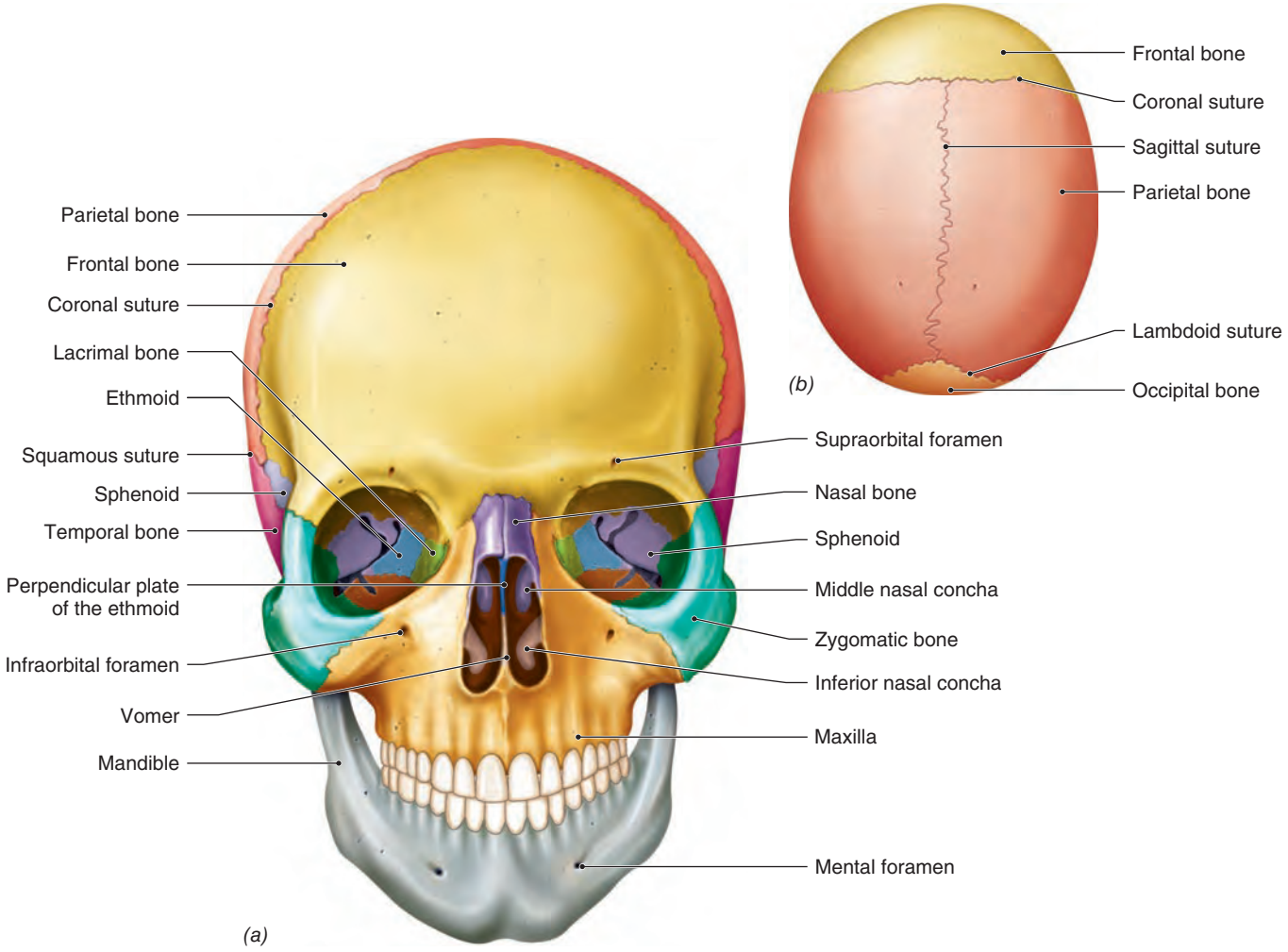


Figure 6.8 *(a)* Anterior view of the skull. *(b)* Superior view of the skull.

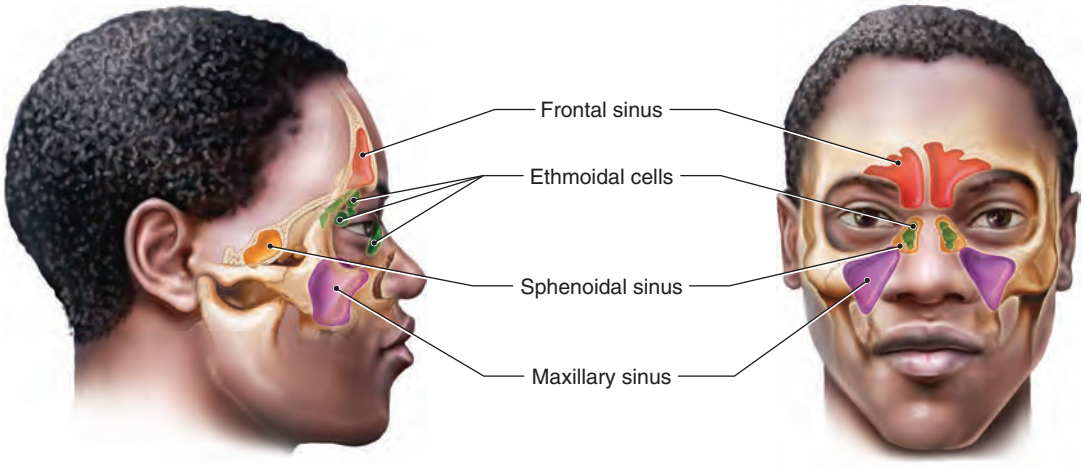


Figure 6.9 Paranasal sinuses are located in the frontal bone, the ethmoid, the sphenoid, and the maxillae. They are connected with the nasal cavity and increase the surface area of the nasal cavity.

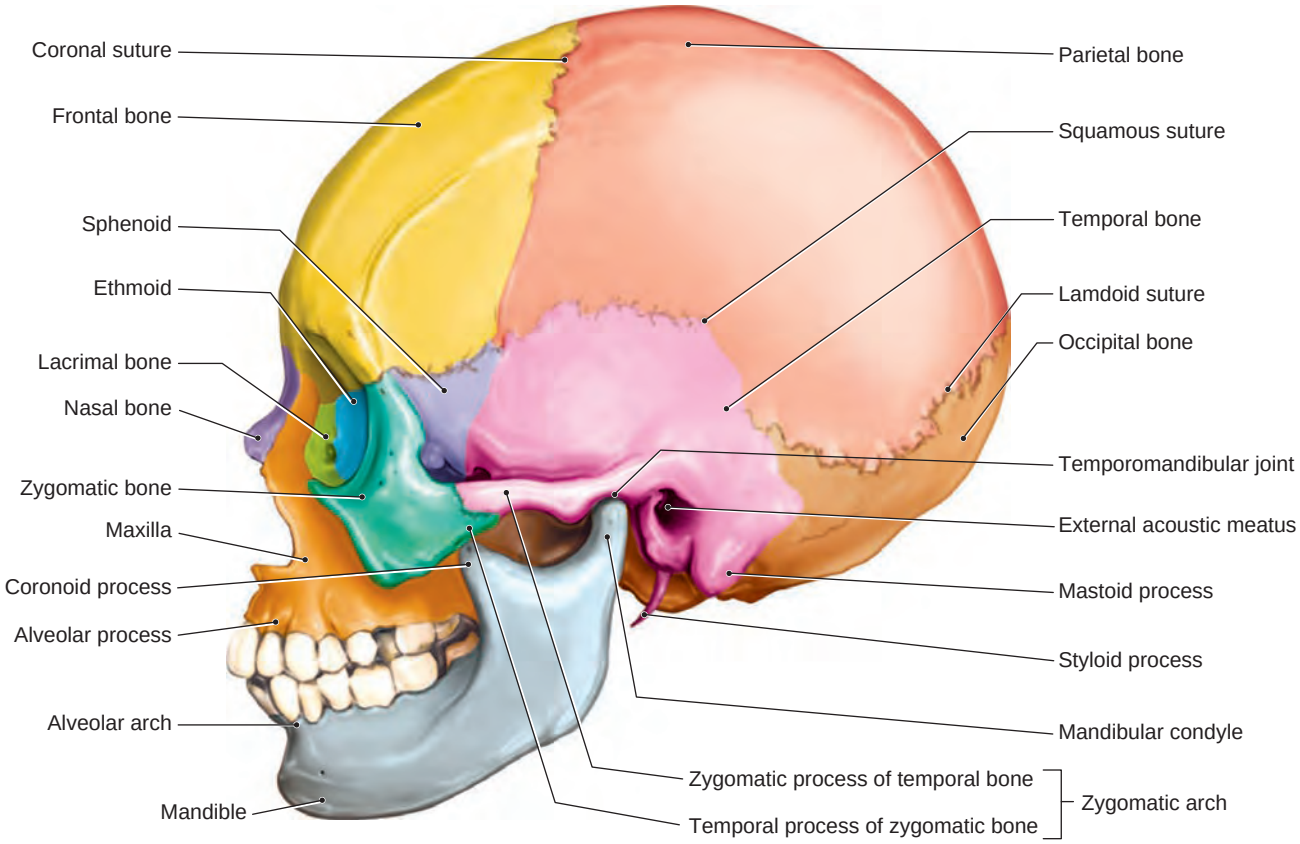


Figure 6.10 Lateral View of the Skull.

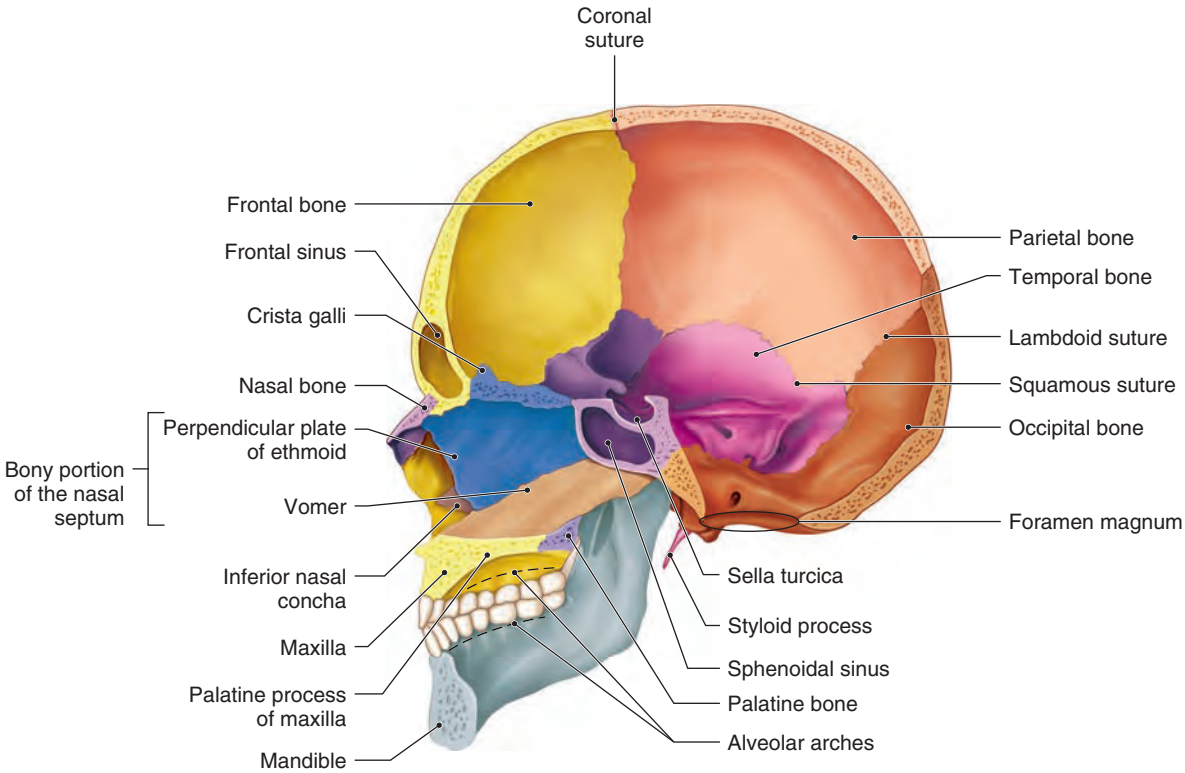


Figure 6.11 Median View of the Skull.

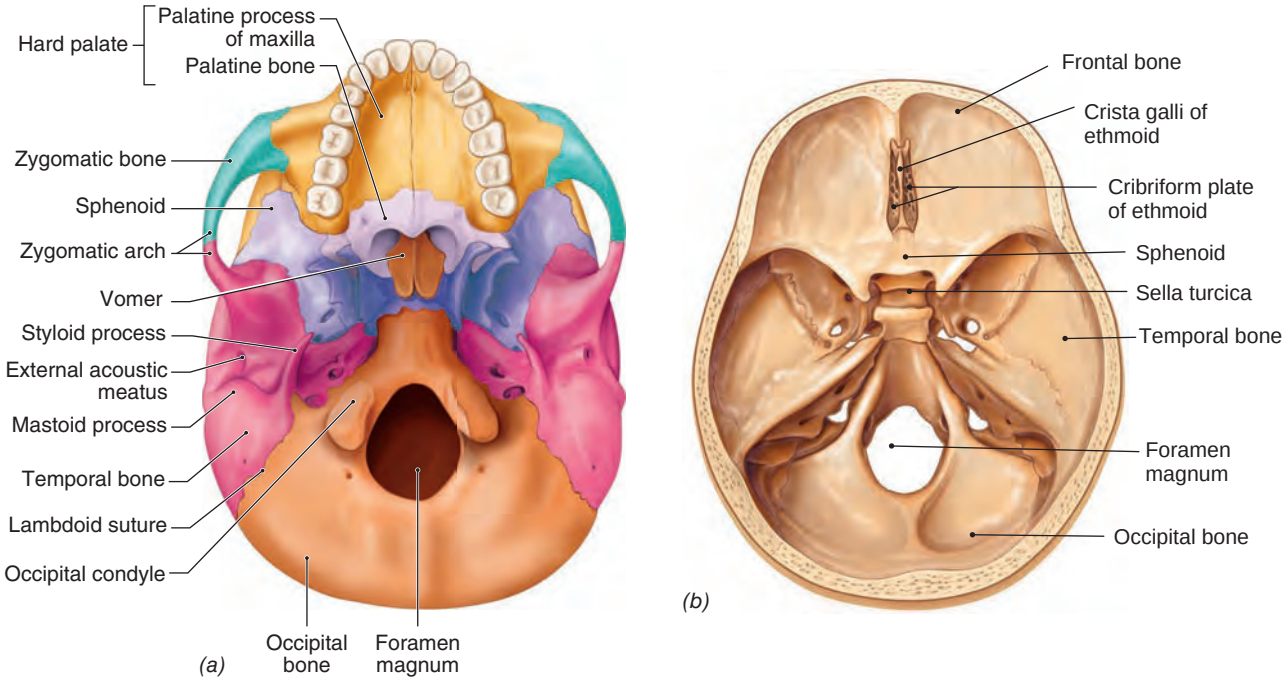


Figure 6.12 *(a)* Inferior view of the skull. *(b)* Superior view of the transverse section of the skull.

The **maxillae** (mak-sil′-ē) form the upper jaw. Each maxilla is formed separately, but they are joined at the midline during embryonic development. The maxillae articulate with all of the other facial bones except the mandible. The *palatine processes* of the maxillae form the anterior portion of the *hard palate* (roof of the mouth and floor of the nasal cavity), part of the lateral walls of the nasal cavity, and the floors of the orbits.

Each maxilla possesses an inferiorly projecting, curved ridge of bone that contains the teeth. This ridge is the *alveolar process*, and the sockets containing the teeth are called *alveoli* (singular, alveolus). The alveolar processes unite at the midline to form the U-shaped maxillary *alveolar arch*. A large *maxillary sinus* is present in each maxilla just inferior to the orbits.

The **palatine** (pal′-ah-tīn) **bones** are fused at the midline to form the posterior portion of the hard palate. Each bone has a lateral portion that projects superiorly to form part of a lateral wall of the nasal cavity.

The **zygomatic bones** (cheekbones) form the prominences of the cheeks and the floors and lateral walls of the orbits. Each zygomatic bone has a posteriorly projecting process, the *temporal process*, that extends to unite with the zygomatic process of the adjacent temporal bone. Together, they form the *zygomatic arch*.

The **lacrimal** (lak′-ri-mal) **bones** are small, thin bones that form part of the medial surfaces of the orbits. Each lacrimal bone is located between the ethmoid and maxilla.

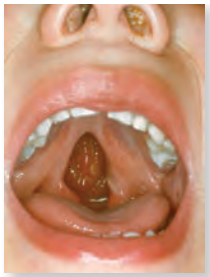
The **nasal** (nā′-zal) **bones** are thin bones fused at the midline to form the bridge of the nose.

The **vomer** is a thin, flat bone located on the midline of the nasal cavity. It joins posteriorly with the perpendicular plate of the ethmoid, and these two bones form the bony part of the nasal septum.

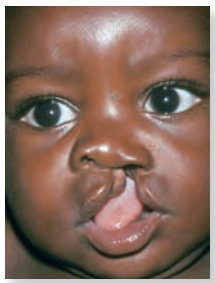
The **inferior nasal conchae** are scroll-like bones attached to the lateral walls of the nasal cavity inferior to

Clinical Insight

The hard palate separates the nasal cavity from the oral cavity, which allows for chewing and breathing to occur at the same time. A *cleft palate* results when the palatine processes of the maxillae and the palatine bones fail to join before birth to form the hard palate. A *cleft lip*, a split upper lip, is often associated with a cleft palate. These congenital deformities can be corrected surgically after birth.



Cleft palate



Cleft lip

the middle nasal conchae of the ethmoid. They project medially into the nasal cavity and serve the same function as the superior and middle nasal conchae of ethmoid.

The **mandible** (lower jaw) is the only movable bone of the skull. It consists of a U-shaped *body* with a superiorly projecting portion, a *ramus*, extending from each end of the body. The superior portion of the body forms the mandibular *alveolar arch*, which contains the alveoli for the teeth. The superior part of each ramus is Y-shaped and forms two projections: an anterior *coronoid process* and a posterior *mandibular condyle*. The coronoid process is a site of attachment for muscles used in chewing. The mandibular condyle articulates with the mandibular fossa of the temporal bone to form a *temporomandibular joint*. These joints are sometimes involved in a variety of dental problems associated with an improper bite.

Associated Bones to the Skull

The **hyoid** (hī′-oyd) **bone** and **auditory ossicles** are known as associated bones to the skull because they are located in or near the skull but are not directly connected with any skull bones. The hyoid bone is a small, U-shaped bone located in the anterior portion of the neck, inferior to the mandible. It does not articulate with any bone. Instead, it is suspended from the styloid processes of the temporal bones by muscles (figure 6.13). Muscles of the tongue are attached to the hyoid bone. The auditory ossicles (malleus, incus, stapes) are the smallest bones in the human body. They articulate with each other in the middle ears and assist in sound conduction and amplification (see chapter 9).

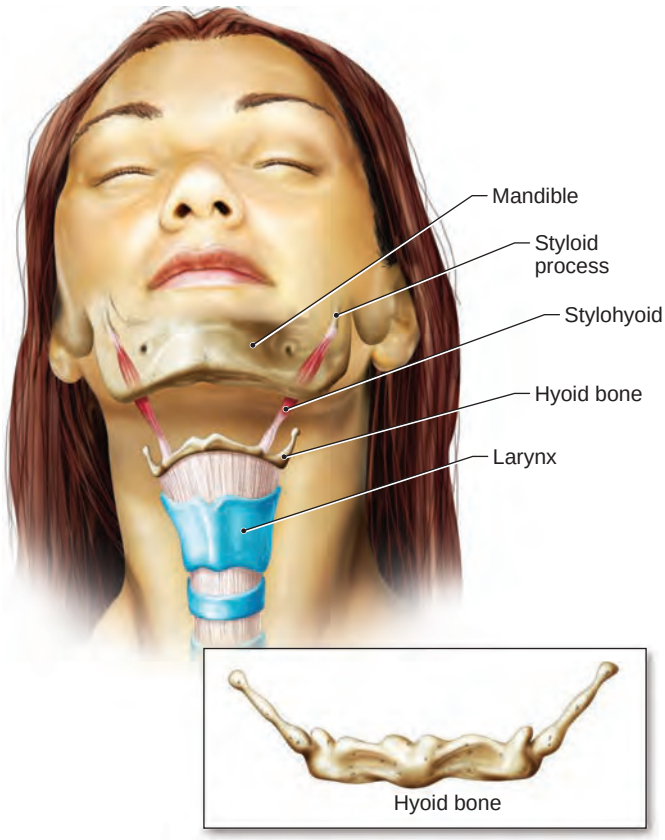


Figure 6.13 The Anterior View of the Hyoid Bone.

The Infant Skull

The skull of a newborn infant is incompletely developed. The face is relatively small with large orbits, and the bones are thin and incompletely ossified. The bones of the cranium are separated by dense connective tissue, with six rather large, nonossified areas called **fontanelles** (fon′-tah-nels) or soft spots (figure 6.14). The frontal bone is formed of two separate parts that fuse later in development. Incomplete ossification of the skull bones and the abundance of dense irregular connective tissue make the skull somewhat flexible and allow for partial compression of the skull to facilitate easier vaginal delivery.

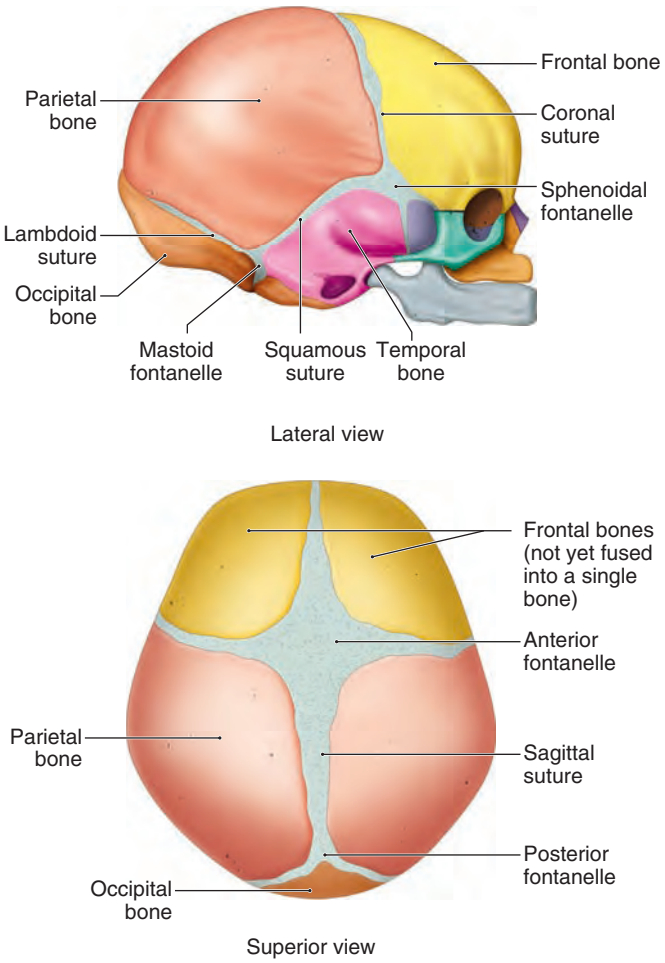


Figure 6.14 There are one anterior, two mastoid, one posterior, and two sphenoidal fontanelles between the cranial bones in the infant's skull. Note the fontanelles and the membranes between the cranial bones.

After birth, they allow for the skull to expand easily and accommodate the rapidly growing brain. Compare the infant skull in figure 6.14 with the adult skull in figure 6.8 and figure 6.10.

Check My Understanding

6. What bones form the cranium?
7. What bones form the face?

Vertebral Column

The vertebral column (spine or backbone) extends from the skull to the pelvis and forms a somewhat flexible but sturdy longitudinal support for the trunk. It is formed of 24 slightly movable vertebrae, the sacrum, and the coccyx. The vertebrae are separated from each other by **intervertebral discs** that serve as shock absorbers and allow bending of the spinal column. Four distinct curvatures can be seen on the lateral view of the vertebral column (figure 6.15). From superior to inferior they are the *cervical, thoracic, lumbar,* and *sacral curvatures.* These curvatures provide flexibility and cushion, and allow the vertebral column to bear body weight more efficiently.

Structure of a Vertebra

Vertebrae are divided into three groups: cervical, thoracic, and lumbar vertebrae. Although each type has a distinctive anatomy, they have many features in common (figure 6.16).

The anterior, drum-shaped mass is the *body,* which serves as the major load-bearing portion of a vertebra. A bony *vertebral arch* surrounds the large *vertebral foramen* through which the spinal cord and nerve roots pass. A

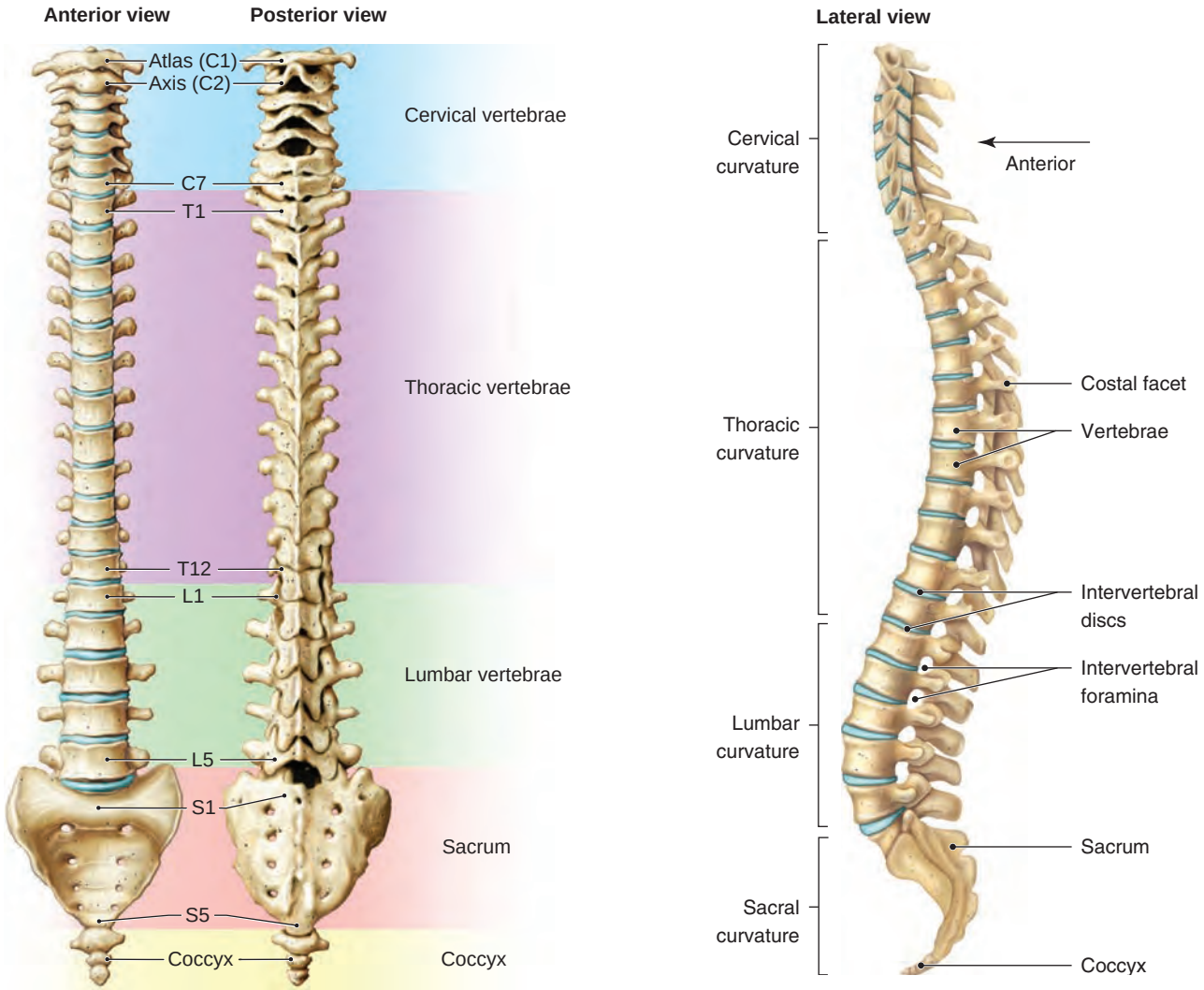


Figure 6.15 The vertebral column consists of 24 movable vertebrae, separated by intervertebral discs, sacrum, and coccyx.

spinous process projects posteriorly and *transverse processes* project laterally from each vertebral arch.

A pair of *superior articular processes* projects superiorly and a pair of *inferior articular processes* projects inferiorly from the vertebral arch. The *articular facet* (fa′-set) of each superior articular process articulates with the articular fact of the inferior articular process of the adjacent vertebra superior to it. When joined by ligaments, the vertebrae form the *vertebral canal* that protects the spinal cord.

Small *intervertebral foramina* occur between adjacent vertebrae. They serve as lateral passageways for spinal nerves that exit the spinal cord (see figure 6.15 and figure 6.16).

Cervical Vertebrae

The first seven vertebrae are the **cervical** (ser′-vi-kul) **vertebrae** (C1–C7) that support the neck. They are unique in having a *transverse foramen* in each transverse process. It serves as a passageway for the vertebral arteries and veins, blood vessels involved in blood flow to and from the brain (figures 6.17*a*–*d*).

The first two cervical vertebrae are distinctly different from the rest. The first vertebra (C1), or **atlas,** whose superior articular facets articulate with the occipital condyles, supports the head. The second vertebra (C2), which is called the **axis,** has a prominent *dens* that projects superiorly from the vertebral body, providing a pivot point for the atlas. When the head is turned, the atlas rotates on the axis (see figure 6.17*a*–*c*).

Thoracic Vertebrae

The 12 **thoracic vertebrae** (T1–T12) are larger than the cervical vertebrae, and their spinous processes are longer and slope inferiorly. The ribs articulate with *costal facets* on the transverse processes and bodies of thoracic vertebrae (figures 6.17*e* and 6.19*b*).

Lumbar Vertebrae

The five **lumbar vertebrae** (L1–L5) have heavy, thick bodies to support the greater stress and weight that is placed on this region of the vertebral column. The spinous processes are blunt and provide a large surface area for the attachment of heavy back muscles (see figures 6.16, 6.17*f*).

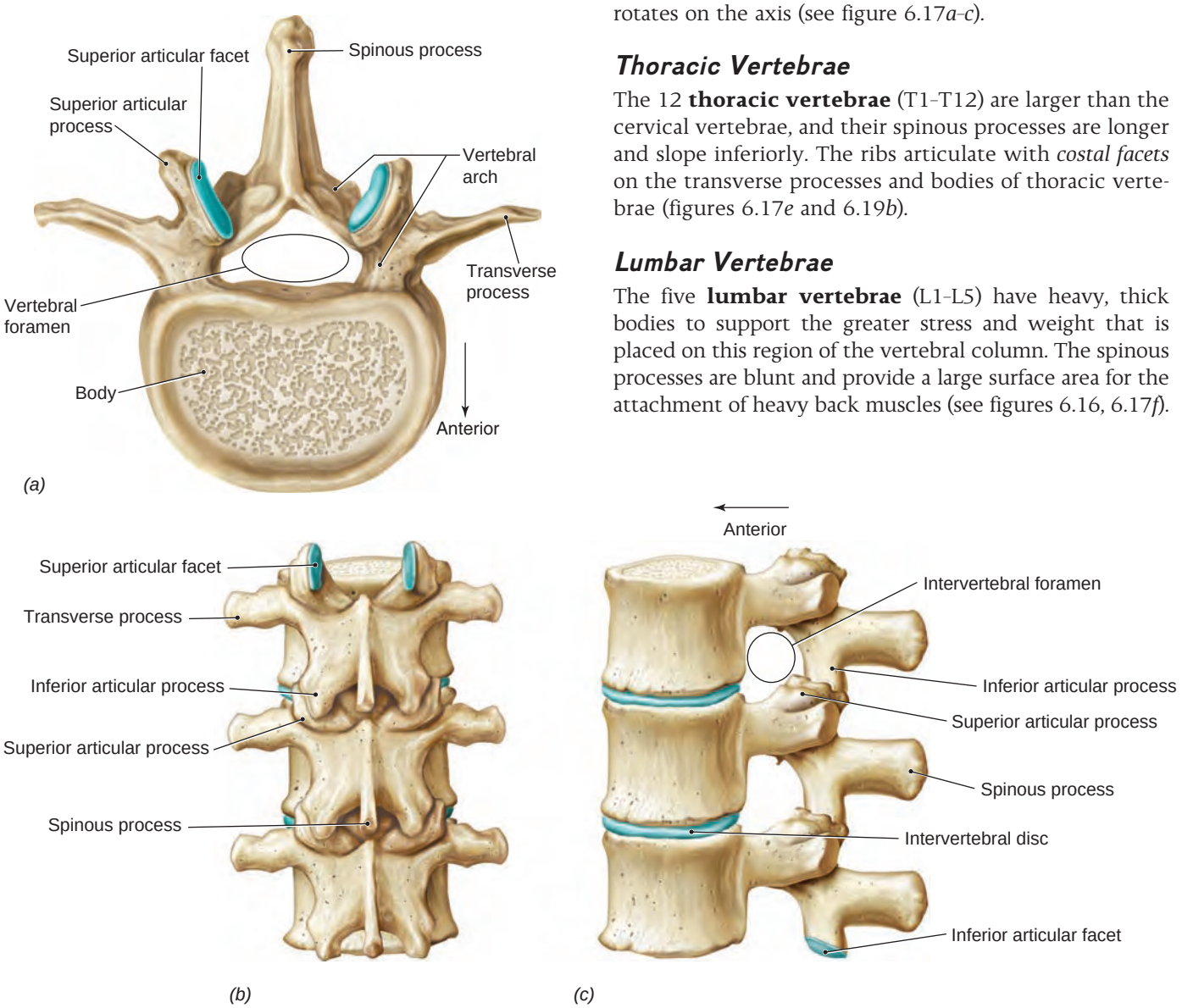
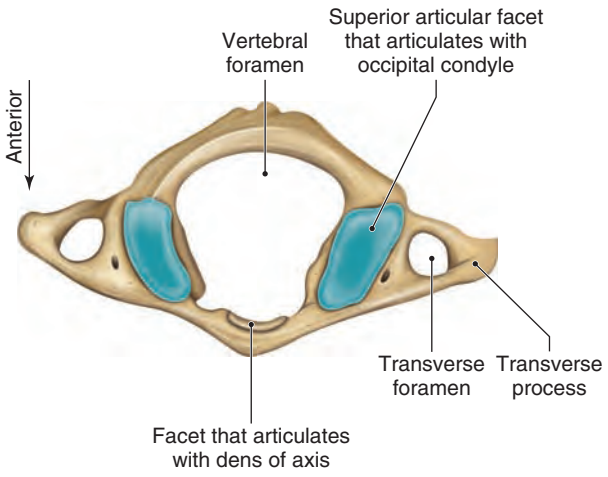
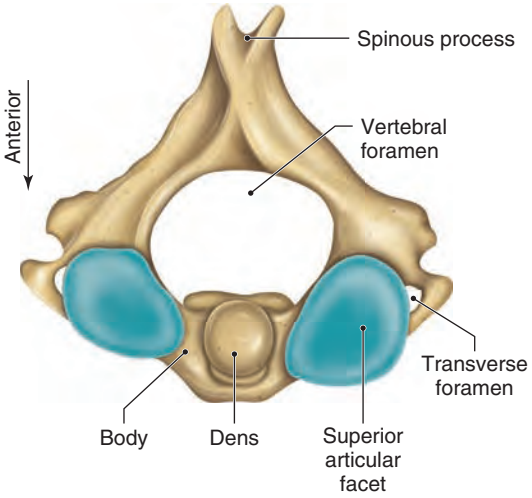


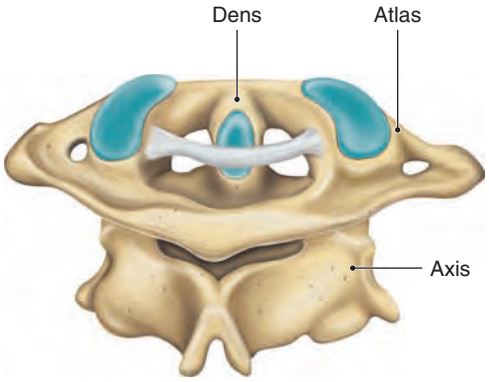
Figure 6.16 *(a)* Superior view of a lumbar vertebra. *(b)* Posterior view of lumbar vertebrae. *(c)* Lateral view of lumbar vertebrae.



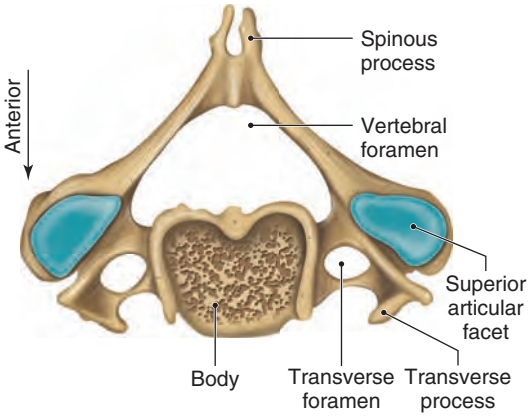
(a) Atlas



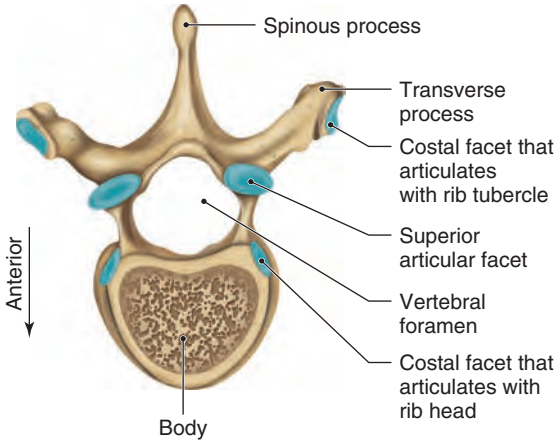
(b) Axis



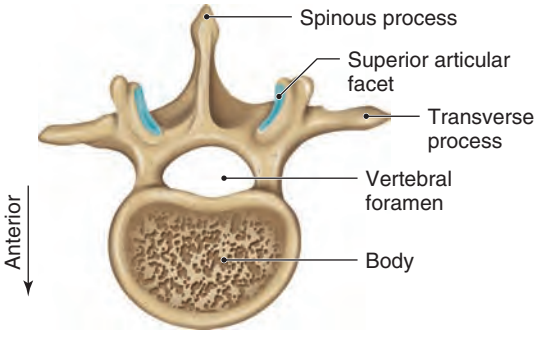
(c) The articulation between an atlas and an axis



(d) A typical cervical vertebra (C3-C7)



(e) A typical thoracic vertebra (T1-T12)



(f) A typical lumbar vertebra (L1-L5)

Figure 6.17 The Structures of Vertebrae.
(a), *(b)*, *(d)*, *(e)* and *(f)* are superior views. *(c)* is a posterior view. Bones are not shown to scale.

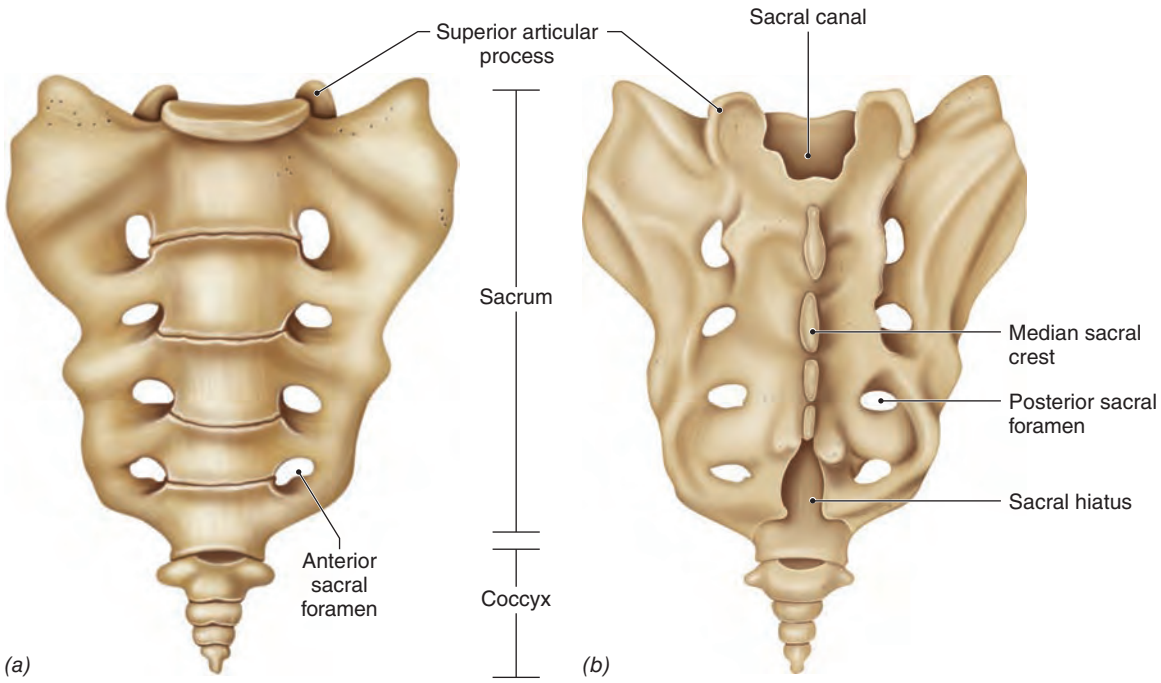


Figure 6.18 *(a)* Anterior view and *(b)* posterior view of the sacrum and coccyx.

Sacrum

The **sacrum** (sā-k′rum) is composed of five fused sacral vertebrae (S1–S5) (figure 6.18). It articulates with the fifth lumbar vertebra and forms the posterior wall of the pelvis. The spinous processes of the fused vertebrae form the *median sacral crest* on the posterior midline. On either side of the median sacral crest are the *posterior sacral foramina,* passageways for blood vessels and nerves. *Anterior sacral foramina* on the anterior surface serve a similar function. The *sacral canal* is a continuation of the vertebral canal that carries spinal nerve roots to the sacral foramina and the *sacral hiatus,* an inferior opening proximal to the coccyx.

Coccyx

The most inferior part of the vertebral column is the **coccyx** (kok′-six), or tailbone, which is formed of three to five fused coccygeal vertebrae.

Thoracic Cage

The thoracic vertebrae, ribs, costal cartilages, and sternum form the **thoracic cage.** It provides protection for the internal organs of the thoracic cavity and supports the superior trunk, pectoral girdle, and upper limbs (figure 6.19).

Ribs

Twelve pairs of **ribs** are attached to the thoracic vertebrae. The *head* of each rib articulates with the costal facet on the body of its own vertebra, and a *tubercle* near the head articulates with the costal facet on the transverse process. The head also articulates with the costal facet on the body of the vertebra superior to it. The *shaft* of each rib curves around the thoracic cage and slopes slightly inferiorly.

The superior seven pairs of ribs are attached directly to the sternum by the **costal** (kos′-tal) **cartilages,** which extend medially from the ends of the ribs. These ribs are the *true ribs.* The remaining five pairs are the *false ribs.* The first three pairs of false ribs are attached by cartilages to the costal cartilages of the ribs just superior to them. The last two pairs of false ribs are called *floating ribs* because they lack cartilages and are not attached anteriorly. The costal cartilages give some flexibility to the thoracic cage.

Sternum

The **sternum,** or breastbone, is a flat, elongated bone located at the midline in the anterior portion of the

Clinical Insight

A biopsy of red bone marrow may be made by a *sternal puncture* because the sternum is covered only by skin and connective tissue. Under local anesthetic, a large-bore hypodermic needle is inserted into the sternum, and red bone marrow is drawn into a syringe.

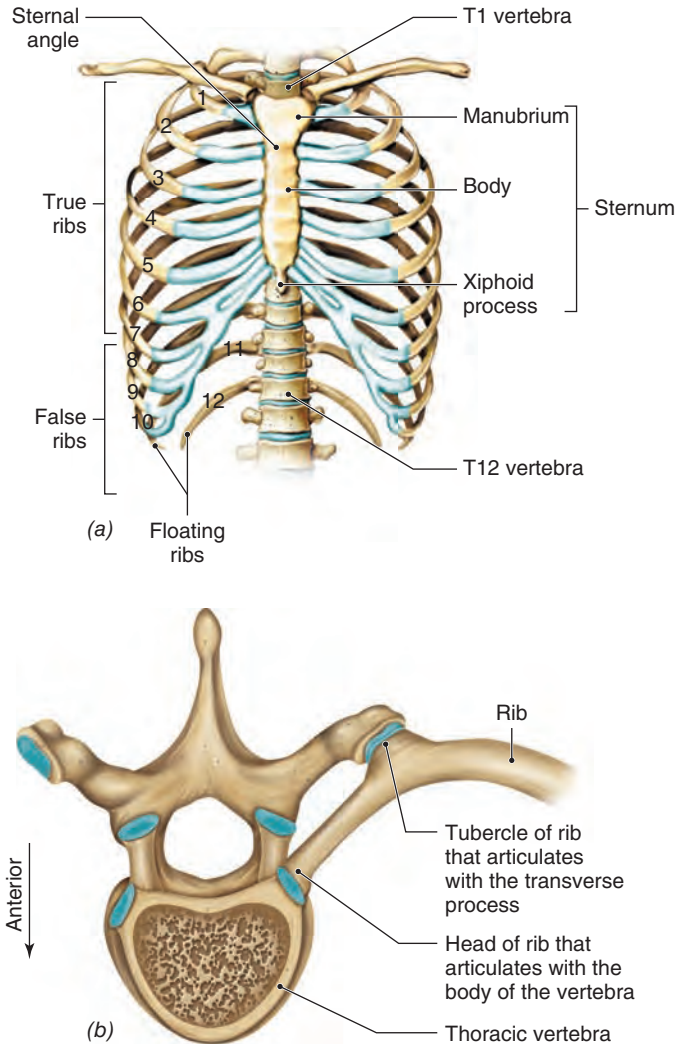


Figure 6.19 Thoracic Cage.
(a) The thoracic cage is formed by thoracic vertebrae, ribs, costal cartilages (colored light blue), and the sternum. *(b)* The articulation between a rib and a thoracic vertebra.

thoracic cage. It consists of three bones that are fused together. The *manubrium* (mah-nū′-brē-um) is the superior portion that articulates with the first two pairs of ribs; the *body* is the larger middle segment; and the *xiphoid* (zĭf′-oyd) *process* is the small inferior portion.

Check My Understanding

8. How do cervical, thoracic, and lumbar vertebrae differ in structure and location?
9. How does the axial skeleton protect vital organs?

6.6 Appendicular Skeleton

Learning Objectives

12. Identify the bones of the appendicular skeleton.
13. Compare the structural and functional differences between pectoral girdle and pelvic girdle.
14. Compare the structural and functional differences between the male and female pelves.
15. Describe how the appendicular skeleton is connected to the axial skeleton.

The appendicular skeleton consists of (1) the pectoral girdle and the bones of the upper limbs, and (2) the pelvic girdle and the bones of the lower limbs (see figure 6.6).

Pectoral Girdle

The **pectoral** (pek′-to-ral) **girdle,** or shoulder girdle, consists of two clavicles (collarbones) and two scapulae (shoulder blades) (figure 6.20). Each S-shaped **clavicle** (klav′-i-cul) articulates with the acromion of a scapula laterally and with the sternum medially. The **scapulae** (skap′-ū-le, singular, *scapula*) are flat, triangular bones located on each side of the vertebral column, but they do not articulate with the axial skeleton. Instead, they are held in place by muscles, an arrangement that enables freedom of movement for the shoulder joints.

The anterior surface of each scapula is flat and smooth where it moves over the ribs. The scapular *spine* runs diagonally across the posterior surface from the *acromion* (ah-krōm′-ē-on) to the medial margin. On its lateral margin is the shallow *glenoid cavity,* which articulates with the head of the humerus. The *coracoid* (kor′-ah-koyd) *process* projects anteriorly from the superior margin of the glenoid cavity and extends inferior to the clavicle.

Upper Limb

The skeleton of each **upper limb** is composed of a humerus, an ulna, a radius, carpal bones, metacarpals, and phalanges (figure 6.21).

Humerus

The **humerus** (hū′-mer-us) articulates with the scapula at the shoulder joint, and the ulna and radius at the elbow joint. The rounded *head* of the humerus fits into the glenoid cavity of the scapula. Just inferior to the head are two large tubercles where muscles attach. The *greater tubercle* (tū′-ber-cul) is on the lateral surface, and the *lesser tubercle* is on the anterior surface. An *intertubercular sulcus* lies between them. Just distal to these tubercles is the *surgical neck,* which gets its name from the frequent fractures that occur in this area. Near the midpoint on the lateral surface is the *deltoid tuberosity* (tū-be-ros′-i-tē), a rough, elevated area where the deltoid attaches.

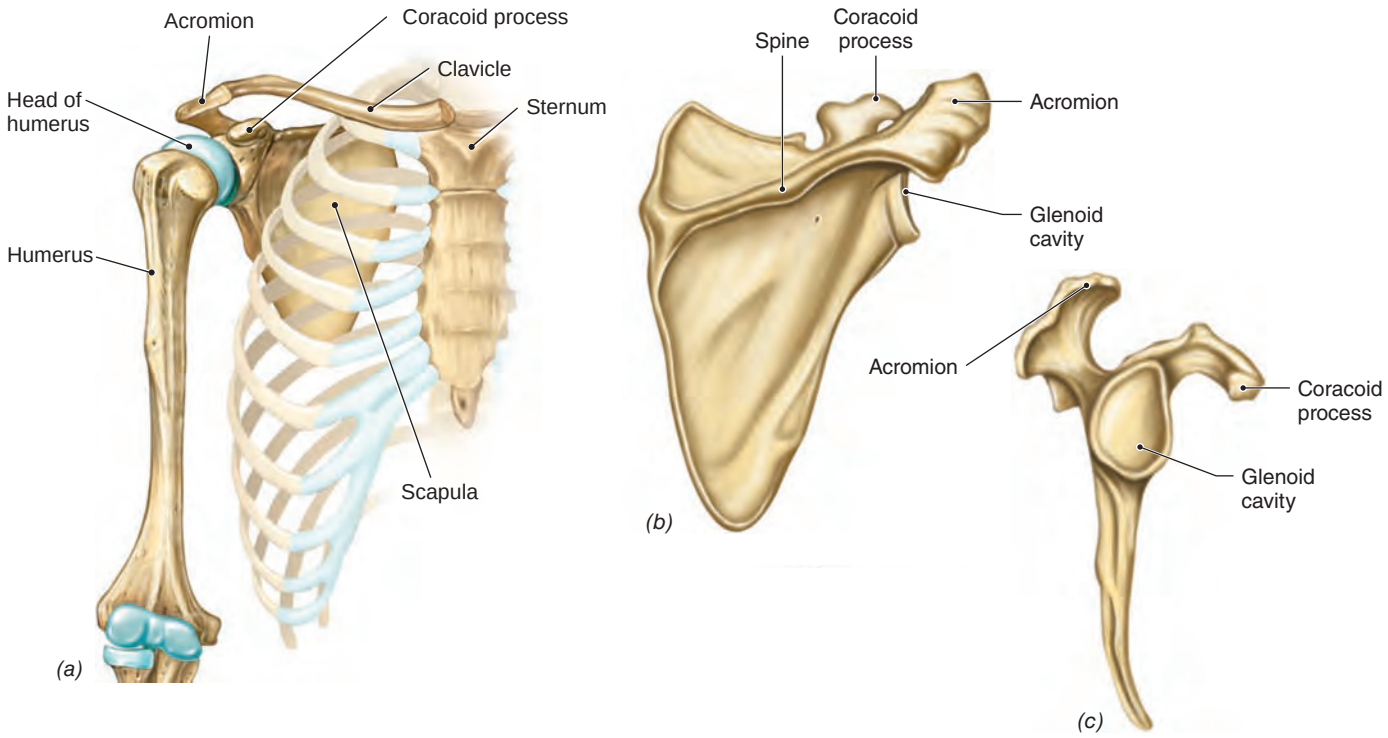


Figure 6.20 The Right Side of the Pectoral Girdle.
(a) The pectoral girdle consists of two scapulae and two clavicles. Note how the head of the humerus articulates with the glenoid cavity of the scapula. The posterior view *(b)* and the lateral view *(c)* of the right scapula.

The distal end of the humerus has two condyles. The *trochlea* (trok′-lē-ah) is the medial condyle, which articulates with the trochlear notch of the ulna. The *capitulum* (kah-pit′-ū-lum) is the lateral condyle, which articulates with the head of the radius. Just proximal to these condyles are two enlargements that project laterally and medially: the *lateral epicondyle* (ep-i-kon′-dil) and the *medial epicondyle*. On the anterior surface between the epicondyles is a depression, the *coronoid* (kor′-o-noyd) *fossa,* that receives the coronoid process of the ulna whenever the upper limb is flexed at the elbow. The *olecranon* (o-lek′-rah-non) *fossa* is in a similar location on the posterior surface of the humerus, and it receives the olecranon of the ulna when the upper limb is extended at the elbow.

Ulna

The **ulna** (ul′-na) is the medial bone of the forearm. The proximal end of the ulna forms the *olecranon,* the bony point of the elbow. The large, half-circle depression just distal to the olecranon is the *trochlear notch,* which articulates with the trochlea of the humerus. This articulation is secured by the *coronoid process* on the distal lip of the notch.

At the distal end, the knoblike *head* of the ulna articulates with the medial surface of the radius and with the wrist bones. The *styloid process* is a small medial projection to which ligaments of the wrist are attached.

Radius

The **radius** (rā′-dē-us) is the lateral bone of the forearm. The disclike *head* of the radius articulates with the lateral proximal surface of the ulna in a way that enables the head to rotate freely when the forearm is rotated. A short distance distally from the head is the *radial tuberosity,* a elevated, roughened area where the biceps brachii attaches. At its distal end, the radius articulates with the carpal bones. A small lateral *styloid process* serves as an attachment site for ligaments of the wrist.

Carpal Bones, Metacarpals, and Phalanges

The skeleton of the hand consists of the carpal bones, metacarpals, and phalanges (figure 6.21*d*). The **carpal** (kar′-pul) **bones,** or wrist bones, consist of eight small bones that are arranged in two transverse rows of four bones each. They are joined by ligaments that allow limited gliding movement.

The **metacarpals,** bones of the palm, consist of five metacarpal bones that are numbered I to V starting with the metacarpal adjacent to the thumb. The bones of the fingers are the **phalanges** (fah-lan′-jēz, singular, *phalanx*).

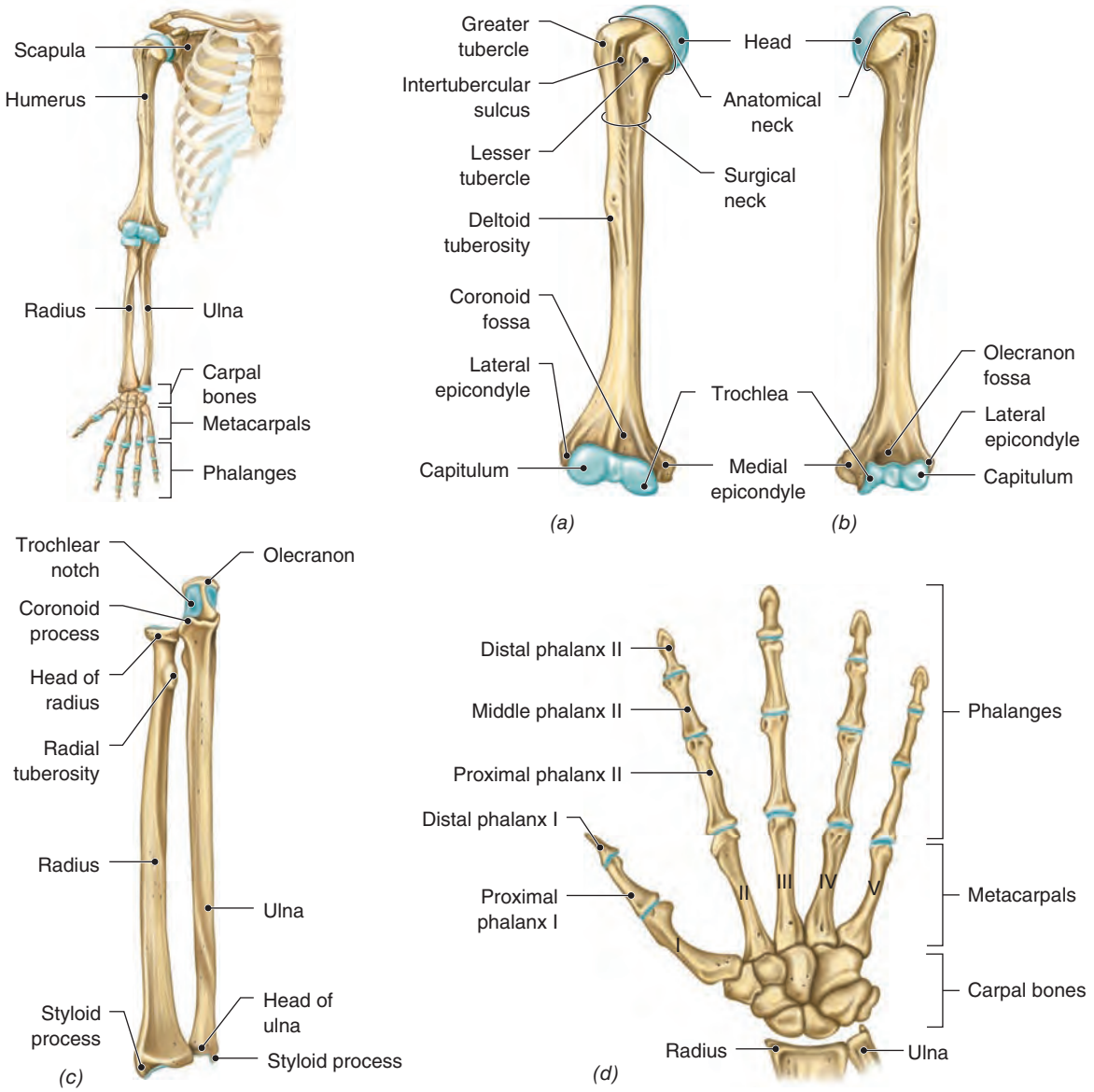


Figure 6.21 The Right Upper Limb.
(a) Anterior view of humerus; *(b)* Posterior view of humerus; *(c)* Anterior view of ulna and radius; *(d)* Posterior view of hand.

Each finger consists of three phalanges (proximal, middle, and distal), except for the thumb, which has only two (proximal and distal).

Pelvic Girdle

The **pelvic** (pel′-vik) **girdle** consists of two **coxal** (kok′sal) **bones,** or hip bones, that support the attachment of the lower limbs. The coxal bones articulate with the sacrum posteriorly and with each other anteriorly to form an almost rigid, bony **pelvis** (plural, *pelves*)**,** as shown in figure 6.22.

Coxal Bones

Each coxal bone is formed by three fused bones–ilium, ischium, and pubis–that join at the *acetabulum* (as-e-tab′-ū-lum), the cup-shaped socket on the lateral surface. The **ilium** is the broad superior portion whose superior margin forms the *iliac crest,* the prominence of the hip. Inferior to the *posterior inferior iliac spine* is the *greater sciatic* (sī-at′-ik) *notch,* which allows the passage of blood vessels and sciatic nerve from the pelvis to the thigh. The *auricular surface* of each ilium joins with the sacrum to form a *sacroiliac joint.*

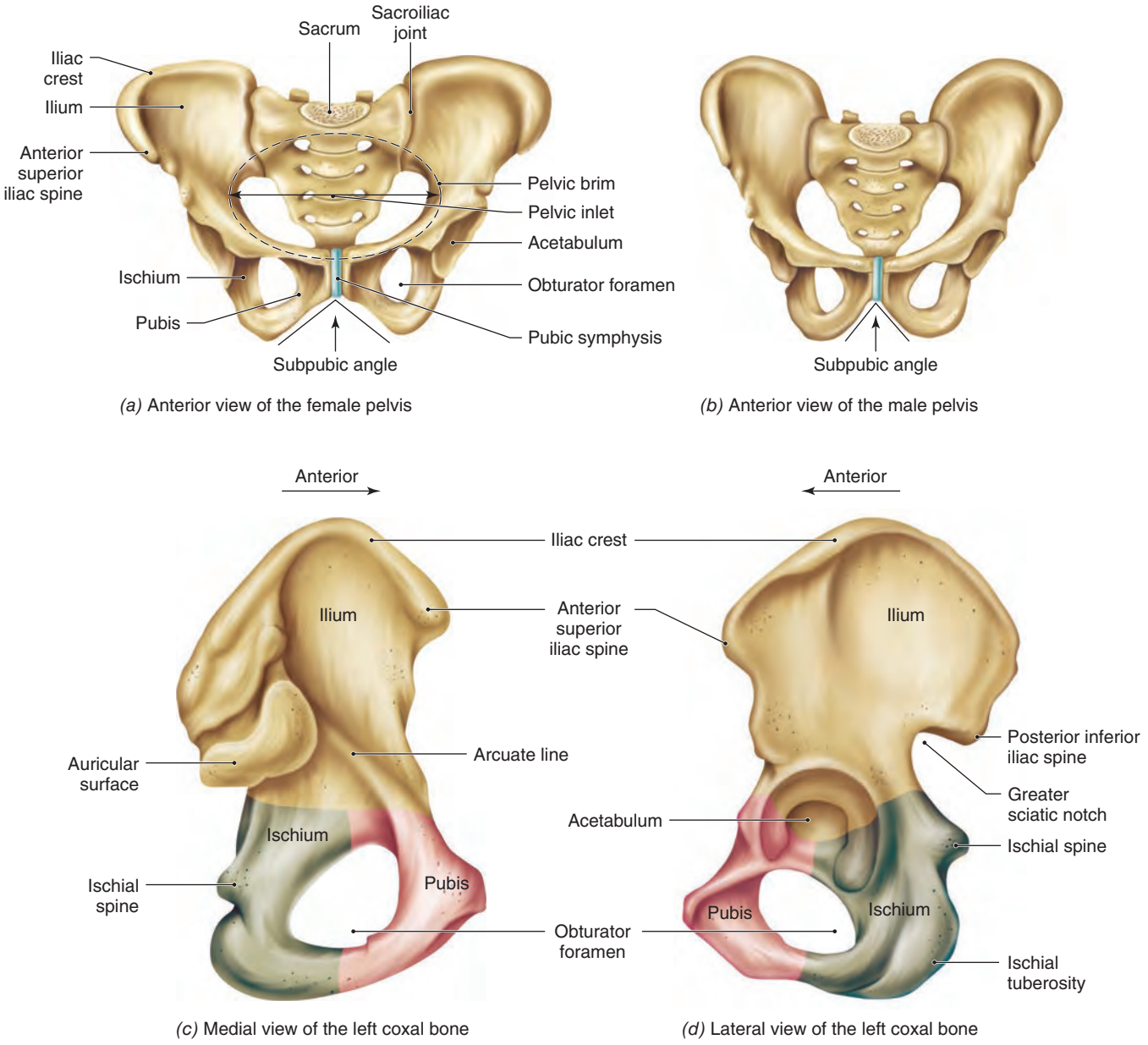


Figure 6.22 Pelves and Coxal Bones.

The **ischium** forms the inferior, posterior portion of a coxal bone and supports the body when sitting. The roughened projection at the posterior, inferior angle of the ischium is the *ischial tuberosity*. Just superior to this tuberosity is the *ischial spine*, which projects medially. The distance between the left and right ischial spines in females is important during childbirth because it determines the diameter of the pelvic opening.

The **pubis** (plural, *pubes*) is the inferior, anterior portion of a coxal bone. A portion of the pubis extends posteriorly to fuse with the anterior extension of the ischium. The large opening created by this junction is the *obturator* (ob-tū-rā′-ter) *foramen*, through which blood vessels and nerves pass into the thigh. The pubes unite anteriorly to form the **pubic symphysis,** where the bones are joined by a pad of fibrocartilage.

Clinical Insight

When giving intramuscular injections in the hip, the region near the greater sciatic notch must be avoided to prevent possible injury to the large blood vessels and nerves in this area.

Table 6.3 Sexual Differences of the Pelves

Characteristic	Male	Female
General structure	Heavier; processes prominent	Lighter; processes not so prominent
Pelvic inlet	Narrower and heart-shaped	Wider and oval-shaped
Subpubic angle	Less than 90°	More than 90°
Relative width	Narrower	Wider
Acetabulum	Faces laterally	Faces laterally but more anteriorly

Table 6.3 lists the major differences between the male and the female pelves. Compare them with the male and female pelves in figure 6.22 and note the adaptations of the female pelvis for childbirth. The **pelvic inlet,** an opening superior to the pelvic cavity, is encircled by the *pelvic brim,* a circular line passing through the *arcuate line* and the superior border of pubis. Its size and shape in females are critical to the success of the birth process.

Clinical Insight

The fetus must pass through the pelvic inlet during birth. Physicians carefully measure this opening before delivery to be sure that it is of adequate size. If not, the baby is delivered via a *cesarean section.* In a cesarean section, a transverse incision is made through the pelvic and uterine walls to remove the infant.

Lower Limb

The bones of each **lower limb** consist of a femur, a patella, a tibia, a fibula, tarsal bones, metatarsals, and phalanges (figure 6.23).

Femur

The **femur,** or thigh bone, is the largest and strongest bone of the body (figure 6.23*a, b*). Structures at the proximal end include the rounded *head,* a short *neck,* and two large processes that are sites of muscle attachment: a superior, lateral *greater trochanter* (trō-kan′-ter) and an inferior, medial *lesser trochanter.* The head of the femur fits into the acetabulum of the coxal bone. The neck is a common site of fractures in older people. At the enlarged distal end are the *lateral* and *medial condyles,* surfaces that articulate with the tibia.

Patella

The **patella,** or kneecap, is located anterior to the knee joint. It is embedded in the tendon of the quadriceps femoris, which extends over the anterior of the knee to insert on the tibia. The patella offers protection to the structures within the knee joint during movement.

Tibia

The **tibia,** or shinbone, is the larger of the two bones of the leg (figure 6.23*c*). It bears the weight of the body. Its enlarged proximal portion consists of the *lateral* and *medial condyles,* which articulate with the femur to form the knee joint. The *tibial tuberosity,* a roughened area on the anterior surface just distal to the condyles, is the attachment site for the patellar ligament. The distal end of the tibia articulates with the talus, a tarsal bone, and laterally with the fibula. The *medial malleolus* (mah-lē-ō′-lus) forms the medial prominence of the ankle.

Fibula

The **fibula** is the slender, lateral bone in the leg (figure 6.23*c*). Both ends of the bone are enlarged. The proximal *head* articulates with the lateral surface of the tibia but is not involved in forming the knee joint. The distal end articulates with the tibia and talus. The *lateral malleolus* forms the lateral prominence of the ankle.

Tarsal Bones, Metatarsals, and Phalanges

The skeleton of the foot consists of the tarsal bones (ankle), metatarsals (instep), and phalanges (toes) (figure 6.23*d, e*). Seven bones compose the **tarsal bones.** The most prominent tarsal bones are the *talus,* which articulates with the tibia and fibula, and the *calcaneus* (kal-kā′n-ē-us), or

Clinical Insight

Total hip replacement (THR) has become commonplace among older persons as a way to overcome the pain and immobility caused by osteoarthritis of the hip joint. This procedure utilizes two prostheses. A polyurethane cup replaces the damaged acetabulum, and a metal shaft and ball replace the diseased head of the femur. Surfaces of the prostheses in contact with bone are porous, allowing bone to grow into them to ensure a firm attachment. Patient recovery involves stabilization of the prostheses while bone grows into them as well as normal healing from the surgery.

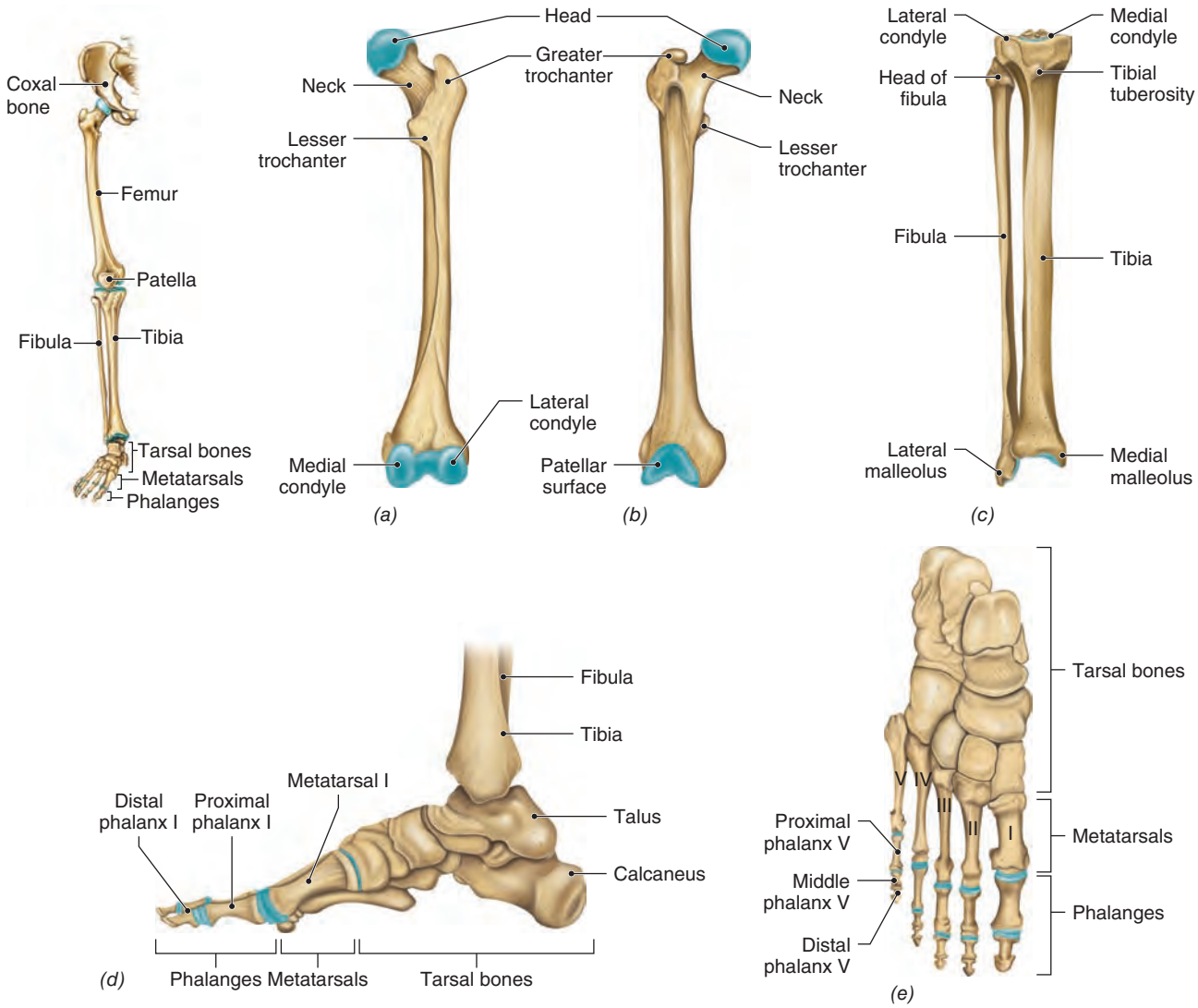


Figure 6.23 The Right Lower Limb.
(a) Posterior view of femur; *(b)* Anterior view of femur; *(c)* Anterior view of tibia and fibula; *(d)* Medial view of foot; *(e)* Superior view of foot.

heel bone. Five **metatarsals** support the instep. They are numbered I to V, starting with the metatarsal adjacent to the great toe. The tarsal bones and metatarsals are bound together by ligaments to form strong, resilient arches of the foot. Each toe consists of three phalanges (proximal, middle, and distal), except for the great toe, which has only two (proximal and distal).

Check My Understanding

10. What bones form the pectoral girdle and upper limbs?
11. What bones form the pelvic girdle and lower limbs?

6.7 Articulations

Learning Objectives

16. Compare the structures, functions, and locations of immovable, slightly movable, and freely movable joints.
17. Compare the types of movements allowed by freely movable joints.
18. Compare the six types of freely movable joints.

The junction between two bones or between a bone and a tooth forms an **articulation**, or **joint.** Joints allow varying degrees of movement and are categorized as immovable, slightly movable, or freely movable. As you read the following descriptions, locate the different types of joints

on the corresponding illustrations of skeletal parts in figures presented earlier in the chapter.

Immovable Joints

Bones forming an immovable joint, or **synarthrosis** (sin-ar-thró′-sis), are tightly joined and are separated by a thin band of dense connective tissue or a thin layer of hyaline cartilage. For example, skull bones, except the mandible, are joined by dense connective tissue called sutures because they resemble stitches (figure 6.24*a*). The joints between bones and teeth are also immovable joints separated by dense connective tissue. The epiphysial plates in growing bones (see figure 6.5), composed of hyaline cartilage, are also immovable joints.

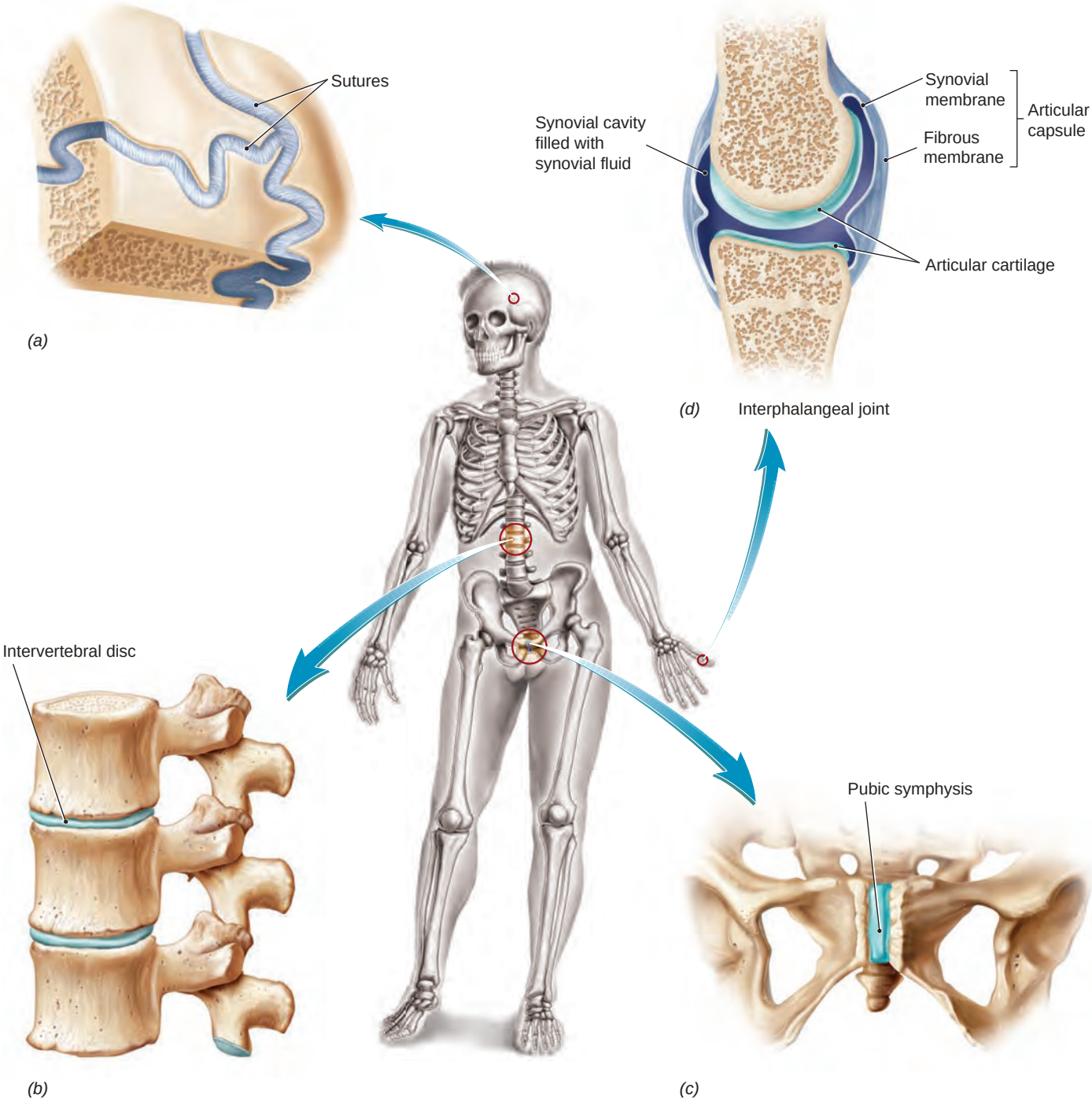


Figure 6.24 Types of Joints.
(a) Suture (synarthrosis); *(b)* Intervertebral disc (amphiarthrosis); *(c)* Pubic symphysis (amphiarthrosis); *(d)* Interphalangeal joint (diarthrosis).

Slightly Movable Joints

Bones forming a slightly movable joint, or **amphiarthrosis** (am-fē-ar-th-rō′-sis), are separated by a layer of cartilage or dense connective tissue. For example, the joints formed by adjacent vertebrae contain intervertebral discs formed of fibrocartilage (figure 6.24*b*). The limited flexibility of the discs allows slight movement between adjacent vertebrae. Other examples include the pubic symphysis (figure 6.24*c*) and sacroiliac joints.

Freely Movable Joints

Most articulations are freely movable. The structure of a freely movable joint, or **diarthrosis** (di-ar-thro′-sis), is more complex. These joints are also called **synovial** (si-no′-ve-al) **joints**. The ends of the bones forming the joint are bound together by an *articular,* or *joint, capsule.* The thick external layer of the capsule, called *fibrous membrane,* is composed of dense irregular connective tissue. The thin internal layer of the capsule, called *synovial* (si-nō′-vē-al) *membrane,* secretes *synovial fluid* that lubricates the joint. The ends of the bones are covered with *articular cartilage,* which protects bones and reduces friction (figure 6.24*d*). **Ligaments,** the cords or bands of dense regular connective tissue that connect bones together, reinforce the joints. Freely movable joints are categorized into several types based on their structure and types of movements.

Plane Joints

A *plane joint* occurs between two flat articular surfaces that slide over each other and allows for movement in one plane. Some examples of plane joints are the joints between carpal bones (figure 6.25*a*), between tarsal bones, and between clavicle and scapula.

Condylar Joints

A *condylar joint* is formed between an oval articular surface and an oval socket and allows for movements in two planes. The joints between carpal bones and radius and between metacarpals and proximal phalanges (figure 6.25*b*) are examples of condylar joints.

Saddle Joint

A *saddle joint* occurs where a saddle-like articular surface fits into a complementary depression, allowing movement in two planes. This type of joint occurs between the trapezium (a carpal bone) and metacarpal I (figure 6.25*c*).

Hinge Joints

A *hinge joint* involves a cylindrical articular surface and a complementary depression. It allows for movement similar to opening and closing a door. The elbow (figure 6.25*d*), knee, and joints between phalanges are all hinge joints.

Pivot Joints

A *pivot joint* involves a cylindrical articular surface and a complementary depression. It allows for rotation movements along a longitudinal axis. Examples of a pivot joint are the joint between atlas and axis (figure 6.25*e*) and the joint between the radius head and the ulna.

Ball-and-Socket Joints

In a *ball-and-socket joint,* a rounded head fits into a rounded socket. It allows for movements in all planes and provides the greatest range of movement of all types of freely movable joints. The ball-and-socket joints in the human body are the shoulder and hip joints (figure 6.25*f*).

Movements at Freely Movable Joints

Movement at a joint results from the contraction of skeletal muscles that span across the joint. The type of movement that occurs is determined by the type of joint and the location of the muscle or muscles involved. The more common types of movements are listed in table 6.4 and illustrated in figure 6.26.

Clinical Insight

Older persons are prone to "breaking a hip," which means that a weakened femur breaks at the neck. This usually is a consequence of osteoporosis, the excessive loss of matrix from bones. Osteoporosis is caused by a combination of factors: insufficient calcium in the diet, lack of minimal exercise, and a decline in sex hormones, especially in postmenopausal women. Not only are older persons more prone to fractures, but healing of fractures takes much longer than in younger persons.

Check My Understanding

12. Where are immovable, slightly movable, and freely movable joints found in the skeleton?
13. What types of freely movable joints occur in the body, and where are they located?

6.8 Disorders of the Skeletal System

Learning Objectives

19. Describe common disorders of bones.
20. Describe common disorders of joints.

Common disorders of the skeletal system may be categorized as disorders of bones or disorders of joints.

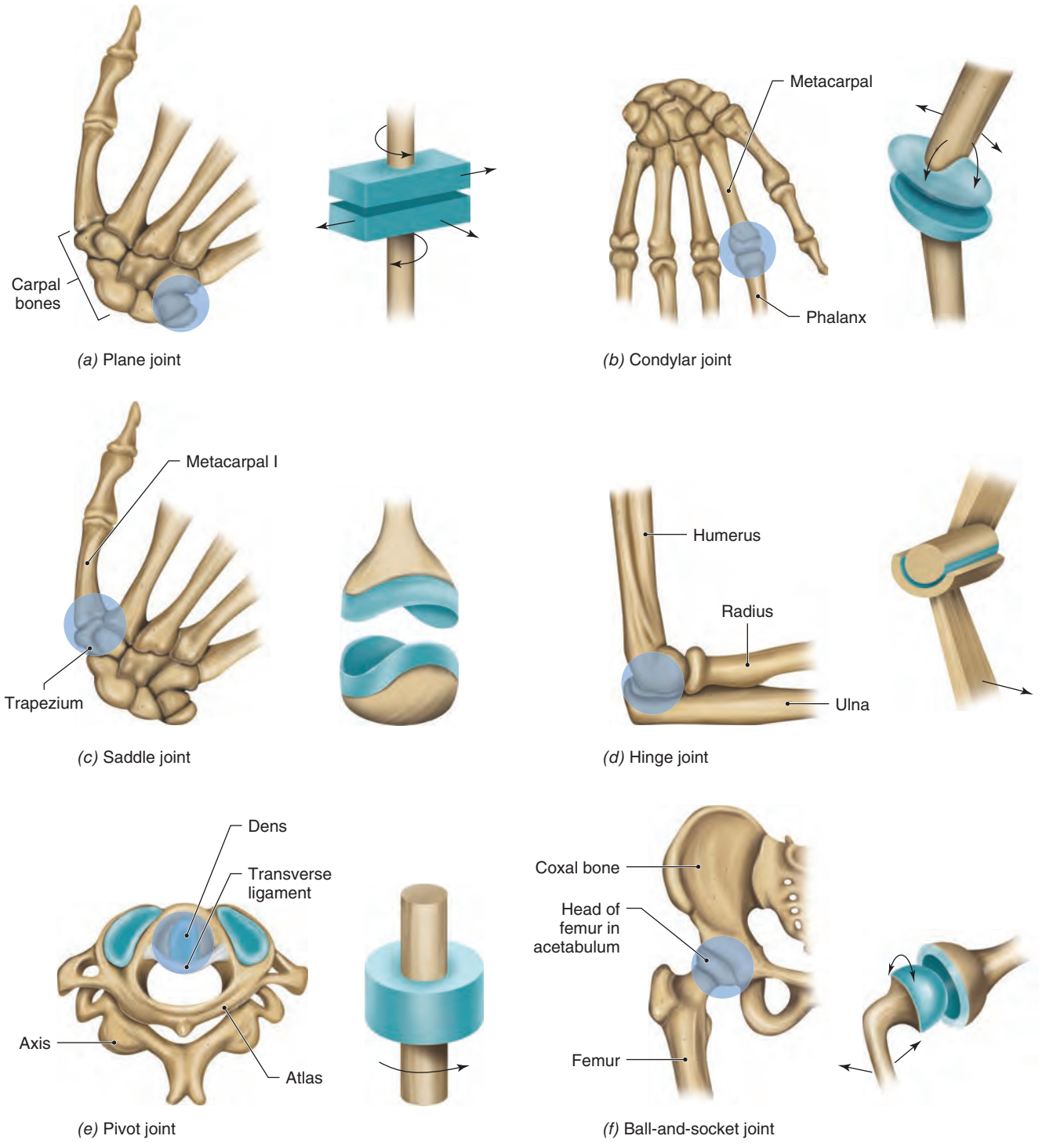


Figure 6.25 Types of Freely Movable Joints.

Orthopedics (or-thō-pē-diks) is the branch of medicine that specializes in treating diseases and abnormalities of the skeletal system.

Disorders of Bones

Fractures are broken bones. Fractures are the most common type of bone injury. Fractures are categorized as either complete or incomplete. There are also several specific subtypes, such as the examples noted here and in figure 6.27.

- **Complete:** The break is completely through the bone.
- **Compound:** A broken bone pierces the skin.
- **Simple:** A bone does not pierce the skin.
- **Comminuted:** The bone is broken into several pieces.

Table 6.4 Movements at Freely Movable Joints

Movements	Description
Flexion	Decrease in the angle of bones forming the joint
Extension	Increase in the angle of bones forming the joint
Hyperextension	Increase in the angle of bones forming the joint beyond the anatomical position
Dorsiflexion	Flexion of the foot at the ankle
Plantar flexion	Extension of the foot at the ankle
Abduction	Movement of a bone away from the midline
Adduction	Movement of a bone toward the midline
Rotation	Movement of a bone around its longitudinal axis
Medial rotation	Rotation of a limb so its anterior surface turns medially
Lateral rotation	Rotation of a limb so its anterior surface turns laterally
Circumduction	Movement of the distal end of a bone in a circle while the proximal end forms the pivot joint
Eversion	Movement of the sole of the foot laterally
Inversion	Movement of the sole of the foot medially
Pronation	Rotation of the forearm when the palm is turned inferiorly or posteriorly
Supination	Rotation of the forearm when the palm is turned superiorly or anteriorly
Protraction	Movement of a body part anteriorly
Retraction	Movement of a body part posteriorly
Elevation	Movement of a body part superiorly
Depression	Movement of a body part inferiorly
Opposition	Movement of the thumb to touch the other four fingers
Reposition	Movement of the thumb back to the anatomical position

- **Segmental:** Only one piece is broken out of the bone.
- **Spiral:** The fracture line spirals around the bone.
- **Oblique:** The break angles across the bone.
- **Transverse:** The break is at right angles to the long axis of the bone.
- **Incomplete:** The bone is not broken completely through.
- **Greenstick:** The break is only on one side of the bone, and the other side of the bone is bowed.
- **Fissured:** The break is a lengthwise split in the bone.

Osteomyelitis is an inflammation of bone and bone marrow caused by bacterial infection. It is treatable with antibiotics but not easily cured.

Osteoporosis (os-tē-ō-pō-rō′-sis) is a weakening of bones due to the removal of bone matrix, which increases the risk of fractures. This is a common problem in older persons due to inactivity and a decrease in hormone production. It is more common in postmenopausal women because of the lack of estrogens. Exercise and calcium supplements retard the decline in bone density. Therapy includes drugs that reduce bone loss or those that promote bone formation. However, such drugs must be used with caution because they can have serious side effects.

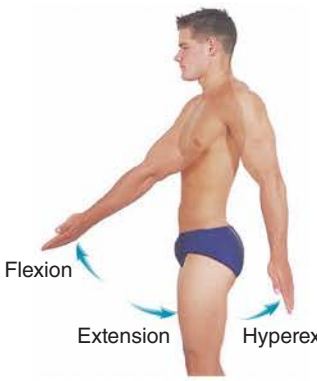
Rickets is a disease of children that is characterized by a deficiency of calcium salts in the bones. Affected children have a bowlegged appearance due to the bending of weakened femurs, tibiae, and fibulae. Rickets results from a dietary deficiency of vitamin D and/or calcium. It is rare in industrialized nations.

Disorders of Joints

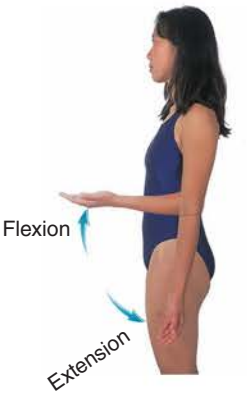
Arthritis (ar-thrī′-tis) is the general term for many different diseases of joints that are characterized by inflammation, swelling (edema), and pain. Rheumatoid arthritis and osteoarthritis are the most common types.

Rheumatoid (rū′-mah-toid) *arthritis* is the most painful and crippling type. It is an autoimmune disorder, in which the joint tissues are attacked by the patient's own defenses. The synovial membrane thickens, synovial fluid accumulates causing swelling, and articular cartilages are destroyed. The joint is invaded by dense irregular connective tissue that ultimately ossifies, making the joint immovable.

Osteoarthritis, the most common type, is a degenerative disease that results from aging and wear. The articular cartilages and the bone deep to the cartilages gradually disintegrate, which causes pain and restricts movement.


Flexion
Extension
Hyperextension


Circumduction

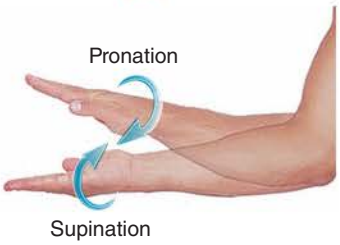

Flexion
Extension

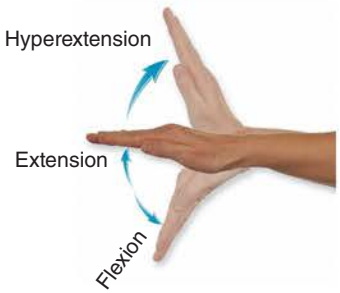

Flexion
Hyperextension

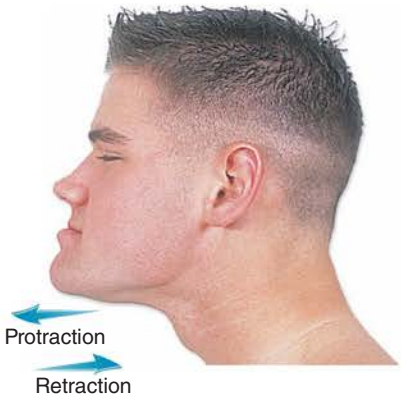

Abduction
Adduction

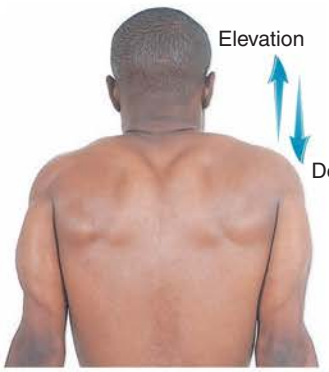

Adduction
Abduction

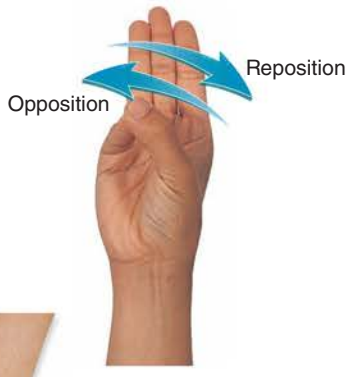

Medial rotation
Lateral rotation
Rotation

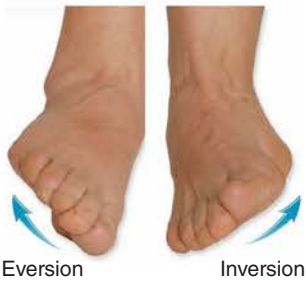

Pronation
Supination

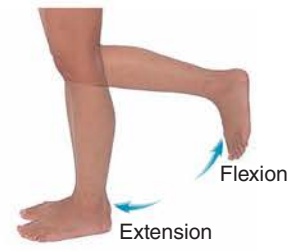

Hyperextension
Extension
Flexion

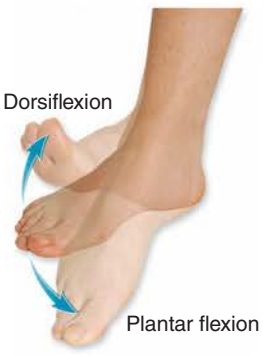

Protraction
Retraction


Elevation
Depression


Opposition
Reposition


Eversion
Inversion


Flexion
Extension


Dorsiflexion
Plantar flexion

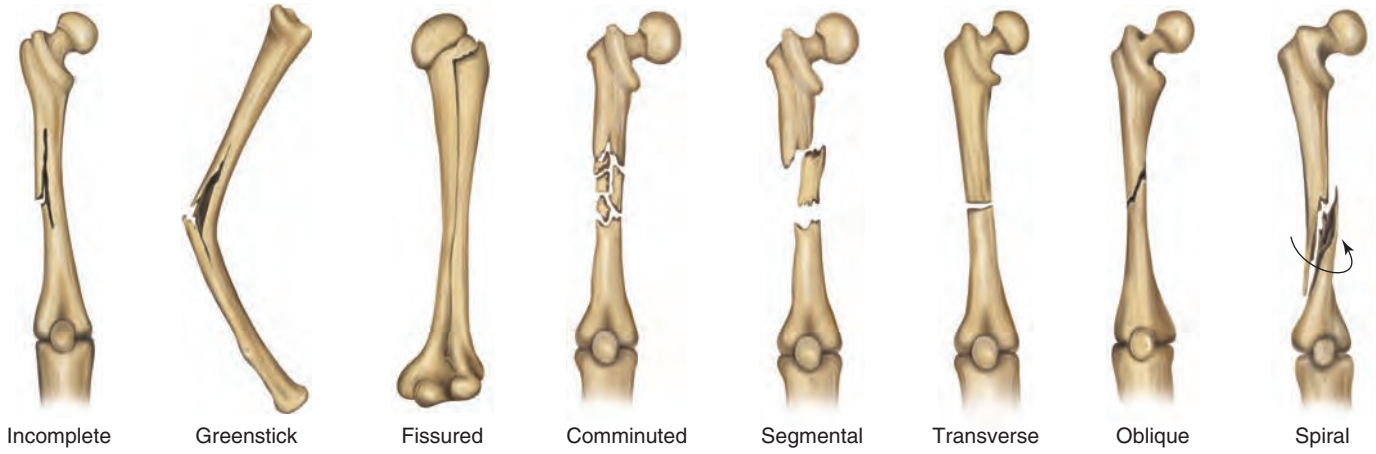


Figure 6.27 Some Types of Bone Fractures.

Dislocation is the displacement of bones forming a joint. Pain, swelling, and reduced movement are associated with a dislocation.

Herniated disc is a condition in which an intervertebral disc protrudes beyond the edge of a vertebra. A ruptured, or slipped, disc refers to the same problem. It is caused by excessive pressure on the vertebral column, which causes the *nucleus pulposus*, the centrally located gelatinous region of the disc, to protrude into the *anulus fibrosus*, the perimeter of the disc. The protruding disc may place pressure on a spinal nerve and cause considerable pain (figure 6.28).

Sprains result from tearing or excessive stretching of the ligaments and tendons at a joint without a dislocation.

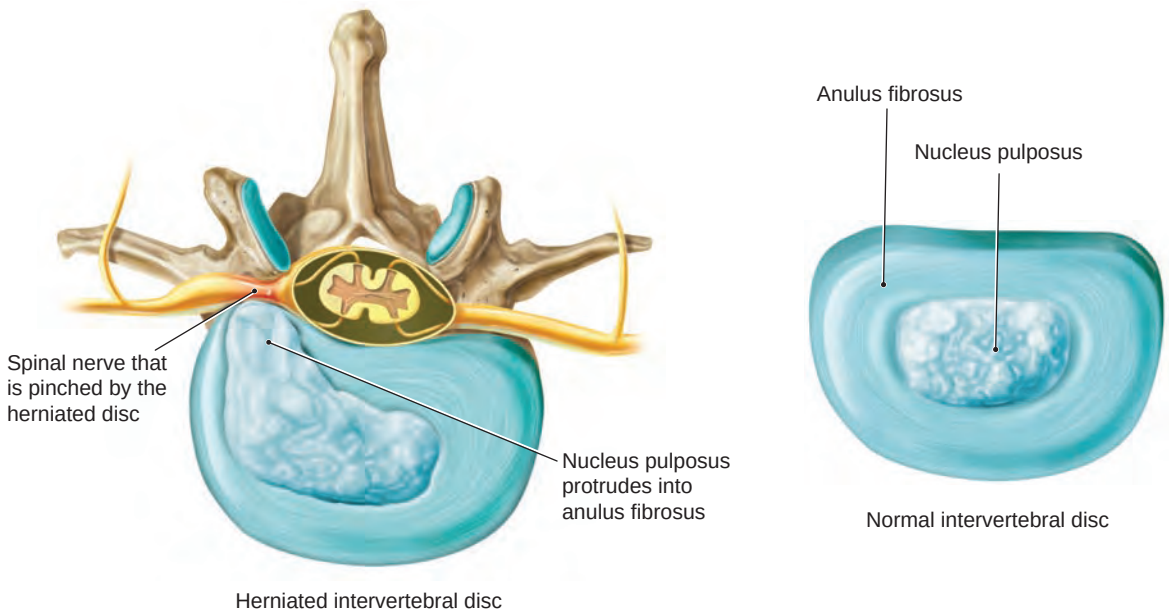


Figure 6.28 Herniated Disc.

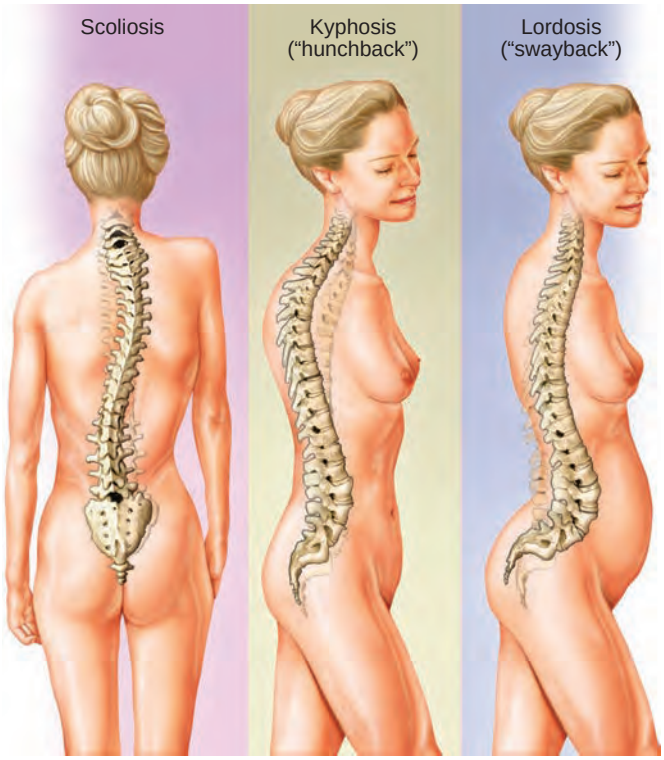


Figure 6.29 Abnormal Spinal Curvatures.

Abnormal spinal curvatures are usually congenital disorders. There are three major types (figure 6.29):

1. *Scoliosis* is an abnormal lateral curvature of the vertebral column. For some reason, it is more common in adolescent girls.
2. *Kyphosis* (kī-fō-sis) is an excessive thoracic curvature of the vertebral column, which produces a hunchback condition.
3. *Lordosis* is an excessive lumbar curvature of the vertebral column, which produces a swayback condition.

Check My Understanding

14. What are some common types of fractures?
15. How do osteoarthritis and rheumatoid arthritis differ?

Chapter Summary

6.1 Functions of the Skeletal System

- The skeletal system provides support for the body and protection for internal organs.
- The bones of the skeleton serve as sites for the attachment of skeletal muscles.
- Formed elements are produced by red bone marrow.
- Bones serve as reservoirs for calcium salts.

6.2 Bone Structure

- Based on shapes, bones are classified into short, long, sutural, flat, irregular, and sesamoid bones.
- The diaphysis is the long shaft of a long bone that lies between the epiphyses, the enlarged ends of the bone.
- Each epiphysis is joined to the diaphysis by an epiphysial plate in immature bones, or by fusion at the epiphysial line in mature bones.
- Articular cartilages protect and cushion the articular surfaces of the epiphyses.
- The periosteum covers the bone surface except for the articular cartilages.
- Compact bone forms the wall of the diaphysis and the thin superficial layer of the epiphyses.
- Spongy bone forms the internal structure of the epiphyses and the internal thin layer of the diaphysis wall.
- The diaphysis contains a medullary cavity filled with yellow marrow.
- Compact bone is formed of numerous osteons.
- Central canals contain blood vessels and nerves.
- Spongy bone is composed of interconnected bony plates called trabeculae. The spaces between trabeculae are filled with red or yellow bone marrow.
- Flat, short, and irregular bones are composed of spongy bone covered by a thin layer of compact bone.

6.3 Bone Formation

- Intramembranous bones are first formed by connective tissue membranes, which are replaced by bone.
- Connective tissue cells are transformed into osteoblasts, which deposit the spongy bone within the membrane.
- Osteoblasts from the periosteum form a layer of compact bone over the spongy bone.
- Endochondral bones are first formed of hyaline cartilage, which is later replaced by bone.
- In long bones, a primary ossification center forms in the center of the diaphysis and extends toward the epiphyses.
- Secondary ossification centers form in the epiphyses.
- An epiphysial plate of cartilage remains between the epiphyses and the diaphysis in immature bones.

- Growth in length occurs at the epiphysial plate, which is gradually replaced by bone.
- Compact bone is deposited by osteoblasts from the periosteum, and they are responsible for growth in the diameter of a bone.
- Osteoclasts hollow out the medullary cavity and reshape the bone.
- Bones are dynamic, living organs that are reshaped throughout life by the actions of osteoclasts and osteoblasts.
- Bone matrix may be removed from bones for other body needs and redeposited in bones later on.
- The number of protein fibers decreases with age. The bones of older persons tend to be brittle and weak due to the loss of fibers and calcium salts, respectively.

6.4 Divisions of the Skeleton

- The skeleton is divided into the axial and appendicular divisions.
- The axial skeleton includes the bones that support the head, neck, and trunk.
- The appendicular skeleton includes the bones of the pectoral girdle and upper limbs and the bones of the pelvic girdle and the lower limbs.

6.5 Axial Skeleton

- The axial skeleton consists of the skull, vertebral column, and thoracic cage.
- The skull consists of cranial and facial bones; all are joined by immovable joints except the mandible.
- The cranial bones are the frontal bone (1), parietal bones (2), sphenoid (1), temporal bones (2), occipital bone (1), and ethmoid (1).
- The facial bones are the maxillae (2), palatine bones (2), zygomatic bones (2), lacrimal bones (2), nasal bones (2), inferior nasal conchae (2), vomer (1), and mandible (1).
- The frontal bone, sphenoid, ethmoid, and maxillae contain paranasal sinuses.
- Cranial bones of an infant skull are separated by membranes and several fontanelles, which allow some flexibility of the skull during birth.
- Associated bones to the skull include a hyoid bone and six auditory ossicles.
- The vertebral column consists of 24 vertebrae, the sacrum, and the coccyx.
- Vertebrae are separated by intervertebral discs and are categorized as cervical (7), thoracic (12), and lumbar (5) vertebrae.
- The first two cervical vertebrae are unique. The atlas rotates on the axis when the head is turned.
- Thoracic vertebrae have costal facets on the body and transverse processes for articulation with the ribs.
- The bodies of lumbar vertebrae are heavy and strong.
- The sacrum is formed of five fused vertebrae and forms the posterior portion of the pelvis.
- The coccyx is formed of three to five fused vertebrae and forms the inferior end of the vertebral column.
- The thoracic cage consists of thoracic vertebrae, ribs, and sternum. It supports the superior trunk and protects internal thoracic organs.
- There are seven pairs of true ribs and five pairs of false ribs. The inferior two pairs of false ribs are floating ribs.
- The sternum is formed of three fused bones: manubrium, body, and xiphoid process.

6.6 Appendicular Skeleton

- The appendicular skeleton consists of the pectoral and pelvic girdles and of the bones of the limbs.
- The pectoral girdle consists of clavicles (2) and scapulae (2), and it supports the upper limbs.
- The bones of the upper limb are the humerus, the ulna, the radius, carpal bones, metacarpals, and phalanges.
- The humerus articulates with the glenoid cavity of the scapula to form the shoulder joint and with the ulna and radius to form the elbow joint.
- The ulna is the medial bone of the forearm. It articulates with the humerus at the elbow and with the radius and carpal bones at the wrist.
- The radius is the lateral bone of the forearm. It articulates with the humerus at the elbow and with the ulna and carpal bones at the wrist.
- The bones of the hand are the carpal bones (8), metacarpals (5), and phalanges (14).
- The carpal bones are joined by ligaments to form the wrist; metacarpal bones support the palm of the hand; and the phalanges are the bones of the fingers.
- The pelvic girdle consists of two coxal bones that are joined to each other anteriorly. It supports the lower limbs.
- Each coxal bone is formed by the fusion of three bones: the ilium, ischium, and pubis.
- The ilium forms the superior portion of a coxal bone and joins with the sacrum to form a sacroiliac joint.
- The ischium forms the inferior, posterior portion of a coxal bone and supports the body when sitting.
- The pubis forms the inferior, anterior part of a coxal bone. The two pubes unite anteriorly at the pubic symphysis.
- A pelvis is formed by two coxal bones and a sacrum. There are structural and functional differences between male and female pelves.
- Each lower limb consists of a femur, a patella, a tibia, a fibula, tarsal bones, metatarsals, and phalanges.
- The head of the femur is inserted into the acetabulum of a coxal bone to form a hip joint. Distally, it articulates with the tibia at the knee joint.
- The patella is a sesamoid bone in the anterior portion of the knee joint.
- The tibia articulates with the femur at the knee joint and with the talus to form the ankle joint.
- The fibula lies lateral to the tibia. It articulates proximally with the tibia and distally with the talus.
- The skeleton of the foot consists of tarsal bones (7), metatarsals (5), and phalanges (14).
- Tarsal bones form the ankle, metatarsal bones support the instep, and phalanges are the bones of the toes.

6.7 Articulations

- There are three types of joints: immovable, slightly movable, and freely movable.
- Bones forming immovable joints are closely joined by a thin layer of dense connective tissue or hyaline cartilage. Sutures in skull and epiphysial plates in growing bones are examples.
- Bones forming slightly movable joints are separated by fibrocartilage or dense connective tissue. Joints between vertebral bodies are examples.
- Bones forming freely movable joints are bound together by an articular capsule. The articular surfaces of the bones are covered by articular cartilages. The joint cavity is lubricated by synovial fluid secreted by the synovial membrane, the internal layer of articular capsule.
- There are six types of freely movable joints: plane, condylar, hinge, saddle, pivot, and ball-and-socket.
- Movements at freely movable joints include flexion, extension, hyperextension, dorsiflexion, plantar flexion, abduction, adduction, rotation, circumduction, inversion, eversion, protraction, retraction, elevation, depression, pronation, supination, opposition, and reposition.

6.8 Disorders of the Skeletal System

- Disorders of bones include fractures, osteomyelitis, osteoporosis, and rickets.
- Disorders of joints include arthritis, dislocation, herniated disc, abnormal spinal curvatures, and sprains.

Self-Review

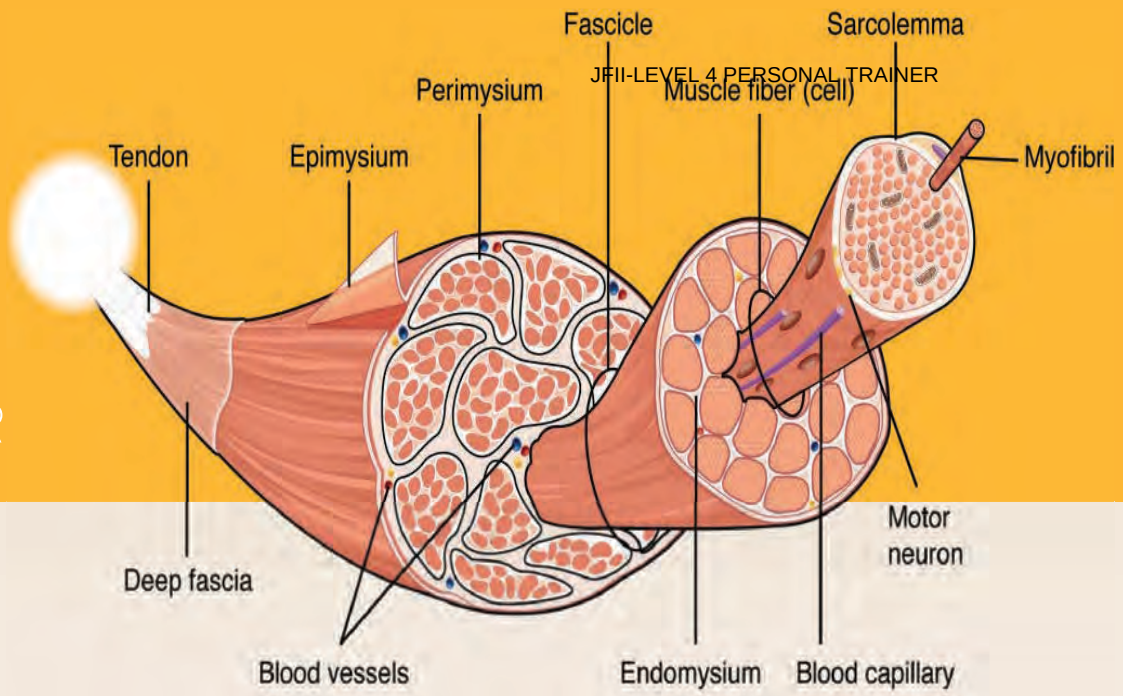
Answers are located in appendix B.

1. The skeletal system provides _____ for the body and _____ for many internal organs.
2. The enlarged ends of a long bone are the _____, which are composed of _____ bone that is coated with a thin layer of compact bone.
3. Blood vessels and nerves enter a bone through a _____.
4. Cranial bones are formed by _____ ossification.
5. Growth in diameter of a long bone occurs by deposition of bone by osteoblasts from the _____.
6. The skull, vertebral column, and thoracic cage are part of the _____ skeleton.
7. The bone forming the lower jaw is the _____, and it articulates with the _____.
8. The first vertebra, the _____, articulates with the _____ bone of the skull.
9. True ribs are attached directly to the sternum by the _____.
10. The clavicles and scapulae form the _____.
11. The arm bone, the _____, articulates with two forearm bones, the _____ and the _____.
12. Each coxal bone is formed of three fused bones: the _____, _____, and _____.
13. The thigh bone is the _____, and it articulates distally with the _____ and _____.
14. Among freely movable joints, the elbow is an example of a _____ joint, and the shoulder is an example of a _____ joint.
15. _____ is a weakening of bones due to removal of bone matrix.

Critical Thinking

1. Explain why both osteoclasts and osteoblasts are required for proper bone development.
2. Bone repairs itself faster than cartilage. Explain why.
3. Why is osteomyelitis more likely to occur after a compound fracture than after a greenstick fracture?
4. Explain how bones may become weakened if the diet is deficient in calcium.

5
CHAPTER



Muscular System

Melanie and a few of her friends head out early one morning for a short hike up a nearby mountain to a scenic overlook. As the wind gusts, forcing the temperature below freezing, they study a map and debate what trail to take. Melanie wonders if they made a good decision to hike today as her hands and feet begin to go numb despite her gloves and lined winter boots. Shivering violently, Melanie follows her friends up the mountain. The hike is strenuous because the trail they chose is both steep and rocky. The heat being created through the vigorous contractions of her skeletal muscles begins to gradually warm her body. In a short while, Melanie notices that she is no longer shivering or feeling the cold around her. By the time Melanie reaches the overlook, she is actually so warm that she begins to sweat. The friends sit on the edge of the overlook enjoying the view and each other's company. As the effects of the cold settle in once more, Melanie happily leads the way down the mountain to where a mug of hot chocolate and a roaring fire are waiting.

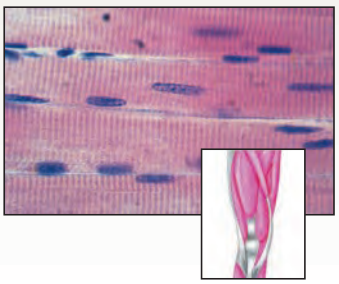
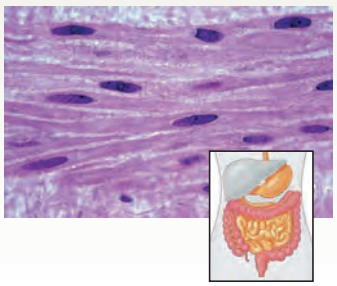
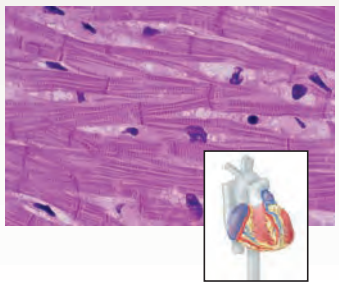
CHAPTER OUTLINE

SELECTED KEY TERMS

Agonist (agogos = leader) A muscle whose contraction leads an action.
Antagonist (anti = against) A muscle whose contraction opposes the action of the agonist.
Aponeurosis (apo = from; neur = cord) A broad sheet of dense regular connective tissue that attaches a muscle to another muscle or connective tissue.
Creatine phosphate An energy storage molecule found in muscle cells.
Insertion The attachment of a muscle that moves when the muscle contracts.
Motor unit A somatic motor neuron and the muscle fibers that it controls.
Muscle fiber A single skeletal muscle cell.
Muscle tone The state of slight contraction in a skeletal muscle.
Myoglobin (myo = muscle) An oxygen-storage molecule in muscle cells.
Neurotransmitter (neuro = nerve; transmit = to send across) A chemical released by terminal boutons of neurons that activates a muscle cell, gland, or another neuron.
Origin The attachment of a muscle that remains fixed when the muscle contracts.
Tendon A narrow band of dense regular connective tissue that attaches a muscle to a bone.
Tetany (tetan = rigid, stiff) A sustained muscle contraction.

MUSCLE TISSUE is the only tissue in the body that is specialized for contraction (shortening). The body contains three types of muscle tissue: skeletal, smooth, and cardiac. Each type of muscle tissue exhibits unique structural and functional characteristics. Contraction of skeletal muscle tissue produces locomotion, movement of body parts, and movement of the skin, as in making facial expressions. Cardiac muscle tissue produces the driving force responsible for pumping blood through the cardiovascular system, as you will see in chapter 12. Smooth muscle tissue is responsible for various internal functions, such as controlling the movement of blood through blood vessels and air through respiratory passageways. It is also directly involved in vision and moving contents through hollow internal organs as described in future chapters. Refresh your understanding of these tissues by referring to the discussion of muscle tissue in chapter 4. Table 7.1 summarizes the characteristics of muscle tissues.

Table 7.1 Types of Muscle Tissue

Characteristic	Skeletal	Smooth	Cardiac
Striations	Present	Absent	Present
Nucleus	Many peripherally located nuclei	Single centrally located nucleus	Usually a single centrally located nucleus
Cells	Long and parallel, called fibers	Short; tapered ends; parallel	Short and branching; intercalated discs join cells end to end to form network
Neural control	Voluntary	Involuntary	Involuntary
Contractions	Fast, variable fatigability; slow, resistant to fatigue	Slow; resistant to fatigue	Rhythmic; resistant to fatigue
Location	Attached to bones, dermis, ligaments, and other muscles	Walls of hollow visceral organs and blood and lymphatic vessels, skin, and inside eyes	Wall of the heart
Micrograph			

7.1 Structure of Skeletal Muscle

Learning Objectives

1. Describe the structure of a skeletal muscle.
2. Explain how a skeletal muscle is attached to a bone or other tissues.
3. Describe the structure of a muscle fiber.
4. Describe a motor unit.
5. Describe the structure and function of a neuromuscular junction.

Skeletal muscles are the organs of the muscular system. They are called skeletal muscles because most of them are attached to bones. A skeletal muscle is composed mainly of skeletal muscle tissue bound together and electrically insulated by connective tissue layers. Individual skeletal muscle cells, called **muscle fibers** due to their long skinny shape, are wrapped in areolar connective tissue. Muscle fibers extend most of the length of a whole muscle and are arranged in small bundles called *muscle fascicles* (fah′-si-kuls) that are each surrounded by a layer of dense irregular connective tissue. A muscle is formed when many muscle fascicles are packaged and held together by an external layer of dense irregular connective tissue. Groups of whole muscles with similar functions are connected by a superficial layer of dense irregular connective tissue called *fascia* (fash′-e-ah). The fascia is deep and connected to the subcutaneous tissue, which is how the muscles can produce skin movement. These muscle connective tissues extend beyond the end of the muscle tissue to form a tough, cordlike **tendon,** which attaches the muscle to a bone (figure 7.1). Fibers of the tendon and periosteum intermesh to form a secure attachment. A few muscles attach to other muscles, dermis, and ligaments, in addition to bones. In these muscles there is a broad, sheetlike attachment called an **aponeurosis.** (ap″-ō-nū-rō′-sis).

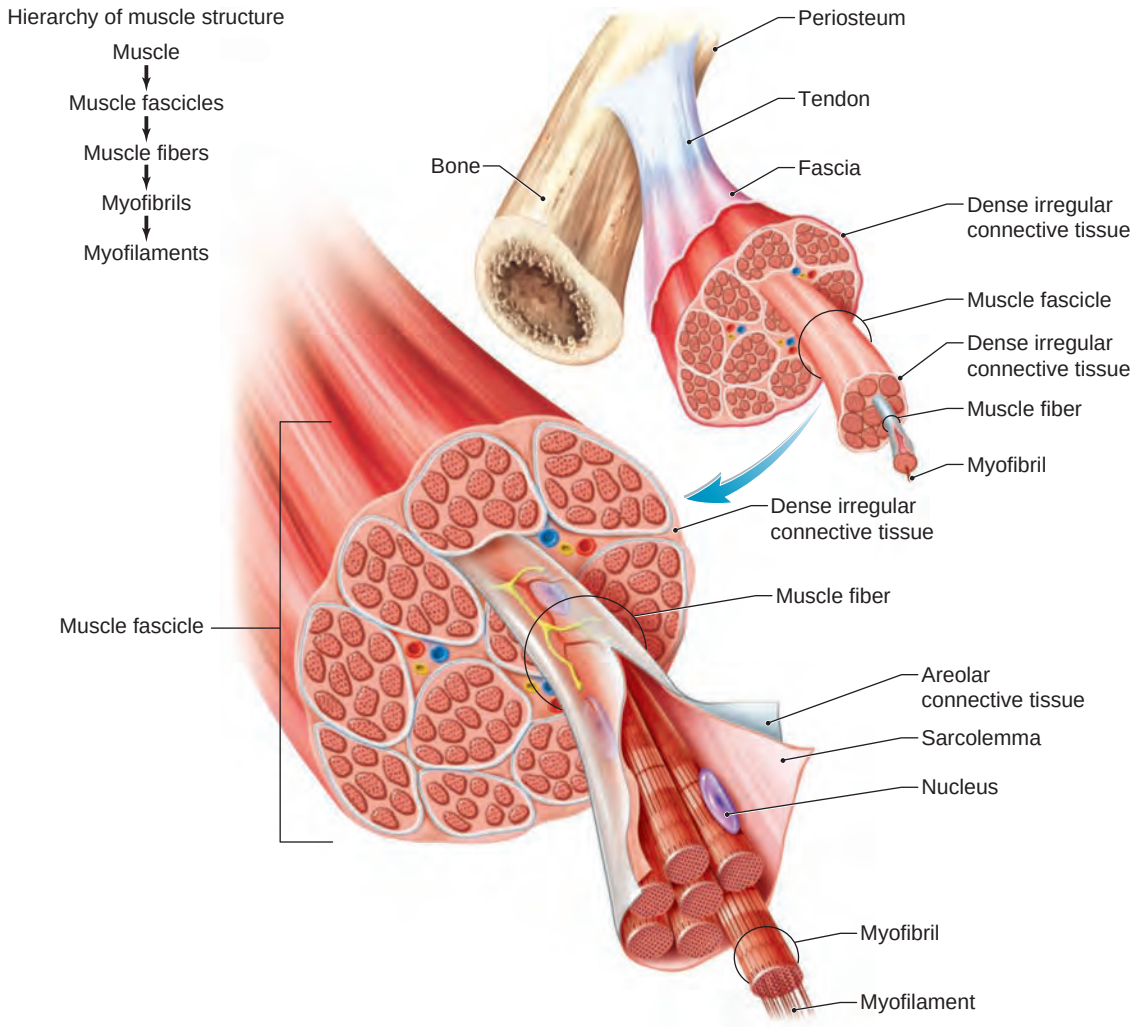


Figure 7.1 A skeletal muscle is primarily composed of skeletal muscle fibers supported and bound together in muscle fascicles by dense irregular connective tissue. Myofibrils are the contractile elements of a muscle fiber.

Skeletal Muscle Fibers

The internal structure of skeletal muscle tissue is so highly specialized that specific terminology is used to describe some muscle fiber structures. The prefixes *sarco-* (flesh) and *myo-* (muscle) are often used in renaming muscular structures. Therefore, the plasma membrane of a muscle fiber is called the **sarcolemma** (sar-kō-lem′-ah), and its cytoplasm is the **sarcoplasm.**

The sarcoplasm contains many threadlike **myofibrils,** which extend the length of the muscle fiber, as shown in figure 7.1. Myofibrils are the contractile elements of a muscle fiber. They consist of two kinds of myofilaments that interact to produce muscle contractions: (1) *thin myofilaments* composed mostly of the protein **actin** and (2) *thick myofilaments* composed of the protein **myosin** (table 7.2).

A thin myofilament consists of two twisted strands of actin molecules joined together like tiny strands of pearls. Two additional proteins, *troponin* and *tropomyosin,* are present in thin myofilaments and play a role in muscle contraction. Double strands of tropomyosin coil over each actin strand and cover the *myosin binding sites.* Troponin occurs at regular intervals on the tropomyosin strands. A thick myofilament is composed of hundreds of myosin molecules, each shaped like a double-headed golf club. The myosin heads are able to attach to the myosin bind sites on the actin molecules to form cross-bridges (figure 7.2). The organization of thin and thick myofilaments within a muscle fiber produces *striations*–the light and dark cross bands that are characteristic of skeletal muscle fibers when viewed microscopically.

Table 7.2 Microscopic Anatomy of a Skeletal Muscle Fiber

Structure	Description/Function
Sarcolemma	Plasma membrane of a muscle fiber maintaining the integrity of the cell
Sarcoplasm	Cytoplasm of a muscle fiber that contains organelles
Nuclei	Contain DNA, which determines cell structure and function
Sarcoplasmic reticulum	Smooth ER in a muscle fiber that stores Ca^{2+}
Transverse tubules	Extensions of the sarcolemma that penetrate into the sarcoplasm carrying muscle impulses, which trigger the release of Ca^{2+} from the sarcoplasmic reticulum
Myofibril	A bundle of myofilaments
Myofilaments	Threadlike contractile proteins that interact to produce contractions

As shown in figure 7.2, the arrangement of thin and thick myofilaments repeats itself throughout the length of a myofibril. These repeating units are called sarcomeres. A **sarcomere** is a functional unit of skeletal muscle–that is, it is the smallest portion of a myofibril capable of contraction. A sarcomere extends from a Z line to the next Z line. **Z lines** are composed of proteins arranged perpendicular to the longitudinal axis of the myofilament. Thin myofilaments are attached to each side of the Z lines and extend toward the middle of the sarcomeres. The *I band,* which is the light band in a micrograph, possesses thin myofilaments only and spans across the Z lines. The *A band,* which is the dark band in a micrograph, spans the length of the thick myofilaments. Note that the ends of the thin myofilaments do not meet, leaving a space at the center of the A band, which contains only thick myofilaments, called the *H band* (pale zone). Proteins that maintain the structure of the center the sarcomere make up the *M line.*

Figure 7.3 illustrates the relationship of the sacroplasmic reticulum and transverse (T) tubules to myofibrils in a muscle fiber. The **sarcoplasmic reticulum** is the name given to the smooth endoplasmic reticulum in a muscle fiber. It plays an important role in contraction by storing and releasing calcium (Ca^{2+}) ions. The **transverse (T) tubules** consist of invaginations of the sarcolemma that penetrate into the sarcoplasm so that they lie alongside and contact the sarcoplasmic reticulum.

Neuromuscular Interaction

A muscle fiber must be stimulated by nerve impulses in order to contract. Nerve impulses are carried from the brain or spinal cord to a muscle fiber by a long, thin process (an axon) of a motor neuron. A *motor neuron* is an action-causing neuron–its nerve impulses produce an action in the target cells. In muscle fibers, this action is contraction and the specific type of motor neuron is called a *somatic motor neuron.*

Motor Units

A somatic motor neuron and all of the muscle fibers to which it attaches, or innervates, form a **motor unit** (figure 7.4). Whereas a muscle fiber is attached to only one motor neuron, a single somatic motor neuron may innervate from 3 to 2,000 muscle fibers. Where precise muscle control rather than strength is needed, such as in the fingers, a motor unit contains very few muscle fibers. Large numbers of motor units are involved in the manipulative movements of the fingers. In contrast, where strength rather than precise control is needed, such as in the postural muscles, a motor unit controls hundreds of muscle fibers. Whenever a motor neuron is activated, it stimulates contraction of all the muscle fibers that it innervates. Neighboring muscle fibers do not contract due to the insulation provided by the connective tissue coverings.

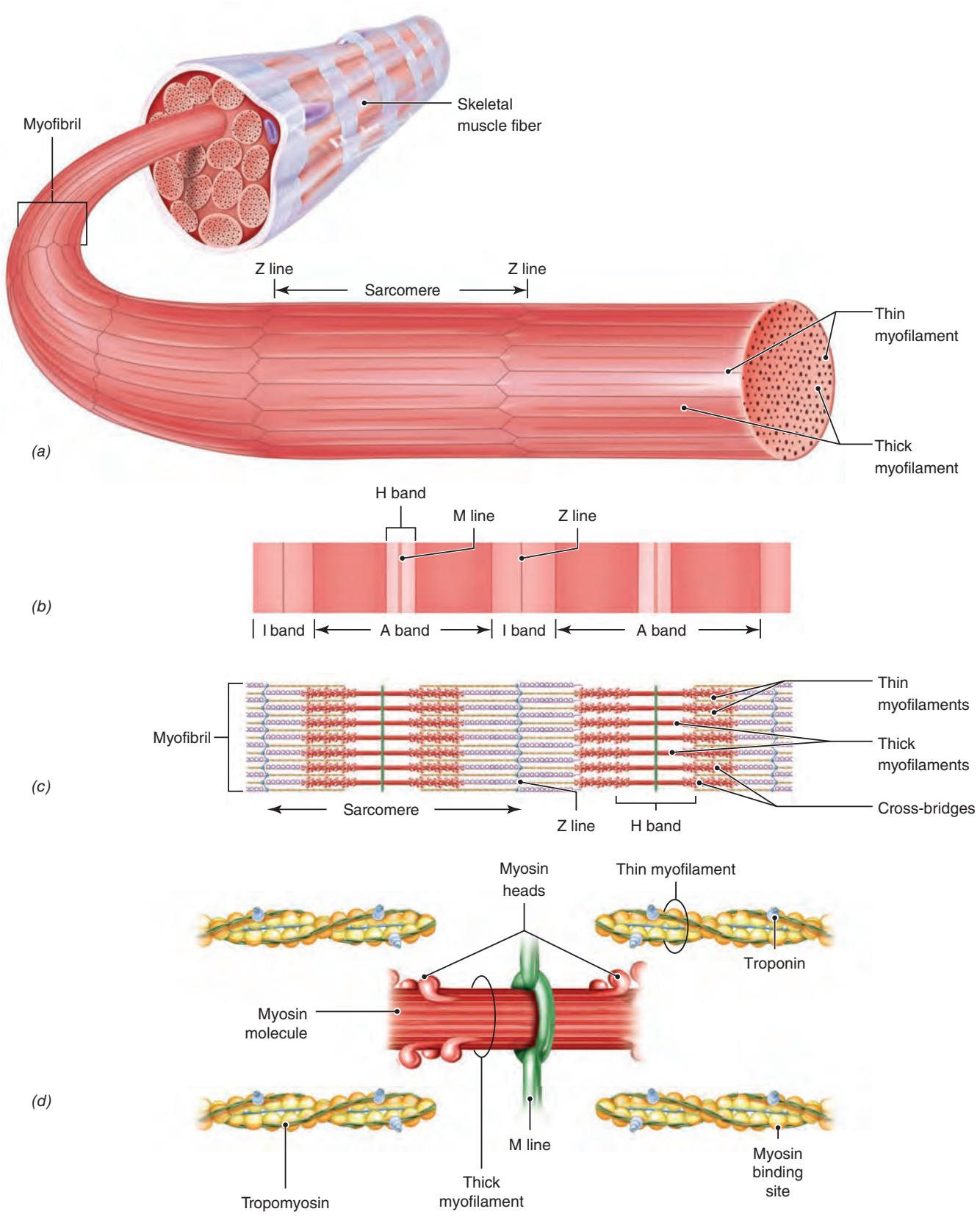


Figure 7.2 Structure of a myofibril. *(a)* A muscle fiber contains many myofibrils. Each myofibril consists of repeating functional units called sarcomeres. *(b)* The characteristic bands of sarcomeres. *(c)* The arrangement of thin and thick myofilaments within the sarcomeres. *(d)* Details of thin myofilaments and thick myofilaments.

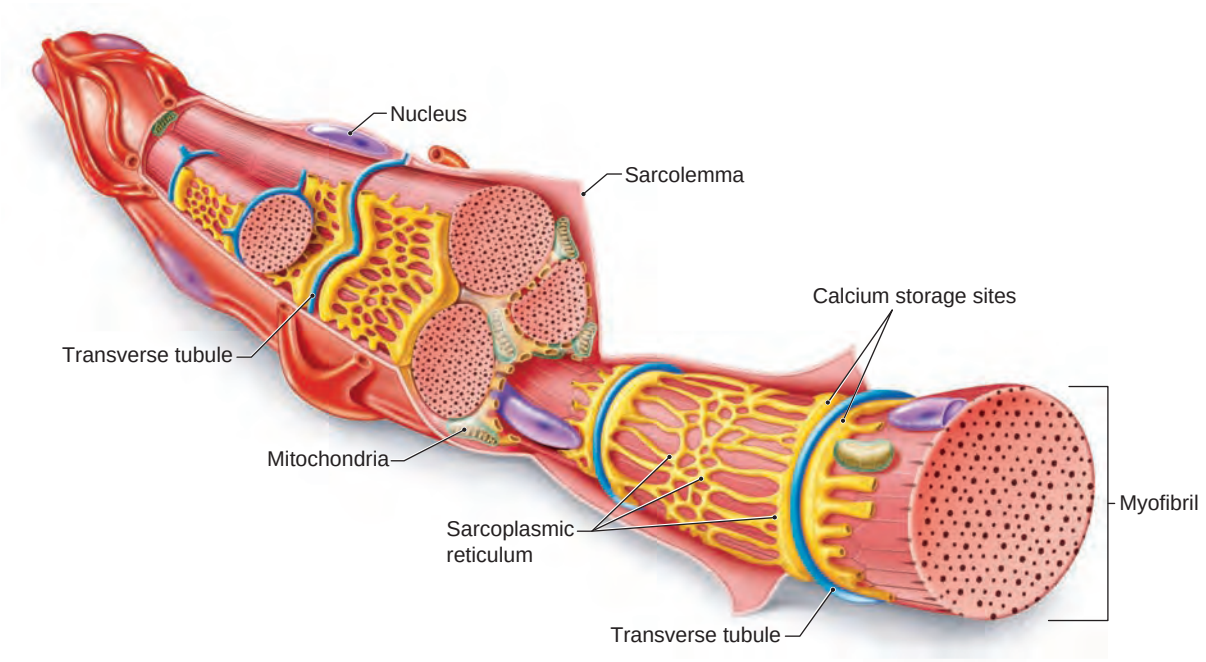


Figure 7.3 A portion of a muscle fiber showing the sarcoplasmic reticulum and the transverse (T) tubules associated with the myofibrils.

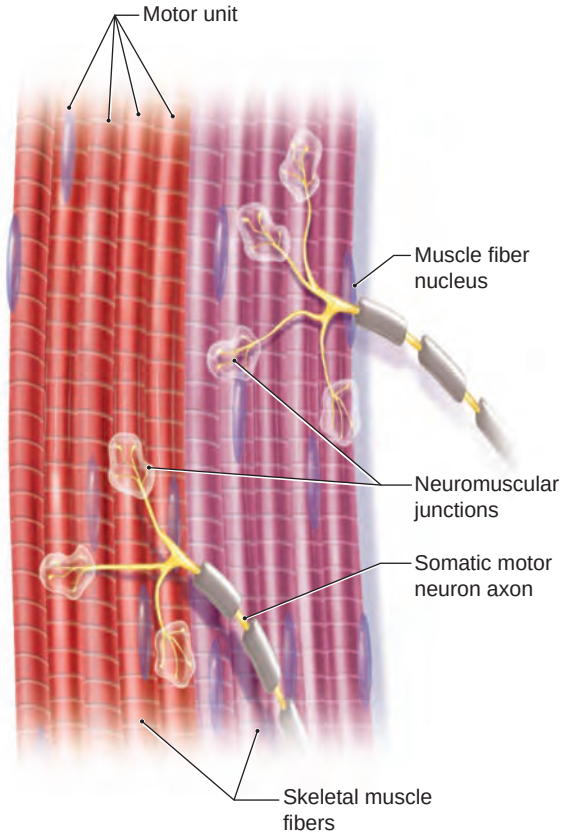


Figure 7.4 A motor unit consists of one somatic motor neuron and all the muscle fibers that it innervates. Note the attachment of the terminal boutons to the muscle fibers.

Neuromuscular Junction

The part of a somatic motor neuron that leads to a muscle fiber is called an *axon.* The connection between the terminal branches of an axon and the sarcolemma of a muscle fiber is known as a **neuromuscular junction** (figure 7.4). As shown in figure 7.5, the *terminal boutons* (axon tips) fit into depressions, the *motor end plates,* in the sarcolemma. The tiny space between the terminal bouton and the motor end plate is the *synaptic cleft.* Numerous secretory vesicles in the terminal bouton contain the **neurotransmitter** (nū-rō-trans′-mit-er) *acetylcholine* (as″-ē-tīl-kō′-lēn) or ACh. When a somatic motor neuron is activated and a nerve impulse reaches the terminal bouton, ACh is released from secretory vesicles into the synaptic cleft. The attachment of ACh to ACh receptors on the motor end plate triggers a series of reactions causing the muscle fiber to contract.

Clinical Insight

Anabolic steroids, substances similar to the male sex hormone testosterone, have been used by some athletes to promote muscle development and strength. However, physicians have warned that such use can produce a number of harmful side effects, including damage to kidneys, increased risk of heart disease and liver cancer, and increased irritability. Other side effects include decreased testosterone and sperm production in males and increased facial hair and deepening of the voice in females.

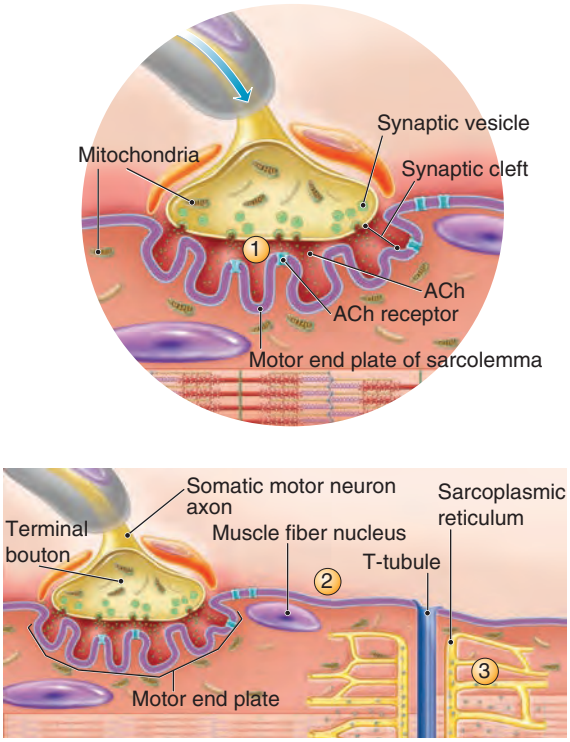


Figure 7.5 A neuromuscular junction is formed by the terminal bouton of a somatic motor neuron and the motor end plate of a muscle fiber. The detailed insert shows the synaptic vesicles, the synaptic cleft, and the folded surface of the motor end plate.

Check My Understanding

1. How are muscle tissue and connective tissue arranged in a skeletal muscle?
2. What composes a muscle fiber?

7.2 Physiology of Skeletal Muscle Contraction

Learning Objectives

6. Describe the physiology of contraction.
7. Explain the cause of excess post-exercise oxygen consumption (EPOC).
8. Explain the all-or-none contraction of muscle fibers.
9. Discuss how graded contractions of whole muscles produce a variety of contraction strengths.

Contraction of a muscle fiber is a complex process that involves a number of rapid structural and chemical changes within the muscle fiber. The molecular mechanism of contraction is explained by the *sliding-filament model* described in the next section.

Mechanism of Contraction

As mentioned in the previous section, in order for a muscle fiber to contract it needs to first be stimulated or "excited" by a somatic motor neuron. The pairing of a nerve impulse (an electrochemical signal) and physical contraction of the muscle fiber is referred to as **excitation-contraction coupling.** Figure 7.5 shows the steps of excitation.

1. Contraction of a muscle fiber is initiated when the terminal bouton of an activated somatic motor neuron releases ACh into the synaptic cleft.
2. Acetylcholine binds to ACh-receptors on the motor end plate causing the formation of a muscle impulse (similar to the nerve impulse that will be described in chapter 8), that spreads over the sarcolemma and is carried into the sarcoplasm by the T tubules.
3. Stimulation of the sarcoplasmic reticulum from the nearby T tubules triggers the release of Ca^{2+} from the sarcoplasmic reticulum into the sarcoplasm.

Figure 7.6 shows the steps of the contraction cycle.

Step 1a–Ca^{2+} within the sarcoplasm binds to troponin, which then causes the tropomyosin strands to change position, exposing the myosin binding sites on actin molecules.
Step 1b–With the myosin binding sites exposed, each myosin head binds to a myosin binding site to form a cross-bridge with the actin molecule.
Step 2–While the cross-bridge is formed the inorganic phosphate detaches, causing the myosin head to pivot and exert a power stroke that pulls the thin myofilaments toward the M line of the sarcomere. ADP detaches during the pivoting of the myosin head.
Step 3–The power stroke causes sliding of the myofilaments past one another, and the sarcomere shortens.
Step 4–A new molecule of ATP binds to the myosin head, causing myosin to release the actin molecule.
Step 5–The detached myosin head returns to its relaxed position and then becomes energized after hydrolyzing the ATP to ADP and Pi.
Step 6–This returns us to **Step 1b,** wherein the energized myosin head reattaches to a new binding site on actin, releases Pi, and uses its energy to repeat the power stroke in **Step 2.** This cycle rapidly repeats itself to maintain a contraction as long as ATP and Ca^{2+} are available.

When the somatic motor neuron stops stimulating the muscle fiber, an enzyme in the synaptic cleft called *acetylcholinesterase* begins decomposing ACh. The breakdown of ACh prevents continued stimulation of the muscle fiber. Consequently, Ca^{2+} is no longer released from the sarcoplasmic reticulum and is instead actively transported

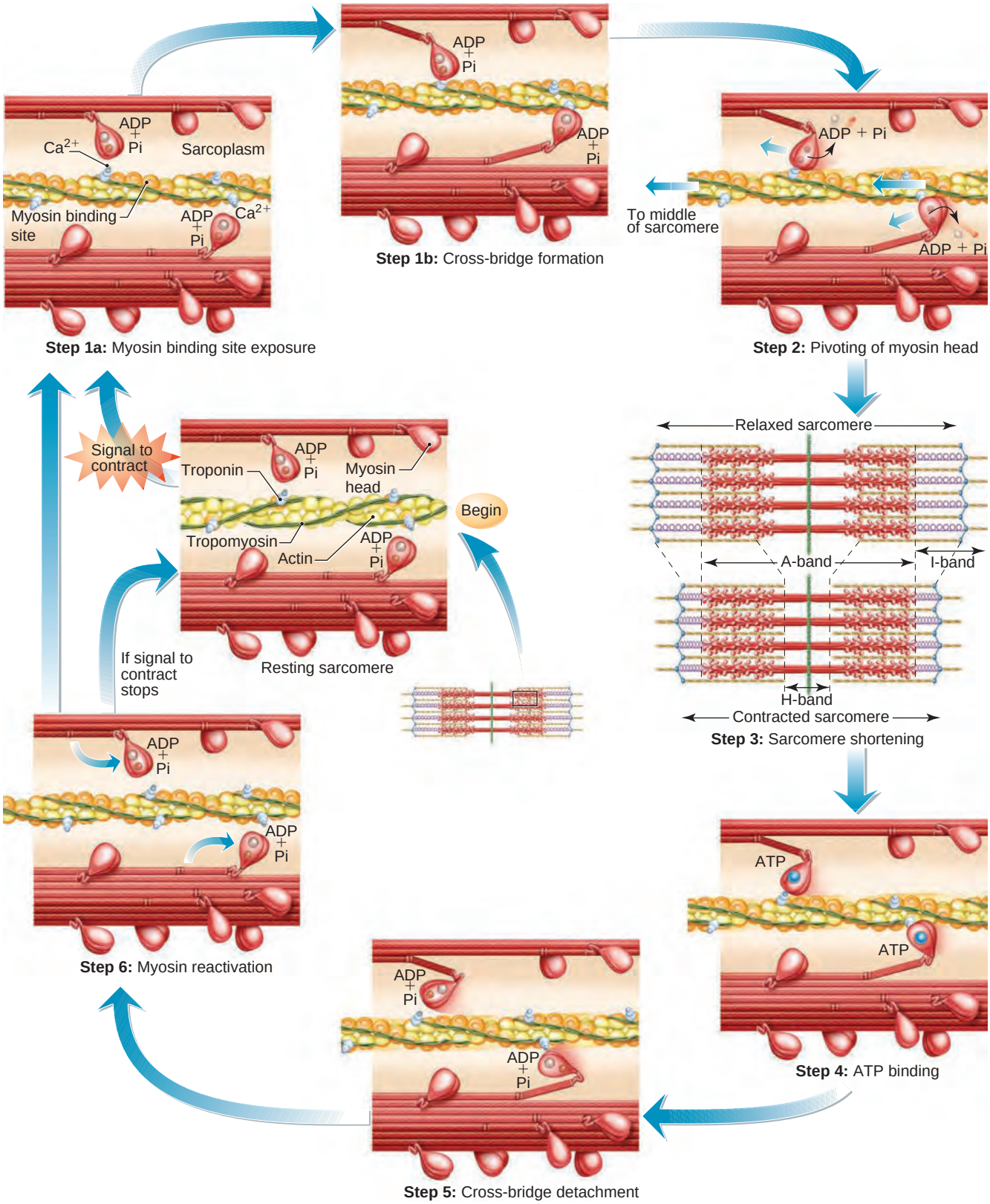


Figure 7.6 Sliding-filament model of muscle contraction. The release of Ca^{2+} into sarcoplasm causes the exposure of myosin binding sites on actin molecules, enabling the contraction cycle to begin. ATP powers the contraction cycle.

from the sarcoplasm into the sarcoplasmic reticulum. This causes Ca^{2+} to unbind troponin, which allows tropomyosin to move back over the myosin binding sites and stop the contraction cycle. The thin and thick myofilaments then slide back to their original positions, moving the Z lines apart, lengthening the sarcomeres (muscle relaxation).

Carefully study figure 7.6, which illustrates the sliding-filament model of muscle contraction. Note the configuration of thin myofilaments and thick myofilaments in a relaxed muscle fiber, how they interact in the steps of the contraction cycle, and how contraction is powered by ATP. Although the sliding myofilaments produce contraction (i.e., the shortening of the sarcomeres), the lengths of the thin myofilaments and thick myofilaments remain unchanged (step 3, figure 7.6).

Energy for Contraction

The energy for muscle contraction comes from ATP molecules in the muscle fiber. Recall that ATP is a product of cellular respiration. However, there is only a small amount of ATP in each muscle fiber. Once it is used up, more ATP must be formed in order for additional contractions to occur. Figure 7.7 summarizes the processes involved in the replenishment of ATP.

While a muscle fiber is relaxed it uses cellular respiration to release energy from nutrients and transfers that energy to the high-energy phosphate bonds of ATP. Once there are sufficient amounts of ATP available in the muscle fiber, the high-energy phosphate is transferred to creatine to form **creatine phosphate (CP),** which serves as a storage form of readily available energy. The resulting ADP is then reconverted to ATP using cellular respiration.

Muscle contraction quickly reduces ATP levels, resulting in the high-energy phosphate group being transferred back from the creatine phosphate to the ADP, forming ATP, which can then be used to power additional contractions (Figure 7.7a).

There is four to six times more creatine phosphate than ATP in a muscle fiber so it is an important source for immediate ATP formation without waiting for the slower process of cellular respiration. However, it can also be depleted in under 10 seconds in a muscle that is contracting repeatedly.

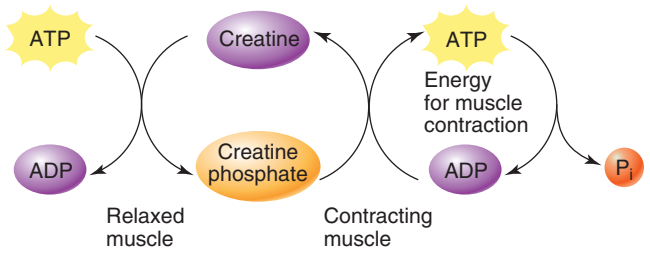
Clinical Insight

The reaction that transfers the phosphate between creatine phosphate and ADP is controlled by an enzyme unique to muscle tissue. When muscle tissue is damaged this enzyme is released into the blood. Elevated levels of the cardiac version of this enzyme in blood tests suggest that a heart attack may have occurred. Blood levels of cardiac troponin can be used as an indicator of heart damage as well.

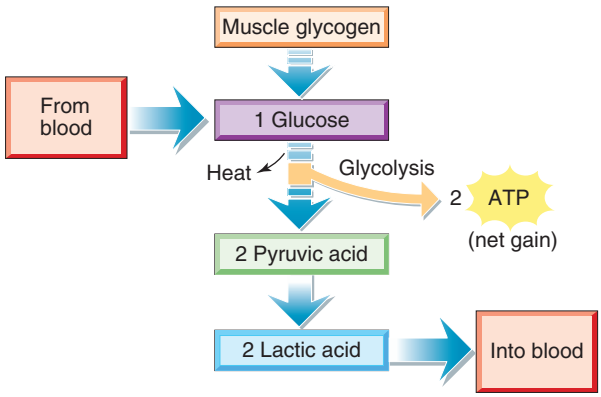
Oxygen and Cellular Respiration

Recall from chapter 3 that cellular respiration is the process of breaking down glucose in two steps: (1) anaerobic respiration in the cytosol and (2) aerobic respiration in the mitochondria. Due to the need of a constant supply for glucose to generate ATP, muscle fibers store large amounts of glucose as **muscle glycogen.** Recall from chapter 2 that glycogen is a polysaccharide of glucose.

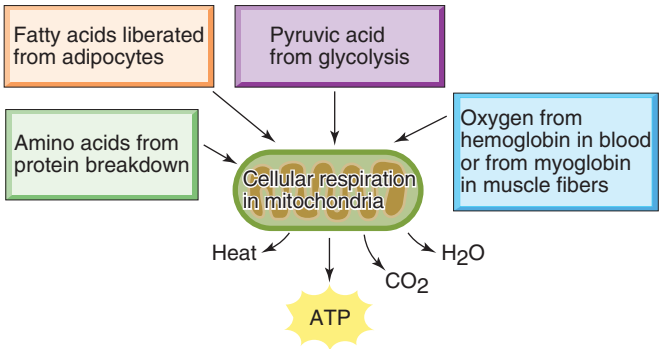
Whether or not a muscle fiber uses just anaerobic respiration or also includes aerobic respiration depends on the availability of oxygen. During periods of strenuous exercise such as weight lifting, muscle fibers will employ mostly anaerobic respiration because the respiratory and



(a) ATP from creatine phosphate



(b) ATP from anaerobic respiration



(c) ATP from aerobic respiration

Figure 7.7 A summary of the sources of ATP in muscle fibers.

cardiovascular systems cannot provide oxygen to muscle fibers quickly enough to maintain aerobic respiration. The muscle fibers will break down glycogen to glucose and glucose to pyruvic acid, in a process called *glycolysis*, forming only a small amount of ATP per molecule of glucose (see Chapter 3 and figure 7.7*b*).

Since anaerobic respiration is not favorable in muscle fibers, muscle tissue is adapted to facilitate aerobic respiration. Muscle tissue possesses a large number of blood vessels and obtains large amounts of oxygen from the blood via **hemoglobin,** the red pigment in red blood cells. Muscle fibers also have a similar pigment, **myoglobin,** which stores oxygen within the sarcoplasm and helps transfer oxygen to the mitochondria. In the same manner that creatine phosphate stores extra energy in times of muscle inactivity, some of the oxygen carried to muscle fibers is transferred from hemoglobin to myoglobin and stored for later use during periods of muscle activity. This function of myoglobin reduces the muscle fiber's dependence on oxygen carried to it by the blood at the onset of exercise. During inactivity or light to moderate physical activity (e.g. endurance training), muscle fibers receive sufficient oxygen to carry on the aerobic respiration. As shown in figure 7.7*c*, this process involves the breakdown of *pyruvic acid* produced in glycolysis, or other organic nutrients, into carbon dioxide and water. In contrast to anaerobic respiration, aerobic respiration provides a large amount of ATP per molecule of glucose (see Chapter 3 and figure 7.7*c*).

Excess Post-Exercise Oxygen Consumption (EPOC)

When a muscle fiber utilizes anaerobic respiration, such as during strenuous exercise, it accumulates lactic acid and depletes its ATP, CP, and oxygen stores. To restore resting conditions within a muscle fiber after activity ceases, respiratory and heart rates remain elevated to support **excess post-exercise oxygen consumption** or **EPOC** (formerly oxygen debt). EPOC is the amount of oxygen required to replenish myoglobin and to produce the ATP needed for the metabolism of the lactic acid in the liver, heart, and skeletal muscles and the restoration of ATP and creatine phosphate in the muscle fibers.

Fatigue

If a muscle is stimulated to contract for a long period, its contractions will gradually decrease until it no longer responds to stimulation. This condition is called **fatigue.** Although the exact mechanism is not known, several factors seem to be responsible for muscle fatigue. The most likely cause of fatigue in long term muscle activity is a lack of available nutrients, such as muscle glycogen and fatty acids, to utilize for ATP production.

Effects of Exercise on Muscles

Exercise has a profound effect on skeletal muscles. Strength training, which involves resistance exercise such as weight lifting, causes a muscle fiber to be repetitively stimulated to maximum contraction. Over time, the repetitive stimulation produces **hypertrophy**–an increase in muscle fiber size and strength. The number of muscle fibers cannot be increased after birth. Instead, hypertrophy results from an increase in the number of myofibrils in muscle fibers, which increases the diameter and strength of the muscle fibers and of the whole muscle itself. In comparison, lack of repetitive stimulation to maximum force causes muscular **atrophy,** which is the reduction in muscle size and strength due to loss of myofibrils. Atrophy can be caused by damage to the nerve stimulating the muscle or lack of use, such as when a limb is in a cast. Aerobic exercise, or endurance training, does not produce hypertrophy. Instead it enhances the efficiency of aerobic respiration in muscle fibers by increasing (1) the number of mitochondria, (2) the efficiency of obtaining oxygen from the blood, and (3) the concentration of myoglobin.

Heat Production

Heat production by muscular activity is an important mechanism in maintaining a normal body temperature. Muscles are active organs that form a large proportion of the body weight. Heat produced by muscles results from cellular respiration and other chemical reactions within the muscle fibers. Recall that 60% of the energy released by cellular respiration is heat energy. Muscle generates so much heat that exercise leads to an increase in body temperature that requires sweating to help remove heat from the body. On the other hand, the major response to a decrease in body temperature is shivering, which is involuntary muscle contractions.

Check My Understanding

3. What are the structure and function of a neuromuscular junction?
4. How do thin and thick myofilaments interact during muscle contraction?
5. What are the roles of ATP and creatine phosphate in muscle contraction?
6. What are the relationships among cellular respiration, lactic acid, and excess post-exercise oxygen consumption?

Contraction Characteristics

When studying muscle contraction, physiologists consider both single-fiber contraction and whole-muscle contraction.

Contraction of a Single Fiber

It is possible to remove a single muscle fiber in order to study its contraction in the laboratory. By using electrical stimuli to initiate contraction and by gradually increasing the strength (voltage) of each stimulus, it has been shown that the fiber will not contract until the stimulus reaches a certain minimal strength. This minimal stimulus is called the **threshold stimulus.**

Whenever a muscle fiber is stimulated by a threshold stimulus or by a stimulus of greater strength, it always contracts *completely*. Thus, a muscle fiber either contracts completely or not at all–contraction is *not* proportional to the strength of the stimulus. This characteristic of individual muscle fibers is known as the **all-or-none response.**

Contraction of Whole Muscles

Much information has been gained by studying the contraction of a whole muscle of an experimental animal. In such studies, electrical stimulation is used to cause contraction, and the contraction is recorded to produce a tracing called a *myogram*.

If a single threshold stimulus is applied, some of the muscle fibers will contract to produce a single, weak contraction (a muscle twitch) and then relax, all within a fraction of a second. The myogram will look like the one shown in figure 7.8. After the stimulus is applied, there is a brief interval before the muscle starts to contract. This interval is known as the *latent phase*. Then, the muscle contracts (shortens) during the *contraction phase* and relaxes (returns to its former length) during the *relaxation phase*. If a muscle is stimulated again after it has relaxed completely, it will contract and produce a similar myogram. A series of single stimuli applied in this manner will yield a myogram like the one in figure 7.9*a*.

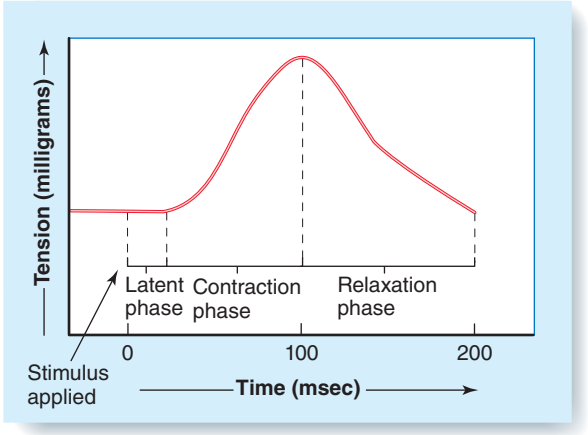


Figure 7.8 A myogram of a single muscle twitch. Note the brief latent phase, contraction phase, and longer relaxation phase.

If the interval between stimuli is shortened so that the muscle fibers cannot completely relax, the force of individual twitches combines by *summation*, which increases the force of contraction. Rapid summation produces incomplete tetany, a fluttering contraction (figure 7.9*b*). If stimuli are so frequent that relaxation is not possible, **tetany** results (figure 7.9*c*). Tetany is a state of sustained contraction without relaxation. In the body, tetany results from a rapid series of nerve impulses carried by somatic motor neurons to the muscle fibers that results in a prolonged state of contraction. Tetany for short time periods is the usual way in which muscles contract to produce body movements.

Graded Responses Unlike individual muscle fibers that exhibit all-or-none responses, whole muscles exhibit *graded responses*–that is, varying degrees of contraction. Graded responses enable the degree of muscle contraction to fit the task being performed. Obviously, more muscle fibers are required to lift a 14 kg (30 lb) weight than to lift a feather. Yet both activities can be performed by the same muscles.

Graded responses are possible because a muscle is composed of many different *motor units*, each responding to different thresholds of stimulation. In the laboratory, a weak stimulus that activates only low-threshold motor units produces a minimal contraction. As the strength of the stimulus is increased, the contractions get stronger as more motor units are activated until a **maximal stimulus** (one that activates all motor units) is applied, which produces a maximal contraction. Further increases in the strength of the stimulus (supramaximal) cannot produce a greater contraction. The same results occur in a normally functioning body. The nervous system provides the stimulation and controls the number of motor units activated in each muscle contraction. The activation of more and more motor units is known as *motor unit recruitment* (figure 7.9*d*).

Muscle Tone Even when a muscle is relaxed, some of its muscle fibers are contracting. At any given time, some of the muscle fibers in a muscle are involved in a sustained contraction that produces a constant partial, but slight, contraction of the muscle. This state of constant partial contraction, called **muscle tone,** keeps a muscle ready to respond. Muscle tone results from the alternating activation of different motor units by the nervous system so that some muscle fibers are always in sustained contraction, as seen in figure 7.10. Muscle tone of postural muscles plays an important role in maintaining erect posture.

Check My Understanding

7. What is meant by the all-or-none response?
8. How are muscles able to make graded responses?

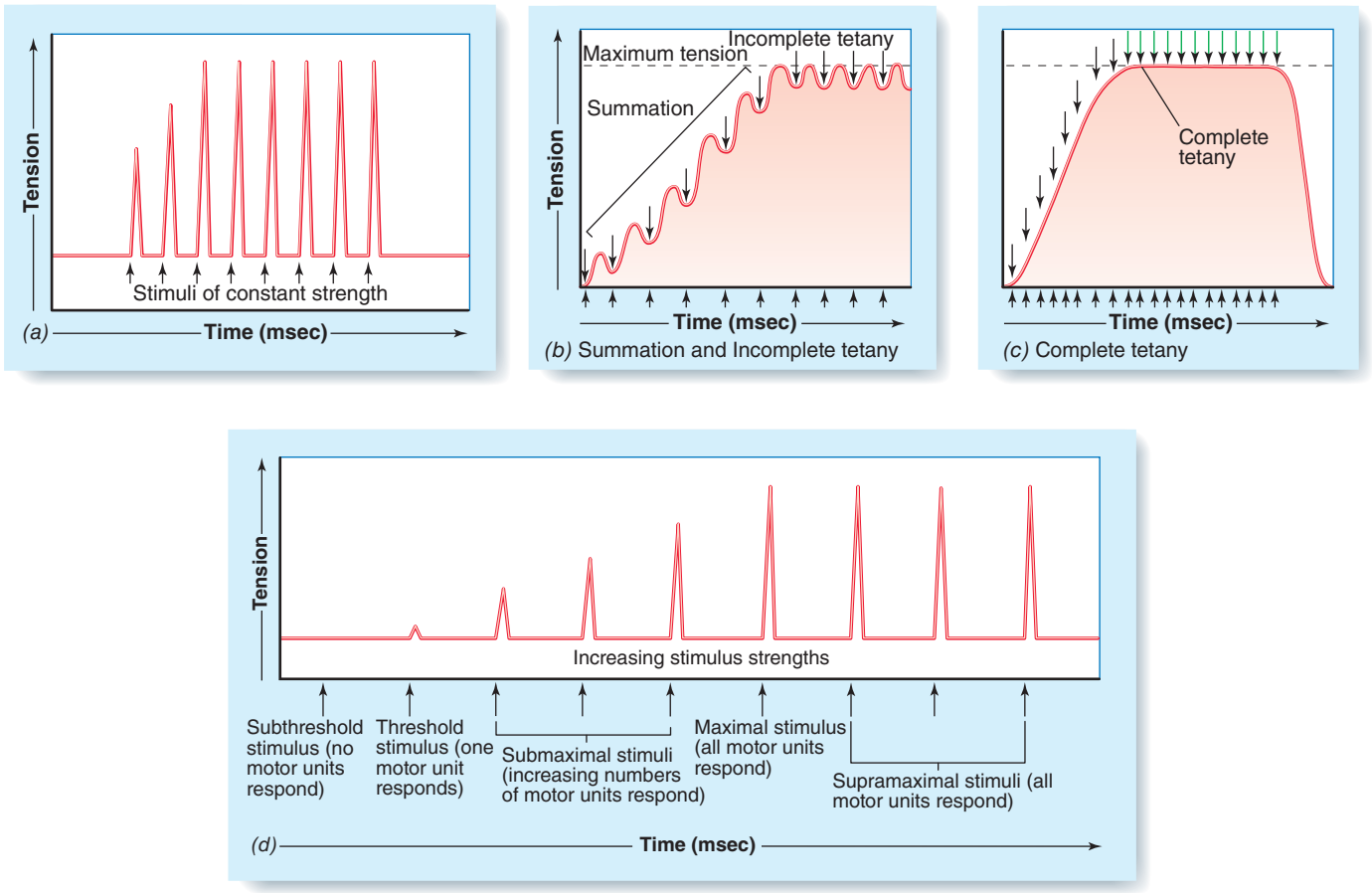


Figure 7.9 Myograms of *(a)* a series of simple twitches, *(b)* summation caused by incomplete relaxation between stimuli, *(c)* tetany, and *(d)* motor unit recruitment.

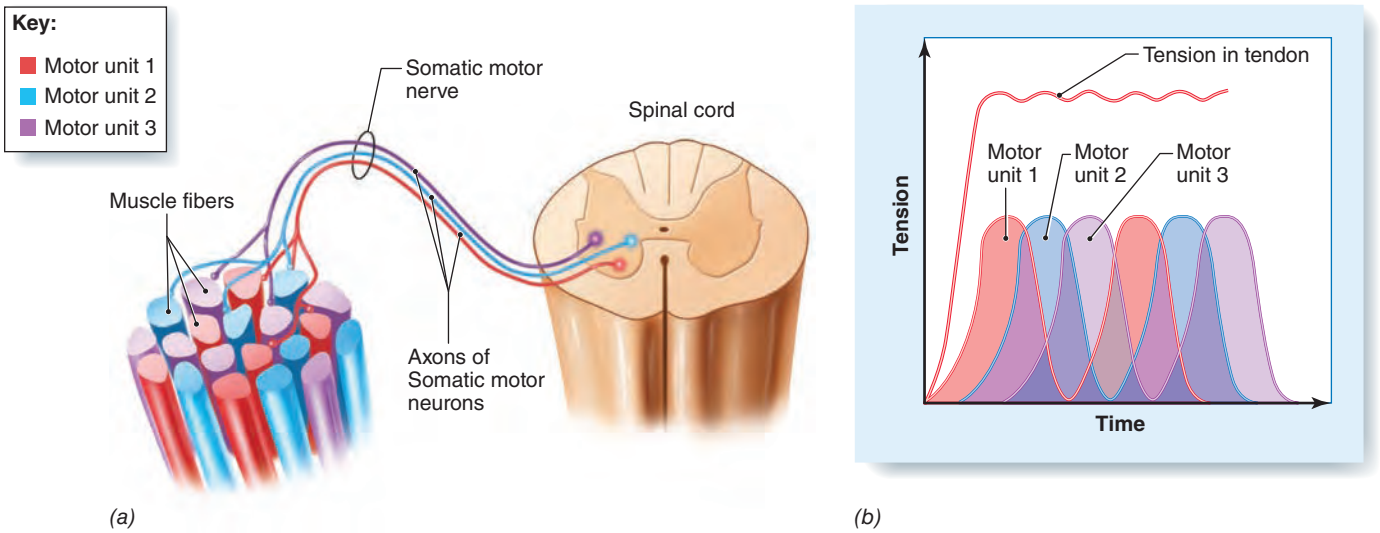


Figure 7.10 *(a)* Anatomy of motor units in a skeletal muscle. *(b)* Myogram showing mechanism of motor unit alternation in muscle tone.

7.3 Actions of Skeletal Muscles

Learning Objectives

10. Explain the relationship between a muscle's origin and insertion and its action.
11. Explain how agonists and antagonists function in the production of body movements.

Skeletal muscles are usually arranged so that the ends of a muscle are attached to bones on each side of a joint. Thus, a muscle usually extends across a joint. The type of movement produced depends upon the type of joint and the locations of the muscle attachments. Common movements at joints were discussed in chapter 6.

Origin and Insertion

During contraction, a bone to which one end of the muscle is attached moves, but the bone to which the other end is attached does not. The movable attachment of a muscle is called the **insertion,** and the immovable attachment is called the **origin.** When a muscle contracts, the insertion is pulled toward the origin.

Consider the *biceps brachii* in figure 7.11. It has two origins, and both are attached to the scapula. The insertion is on the radius, and the muscle lies along the anterior surface of the humerus. When the biceps brachii contracts, the insertion is pulled toward the origin, which results in the flexion of the forearm at the elbow.

Most muscle contractions are *isotonic contractions*, which cause movement at a joint. Walking and breathing are examples. However, some contractions may not produce movement but only increase tension within a muscle. Contractions that maintain body posture are good examples. Such contractions are *isometric contractions*.

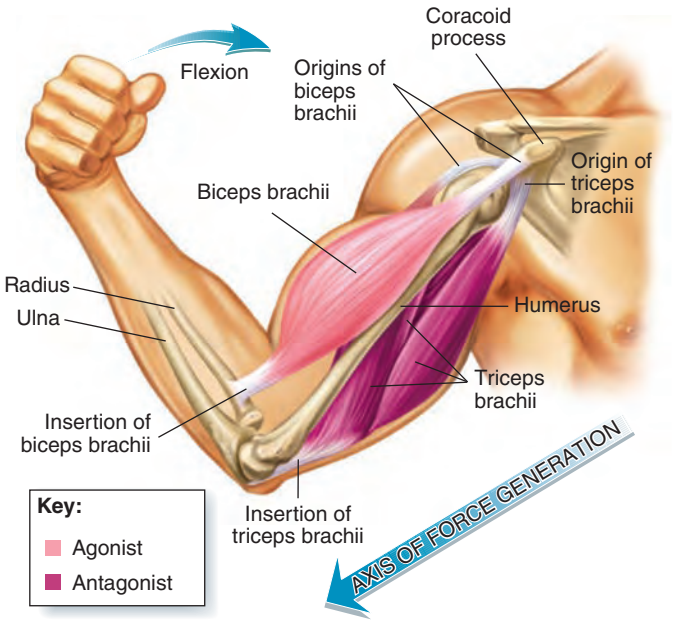


Figure 7.11 Demonstration of the actions of agonists and antagonists with origins and insertions labeled.

Muscle Interactions

Muscles function in groups rather than singly, and the groups are arranged to provide opposing movements. For example, if one group of muscles produces flexion, the opposing group produces extension. A group of muscles producing an action are called **agonists,** and the opposing group of muscles are called **antagonists.** When agonists contract, antagonists must relax, and vice versa, for movement to occur. If both groups contract simultaneously, the movable body part remains rigid. Figure 7.11 illustrates how the biceps brachii is the agonist of forearm flexion, while the triceps brachii is the antagonist.

7.4 Naming of Muscles

Learning Objective

12. List the criteria used for naming muscles.

Learning the complex names and functions of muscles can be confusing. However, the names of muscles are informative if their meaning is known. A few of the criteria used in naming muscles and examples of terms found in the names of muscles are listed below:

- **Function:** extensor, flexor, adductor, and pronator.
- **Shape:** trapezius (trapezoid), rhomboid (rhombus), deltoid (delta-shaped or triangular), biceps (two heads).
- **Relative position:** external, internal, abdominal, medial, lateral.
- **Location:** intercostal (between ribs), pectoralis (chest).
- **Site of attachment:** temporalis (temporal bone), zygomaticus (zygomatic bone).
- **Origin and insertion:** sternohyoid (sternum = origin; hyoid = insertion), sternocleidomastoid (sternum and clavicle = origins; mastoid process = insertion).
- **Size:** maximus (larger or largest), minimus (smaller or smallest), brevis (short), longus (long).
- **Orientation of fibers:** oblique (diagonal), rectus (straight), transversus (across).

7.5 Major Skeletal Muscles

Learning Objectives

13. Describe the location and action of the major muscles of the body.
14. Identify the major muscles on a diagram.

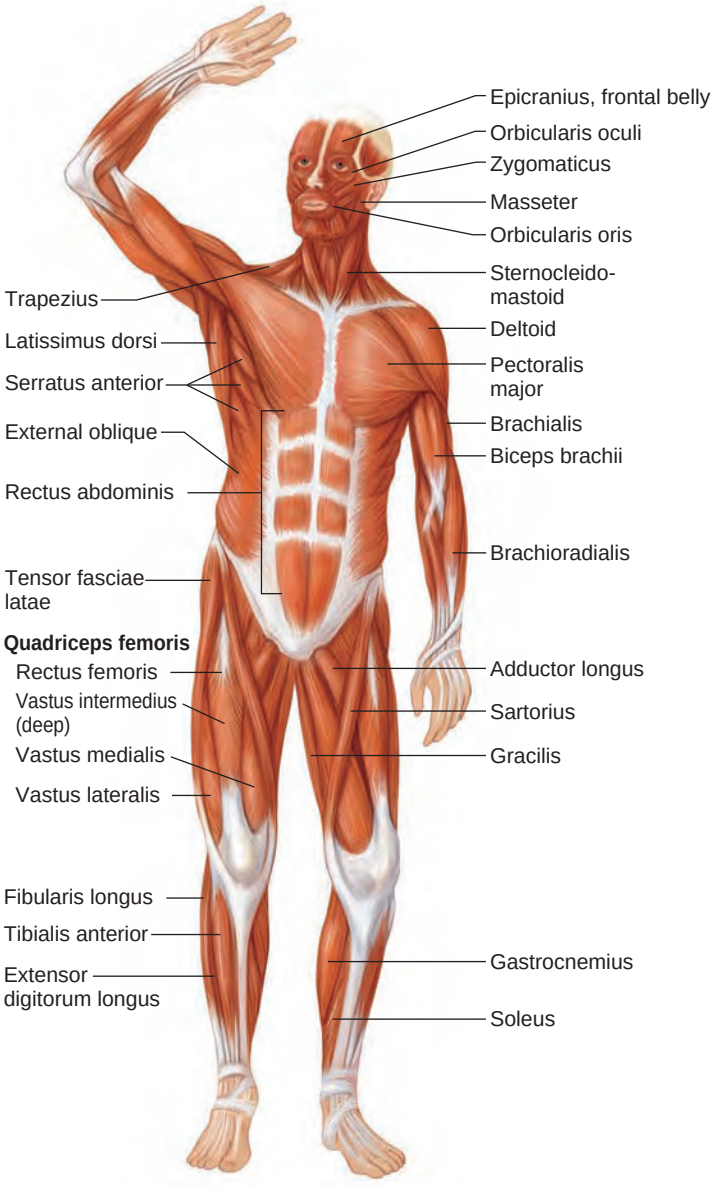


Figure 7.12 Anterior view of superficial skeletal muscles.

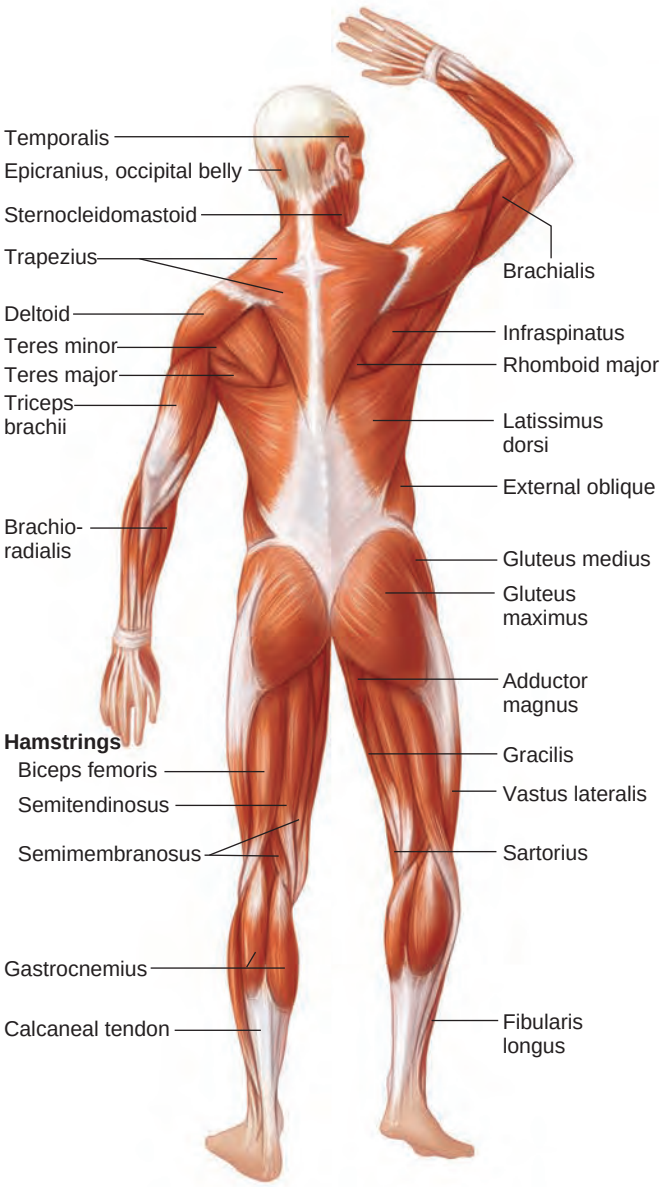


Figure 7.13 Posterior view of superficial skeletal muscles.

This section is concerned with the name, location, attachment, and action of the major skeletal muscles. There are more than 600 muscles in the body, but only a few of the major muscles are considered here. Most of this information is presented in tables and figures to aid your learning. The tables are organized according to the primary actions of the muscles. The pronunciation of each muscle is included, because being able to pronounce the names correctly will help you learn the names of the muscles.

As you study this section, locate each muscle listed in the tables on the related figures 7.12 to 7.25. This will help you visualize the location and action of each muscle. Also, if you visualize the locations of the origin and insertion of a muscle, its action can be determined because contraction pulls the insertion toward the origin. It may help to refresh your understanding of the skeleton by referring to appropriate figures in chapter 6. Begin your study by examining figures 7.12 and 7.13 to learn the major superficial muscles that will be considered in more detail as you progress through the chapter.

Muscles of Facial Expression and Mastication

Muscles of the face and scalp produce the facial expressions that help communicate feelings, such as anger, sadness, happiness, fear, disgust, pain, and surprise. Most have origins on skull bones and insertions on the dermis of the skin (table 7.3 and figure 7.14).

Table 7.3 Muscles of Facial Expression

Muscle	Origin	Insertion	Action
Buccinator (buk′-si-nā-tor)	Lateral surfaces of maxilla and mandible	Orbicularis oris	Compresses cheeks inward
Epicranius (ep-i-krā′-nē-us)	This muscle consists of two parts: the frontal belly and the occipital belly. They are joined by the epicranial aponeurosis, which covers the top of the skull.		
Frontal belly	Epicranial aponeurosis	Skin and muscles superior to the eyes	Elevates eyebrows and wrinkles forehead
Occipital belly	Base of occipital bone	Epicranial aponeurosis	Pulls scalp posteriorly
Orbicularis oculi (or-bik′-ū-lar-is ok′-ū-li)	Frontal bone and maxillae	Skin around eye	Closes eye
Orbicularis oris (or-bik′-ū-lar-is- o′-ris)	Muscles around mouth	Skin around lips	Closes and puckers lips; shapes lips during speech
Platysma (plah-tiz′-mah)	Fascia of superior chest	Mandible and muscles around mouth	Draws angle of mouth inferiorly
Zygomaticus (zī-gō-mat′-ik-us)	Zygomatic bone	Orbicularis oris at angle of the mouth	Elevates corners of mouth (smiling)

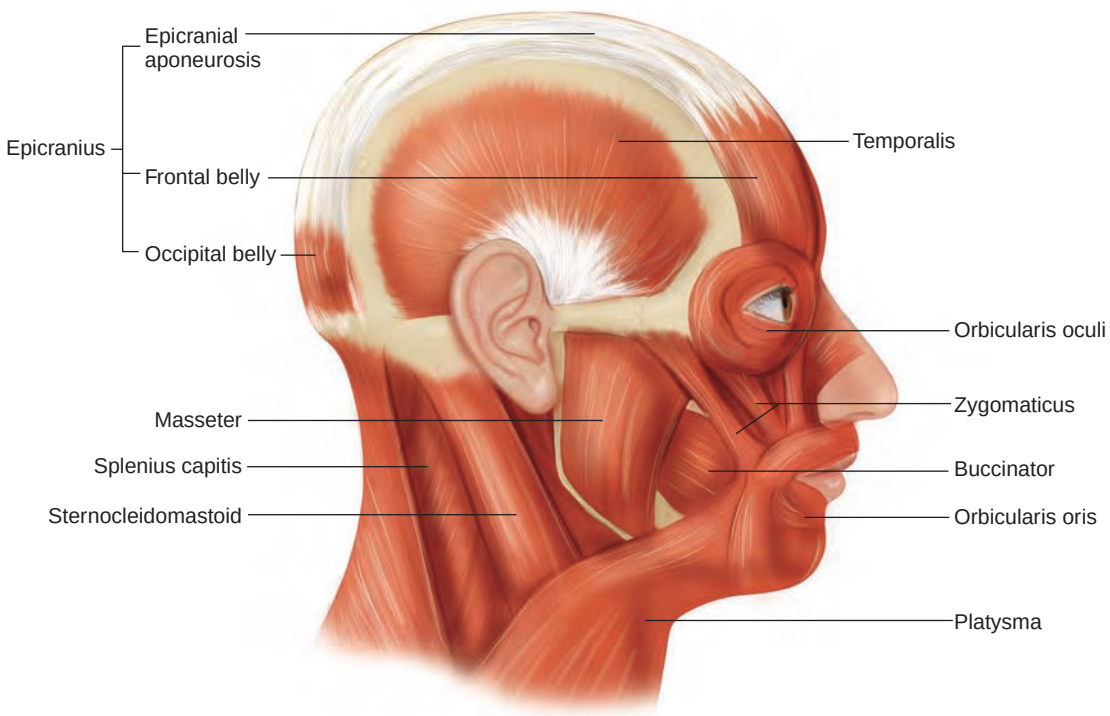


Figure 7.14 Muscles of facial expression and mastication.

The *epicranius* is an unusual muscle. It has a large *epicranial aponeurosis* that covers the top of the skull and two contractile portions: the *frontal belly* over the frontal bone and the *occipital belly* over the occipital bone.

Two major pairs of muscles elevate the mandible in the process of mastication (chewing): the *masseter* and the *temporalis* (table 7.4 and figure 7.14).

Muscles That Move the Head

Several pairs of neck muscles are responsible for flexing, extending, and rotating the head. Table 7.5 lists two of the major muscles that perform this function: the *sternocleidomastoid* and the *splenius capitis*. As noted in table 7.8, the *trapezius* can also extend the head, although this is not its major function (figures 7.14, 7.15, and 7.16).

Table 7.4 Muscles of Mastication

Muscle	Origin	Insertion	Action
Masseter (mas-se′-ter)	Zygomatic arch	Lateral surface of mandible	Elevates mandible
Temporalis (tem-po-ra′-lis)	Temporal bone	Coronoid process of mandible	Elevates mandible

Table 7.5 Muscles That Move the Head

Muscle	Origin	Insertion	Action
Sternocleidomastoid (ster-nō-klī-dō-mas′-toid)	Clavicle and sternum	Mastoid process of temporal bone	Contraction of both muscles flexes head toward chest; contraction of one muscle turns head away from contracting muscle
Splenius capitis (splē′-nē-us kap′-i-tis)	Inferior cervical and superior thoracic vertebrae	Mastoid process of temporal bone	Contraction of both muscles extends head; contraction of one muscle turns head toward same side as contracting muscle

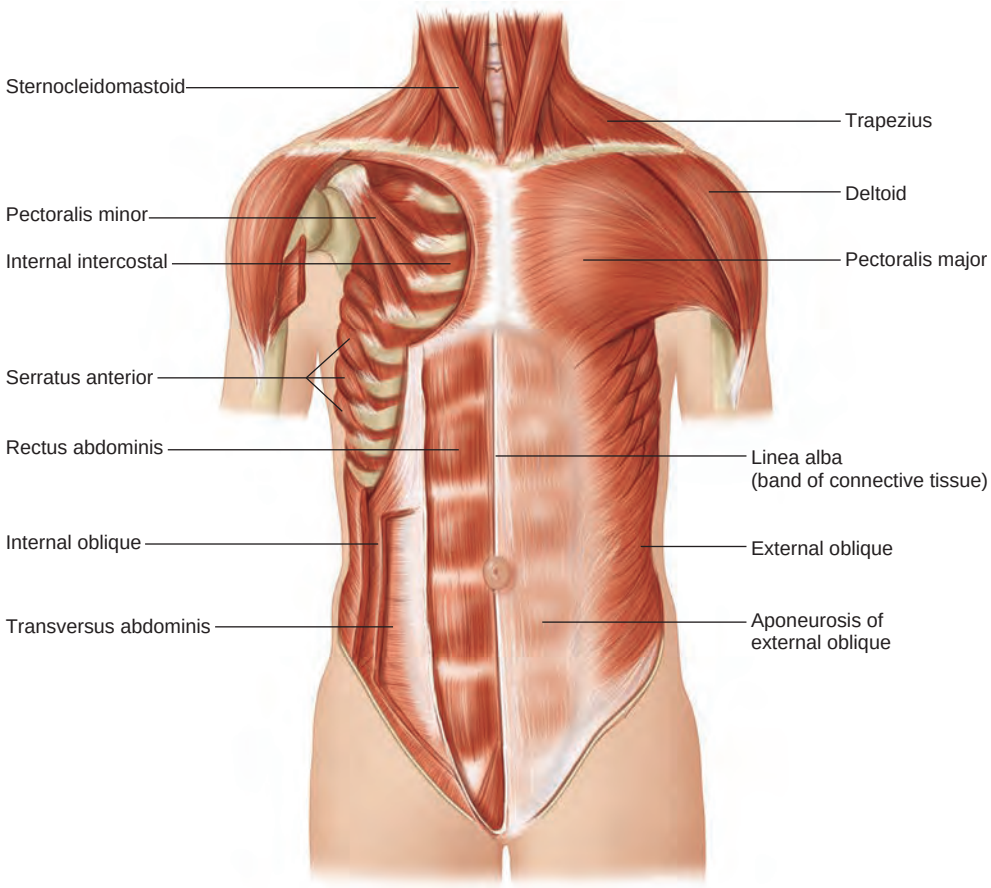


Figure 7.15 Muscles of the anterior chest and abdominal wall. The right pectoralis major is removed to show the deep muscles.

Muscle of the Abdominal Wall

The abdominal muscles are paired muscles that provide support for the anterior and lateral portions of the abdominal and pelvic regions, including support for the internal organs. The muscles are named for the direction of their muscle fibers: *rectus abdominis, external oblique, internal oblique,* and *transversus abdominis.* They are arranged in overlapping layers and are attached by larger

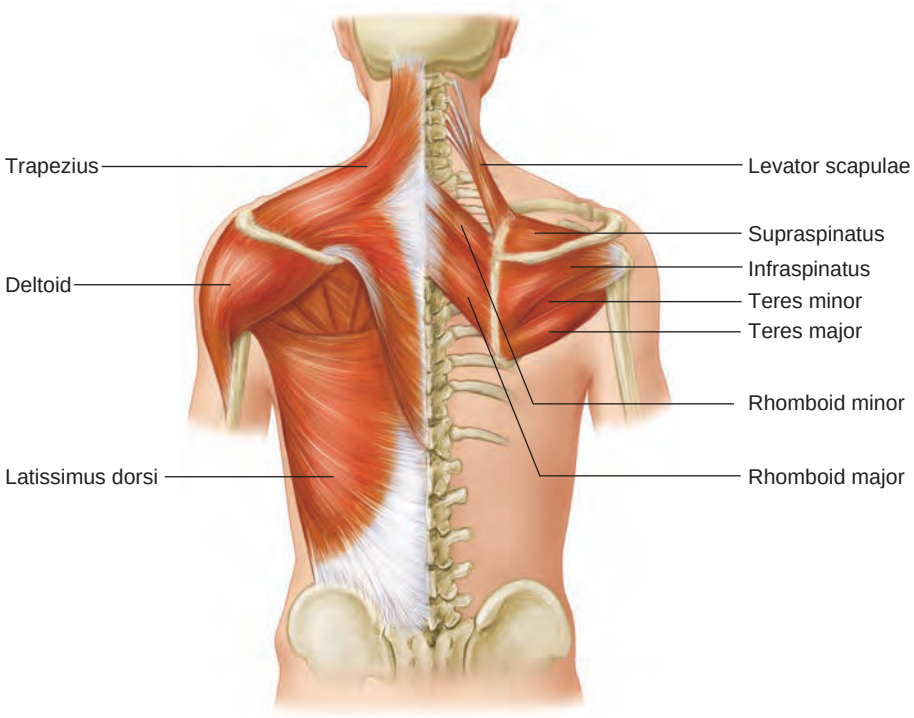


Figure 7.16 Muscles of the posterior shoulder. The right trapezius is removed to show deep muscles.

aponeuroses that merge at the anterior midline to form the *linea alba,* or white line (table 7.6 and figure 7.15).

Muscles of Breathing

Movement of the ribs occurs during breathing and is brought about by the contraction of two sets of muscles that are located between the ribs. The *external intercostals* elevate and protract the ribs during inspiration, and the *internal intercostals* depress and retract the ribs during expiration (table 7.7 and figure 7.15). The primary breathing muscle is the *diaphragm,* a thin sheet of muscle that separates the thoracic and abdominal cavities.

Muscles That Move the Pectoral Girdle

Pectoral girdle muscles originate on bones of the axial skeleton and insert on the scapula or clavicle. Because the scapula is supported mainly by muscles, it can be moved more freely than the clavicle. The *trapezius* is a superficial trapezoid-shaped muscle that covers much of the superior back. The *rhomboid major* and *minor* and the *levator scapulae* lie deep to the trapezius. Each *serratus anterior* is located on the lateral surface of the superior ribs near the axillary region. The *pectoralis minor* lies deep to the pectoralis major. It protracts and depresses the scapula (table 7.8 and figures 7.15 to 7.18).

Table 7.6 Muscles of the Abdominal Wall

Muscle	Origin	Insertion	Action
Rectus abdominis (rek′-tus ab-dom′-i-nis)	Pubic symphysis and pubis	Xiphoid process of sternum and costal cartilages of ribs 5 to 7	Tightens abdominal wall; flexes the vertebral column
External oblique (eks-ter′-nal o-blēk′)	Anterior surface of inferior eight ribs	Iliac crest and linea alba	Tightens abdominal wall; rotation and lateral flexion of the vertebral column
Internal oblique (in-ter′-nal o-blēk′)	Iliac crest and inguinal ligament	Cartilage of inferior four ribs, pubis, and linea alba	Same as above
Transversus abdominis (trans-ver′-sus ab-dom′-i-nis)	Iliac crest, cartilages of inferior six ribs, processes of lumbar vertebrae	Pubis and linea alba	Tightens abdominal wall

Table 7.7 Muscles of Breathing

Muscle	Origin	Insertion	Action
Diaphragm (dī-a-fram)	Lumbar vertebrae, costal cartilages of inferior ribs, xiphoid process	Central tendon located at midpoint of muscle	Forms floor of thoracic cavity; depresses during contraction, causing inspiration
External intercostals (eks-ter′-nal in-ter-kos′-tals)	Inferior border of rib above	Superior border of rib below	Elevates and protracts ribs during inspiration
Internal intercostals (in-ter′-nal in-ter-kos′-tals)	Superior border of rib below	Inferior border of rib above	Depresses and retracts ribs during expiration

Table 7.8 Muscles That Move the Pectoral Girdle

Muscle	Origin	Insertion	Action
Trapezius (trah-pē-zē′-us)	Occipital bone; cervical and thoracic vertebrae	Clavicle; spine and acromion of scapula	Elevates clavicle; adducts and elevates scapula; extends head
Rhomboid major and minor (rom-boid)	Superior thoracic vertebrae	Medial border of scapula	Adducts and elevates scapula
Levator scapulae (le-va′-tor skap′-ū-lē)	Cervical vertebrae	Superior medial margin of scapula	Elevates scapula
Serratus anterior (ser-ra′-tus)	Superior eight to nine ribs	Medial border of scapula	Depresses, protracts, and rotates scapula
Pectoralis minor (pek-to-rah′-lis)	Anterior surface of superior ribs	Coracoid process of scapula	Depresses and protracts scapula

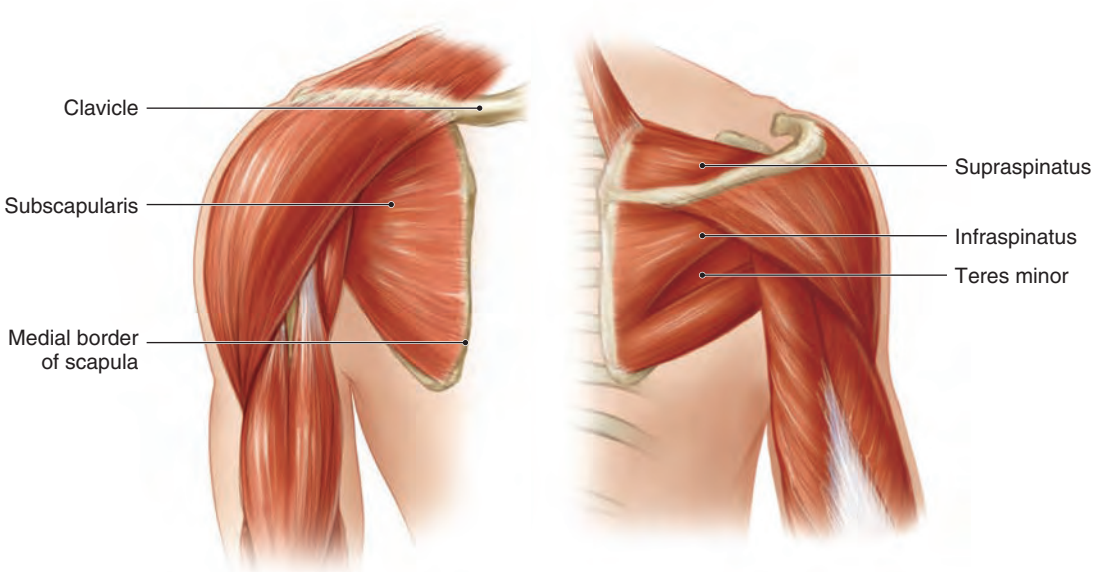


Figure 7.17 Muscles of the rotator cuff. *(a)* Anterior view showing subscapularis. *(b)* Posterior view showing supraspinatus, infraspinatus, and teres minor. *(c)* A gymnast on the rings must have a strong rotator cuff.

Muscles That Move the Arm and Forearm

Movement of the humerus is enabled by the muscles that originate on the pectoral girdle, ribs, or vertebrae and insert on the humerus. The arrangement of these muscles and the ball-and-socket joint between the humerus and scapula enable great freedom of movement for the arm. The *pectoralis major* is the large superficial muscle of the chest. The *deltoid* is the thick muscle that caps the

shoulder joint. The *supraspinatus, infraspinatus,* and *teres minor* cover the posterior surface of the scapula. The anterior surface of each scapula is covered by the *subscapularis.* These four muscles and their tendons surround the head of the humerus at the shoulder joint, making up the **rotator cuff** (figure 7.17). The muscles and tendons of the rotator cuff are the only structures stabilizing the shoulder joint; thus the joint is fairly unstable compared to other joints. However, this relative lack of stability is what allows the shoulder's mobility. The *latissimus dorsi* is a broad, sheetlike muscle that covers the inferior back. The *teres major* assists the latissimus dorsi and is located just superior to it. (table 7.9 and figures 7.15 to 7.17).

Muscles moving the forearm originate on either the humerus or the scapula and insert on either the radius or the ulna. Three flexors occur on the anterior surface of the arm: the *biceps brachii, brachialis,* and *brachioradialis.* One extensor, the *triceps brachii,* is located on the posterior surface of the arm (table 7.10 and figures 7.15, 7.18, and 7.19).

Check My Understanding

9. What are the names and locations of the two parts of the epicranius muscle?
10. What muscles are involved in chewing your food?
11. What muscles turn your head to the side?
12. What muscle separates the abdominal and thoracic cavities?
13. What are the names of the abdominal muscles from deep to superficial?
14. What three muscles elevate the scapula?

Table 7.9 Muscles That Move the Arm

Muscle	Origin	Insertion	Action
Pectoralis major (pek-tō-rah′-lis)	Clavicle, sternum, and cartilages of superior ribs	Greater tubercle of humerus	Adducts, flexes, and medially rotates arm
Deltoid (del′-toid)	Clavicle and spine, and acromion of scapula	Deltoid tuberosity of humerus	Abducts, flexes, and extends arm
Latissimus dorsi (lah-tis′-i-mus dor′sī)	Inferior thoracic and lumbar vertebrae; sacrum; inferior ribs; iliac crest	Intertubercular sulcus of humerus	Adducts, extends, and medially rotates arm
Teres major (te′r-ez)	Inferior angle of scapula	Distal to lesser tubercle of humerus	Same as above
Rotator cuff muscles	These four muscles stabilize the shoulder joint		
Supraspinatus (su-prah-spī′-na-tus)	Superior to spine of scapula	Greater tubercle of humerus	Abducts arm
Infraspinatus (in-frah-spī′-na-tus)	Inferior to spine of scapula	Greater tubercle of humerus	Laterally rotates arm
Teres minor	Lateral border of scapula	Greater tubercle of humerus	Laterally rotates arm
Subscapularis (sŭ-skap-ŭ-lār′ris)	Anterior surface of scapula	Lesser tubercle of humerus	Medially rotates arm

Table 7.10 Muscles That Move the Forearm

Muscle	Origin	Insertion	Action
Biceps brachii (bī′-seps brā′-kē-ī)	Coracoid process and tubercle superior to glenoid cavity of scapula	Radial tuberosity of radius	Flexes forearm and supination, also flexes arm
Brachialis (brā′-kē-al-is)	Distal, anterior surface of humerus	Coronoid process of ulna	Flexes forearm
Brachioradialis (brā-kē-ō-rā-dē-a′-lis)	Lateral surface of distal end of humerus	Lateral surface of radius superior to styloid process	Flexes forearm
Triceps brachii (trī′-seps brā′-kē-ī)	Lateral and medial surfaces of humerus and tubercle inferior to glenoid cavity of scapula	Olecranon of ulna	Extends forearm, also extends arm

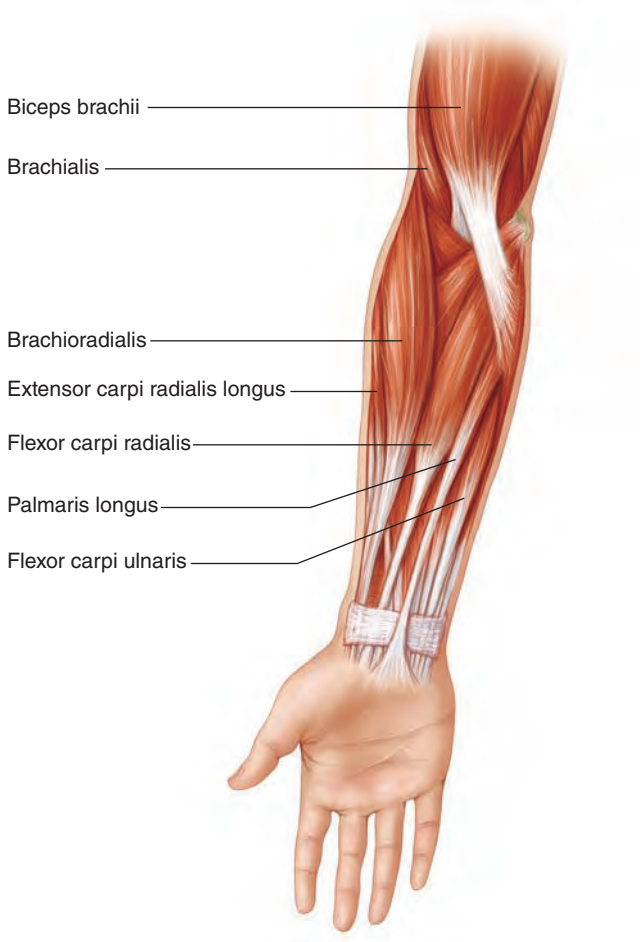


Figure 7.18 Muscles of the anterior forearm.

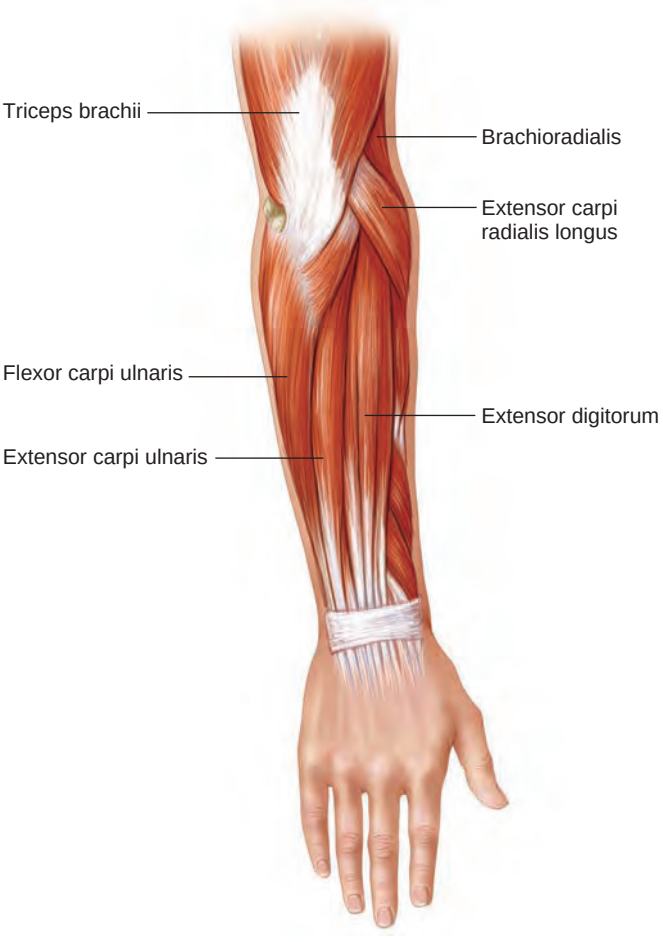


Figure 7.19 Muscles of the posterior forearm.

Muscles That Move the Wrist and Fingers

Many muscles that produce the various movements of the wrist and fingers are located in the forearm. Only a few of the larger superficial muscles are considered here. They originate from the distal end of the humerus and insert on carpal bones, metacarpals, or phalanges. Flexors on the anterior surface include the *flexor carpi radialis, flexor carpi ulnaris,* and *palmaris longus.* Extensors on the posterior surface include the *extensor carpi radialis longus, extensor carpi ulnaris,* and *extensor digitorum* (table 7.11; and figures 7.18 and 7.19). Note that the tendons of these muscles are held in position by a circular ligament at the wrist.

Check My Understanding

15. What muscle abducts and extends your arm?
16. What muscle extends your forearm?
17. What muscle extends your fingers?

Muscles That Move the Thigh and Leg

Muscles moving the thigh span the hip joint. They insert on the femur, and most originate on the pelvic girdle. The *iliacus* and *psoas major* are located anteriorly, the *gluteus maximus* is located posteriorly and forms the buttocks, the *gluteus medius* is located deep to the gluteus maximus posteriorly and extends laterally, and the *tensor fasciae latae* is located laterally. The *adductor longus* and *adductor magnus* are both located medially (table 7.12 and figures 7.20, 7.21, and 7.22).

The leg is moved by muscles located in the thigh. They span the knee joint and originate on the pelvic girdle or femur and insert on the tibia or fibula. The **quadriceps femoris** is composed of four muscles that have a common tendon that inserts on the patella. However, this tendon continues as the patellar ligament, which attaches to the tibial tuberosity–the functional insertion for these muscles. The *biceps femoris, semitendinosus,* and *semimembranosus* on the posterior surface of the thigh are often collectively called the **hamstrings.** The medially

Table 7.11 Muscles That Move the Wrist and Fingers

Muscle	Origin	Insertion	Action
Flexor carpi radialis (flek′-sor kar′-pī rā-dē-a′-lis)	Medial epicondyle of humerus	Metacarpals II and III	Flexes and abducts wrist
Flexor carpi ulnaris (flek′-sor kar′-pī ul-na′-ris)	Medial epicondyle of humerus and olecranon of ulna	Carpal bones and metacarpal V	Flexes and adducts wrist
Palmaris longus (pal-ma′-ris long′-gus)	Medial epicondyle of humerus	Fascia of palm	Flexes wrist
Extensor carpi radialis longus (eks-ten′-sor kar′-pī rā-dē-a′-lis long′-gus)	Lateral epicondyle of humerus	Metacarpal II	Extends and abducts wrist
Extensor carpi ulnaris (eks-ten′-sor kar′-pī ul-na′-ris)	Lateral epicondyle of humerus	Metacarpal V	Extends and adducts wrist
Extensor digitorum (eks-ten′-sor dij-i-to′-rum)	Lateral epicondyle of humerus	Posterior surfaces of phalanges II–V	Extends fingers

Table 7.12 Muscles That Move the Thigh

Muscle	Origin	Insertion	Action
Iliacus (il′-ē-ak-us)	Fossa of ilium	Lesser trochanter of femur	Flexes thigh
Psoas major (so′-as)	Lumbar vertebrae	Lesser trochanter of femur	Flexes thigh
Gluteus maximus (glū′-tē-us mak′-si-mus)	Posterior surfaces of ilium, sacrum, and coccyx	Posterior surface of femur and iliotibial tract	Extends and laterally rotates thigh
Gluteus medius (glū′-tē-us mē′-dē-us)	Lateral surface of ilium	Greater trochanter of femur	Abducts and medially rotates thigh
Tensor fasciae latae (ten′-sor fash′-ē-ē lah-tē′)	Anterior iliac crest	Iliotibial tract	Flexes and abducts thigh
Adductor longus (ad-duk′-tor long′-gus)	Pubis near pubic symphysis	Posterior surface of femur	Adducts, flexes, and laterally rotates thigh
Adductor magnus (ad-duk′-tor mag′-nus)	Inferior portion of ischium and pubis	Same as above	Same as above

Clinical Insight

Intramuscular injections are commonly used when quick absorption is desired. Such injections are given in three sites: (1) the lateral surface of the deltoid; (2) the gluteus medius in the superior, lateral portion of the buttock; and (3) the vastus lateralis near the midpoint of the lateral surface of the thigh. These injection sites are chosen because there are no major nerves or blood vessels present that could be damaged, and the muscles have a good blood supply to aid absorption. The site chosen may vary with the age and condition of the patient.

located *gracilis* has two insertions that give it dual actions. The long, straplike *sartorius* extends diagonally across the anterior surface of the thigh and spans both the hip and knee joints. Its contraction enables the legs to cross (tables 7.12, and 7.13 and figures 7.20, 7.21, and 7.22).

Muscles That Move the Foot and Toes

Many muscles are involved in the movement of the foot and toes. They are located in the leg and originate on the femur, tibia, or fibula and insert on the tarsal bones, metatarsals, or phalanges. The posterior leg muscles include the *gastrocnemius* and *soleus*, which insert through a common tendon, the calcaneal (Achilles) tendon, which attaches to the calcaneus. The *tibialis*

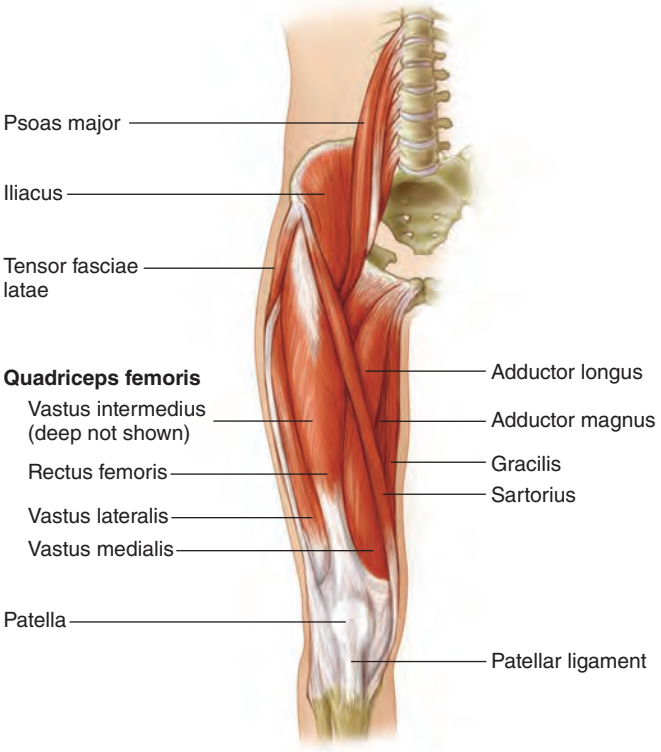


Figure 7.20 Muscles of the anterior right thigh. (Note that the vastus intermedius is deep to the rectus femoris and is not visible in this view.)

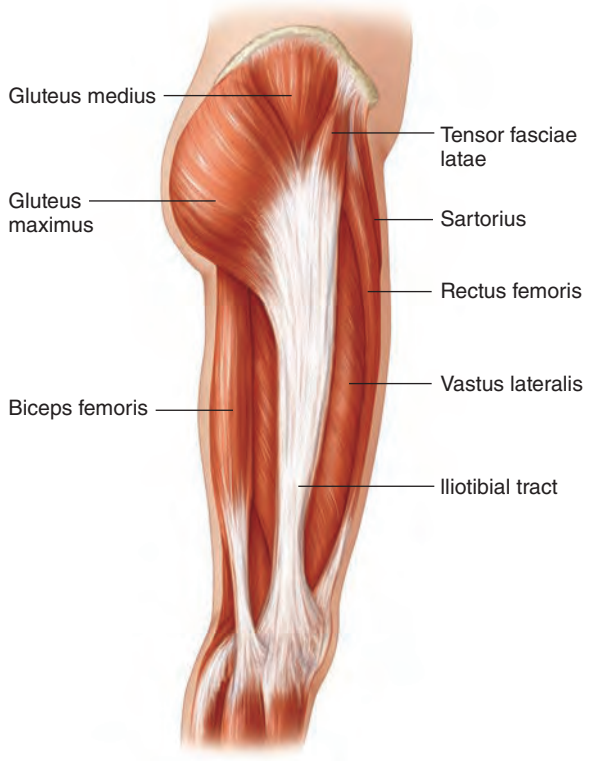


Figure 7.21 Muscles of the lateral right thigh.

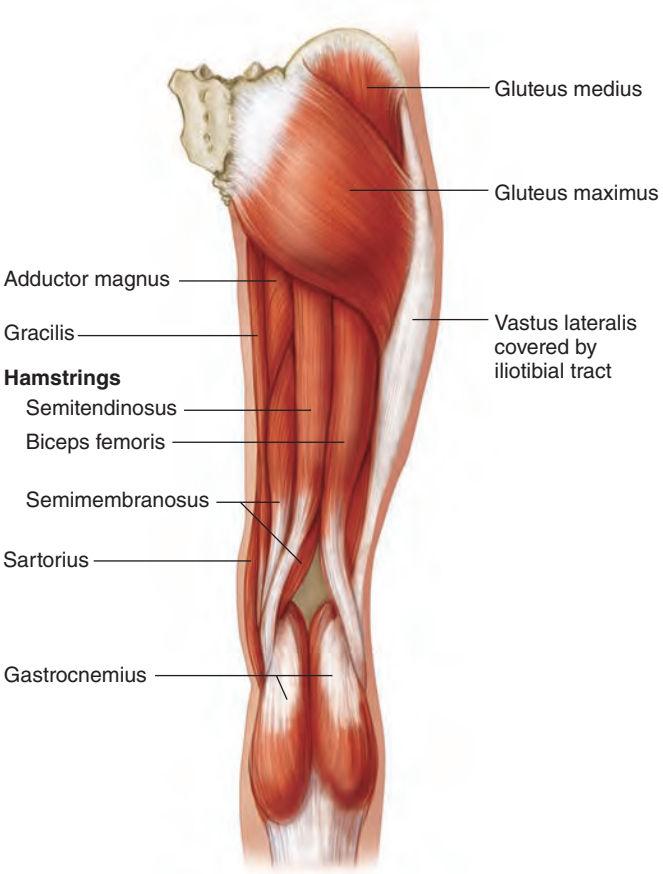


Figure 7.22 Muscles of the posterior right thigh.

anterior is anteriorly located, and the *extensor digitorum longus* lies lateral to it. Note that although the extensor digitorum extends the toes, as its name implies, it also dorsiflexes the foot. The *fibularis longus* is located on the lateral surface of the leg (table 7.14 and figures 7.23 to 7.25).

Note how the tendons are held in position by the bands of ligaments at the ankle.

Clinical Insight

Repeated stress from athletic activities may cause inflammation of a tendon, a condition known as *tendonitis*. Tendons associated with the shoulder, elbow, hip, and knee joints are most commonly affected.

Check My Understanding

18. Name the muscles that flex the thigh.
19. What are the four parts of the quadriceps femoris?
20. What is the action of muscles inserting on the calcaneus?

Table 7.13 Muscles That Move the Leg

Muscle	Origin	Insertion	Action
Quadriceps femoris (quad′-ri-seps fem′-or-is)	Four muscles of the anterior thigh that extend the leg.		
Rectus femoris (rek′-tus fem′-or-is)	Anterior inferior iliac spine and superior margin of acetabulum	Patella; tendon continues as patellar ligament, which attaches to tibial tuberosity	Extends leg and flexes thigh
Vastus lateralis (vas′-tus lat-er-a′lis)	Greater trochanter and posterior surface of femur	Same as above	Extends leg
Vastus medialis (vas′-tus me-de-a′lis)	Medial and posterior surfaces of femur	Same as above	Extends leg
Vastus intermedius (vas′-tus in-ter-mē′dē-us)	Anterior and lateral surfaces of femur	Same as above	Extends leg
Hamstrings	Three distinct muscles of the posterior thigh that flex leg and extend thigh.		
Biceps femoris (bi′-seps fem′-or-is)	Ischial tuberosity and posterior surface of femur	Head of fibula and lateral condyle of tibia	Flexes and laterally rotates leg; extends thigh
Semitendinosus (sem-ē-ten-di-nō′-sus)	Ischial tuberosity	Medial surface of tibia	Flexes and medially rotates leg; extends thigh
Semimembranosus (sem-ē-mem-brah-nō′-sus)	Ischial tuberosity	Medial condyle of tibia	Flexes and medially rotates leg; extends thigh
Gracilis (gras′-il-is)	Pubis near pubic symphysis	Medial surface of tibia	Adducts thigh; flexes leg and locks knee
Sartorius (sar-to′r-ē-us)	Anterior superior iliac spine	Medial surface of tibia	Flexes thigh and leg; abducts and laterally rotates thigh

Table 7.14 Muscles That Move the Foot and Toes

Muscle	Origin	Insertion	Action
Gastrocnemius (gas-trōk-nē′m-ē-us)	Medial and lateral condyles of femur	Calcaneus by the calcaneal tendon	Plantar flexes foot and flexes leg
Soleus (sō′l-ē-us)	Posterior surface of tibia and fibula	Calcaneus by the calcaneal tendon	Plantar flexes foot
Fibularis longus (fib-yu-lar-ris long′-gus)	Lateral condyle of tibia and head and body of fibula	Metatarsal I and tarsal bones	Plantar flexes and everts foot; supports arch
Tibialis anterior (tib-ē-a′l-is an-te′rē-or)	Lateral condyle and surface of tibia	Metatarsal I and tarsal bones	Dorsiflexes and inverts foot
Extensor digitorum longus (eks-ten′-sor dig-i-tor′-um long′-gus)	Lateral condyle of tibia and anterior surface of fibula	Phalanges of toes II-V	Dorsiflexes and everts foot; extends toes

7.6 Disorders of the Muscular System

Learning Objective

15. Describe the major disorders of the muscular system.

Some disorders of the muscle system may result from factors associated only with muscles, while others are caused by disorders of the nervous system. Certain neurological disorders are included here because of their obvious effect on muscle action.

Muscular Disorders

Cramps involve involuntary, painful tetany. The precise cause is unknown, but a cramp seems to result from chemical changes in the muscle, such as ionic imbalances or ATP deficiencies. Sometimes a severe blow to a muscle can produce a cramp.

Fibrosis (fī-brō′-sis) is an abnormal increase of connective tissue in a muscle. Usually, it results from connective tissue replacing dead muscle fibers following an injury.

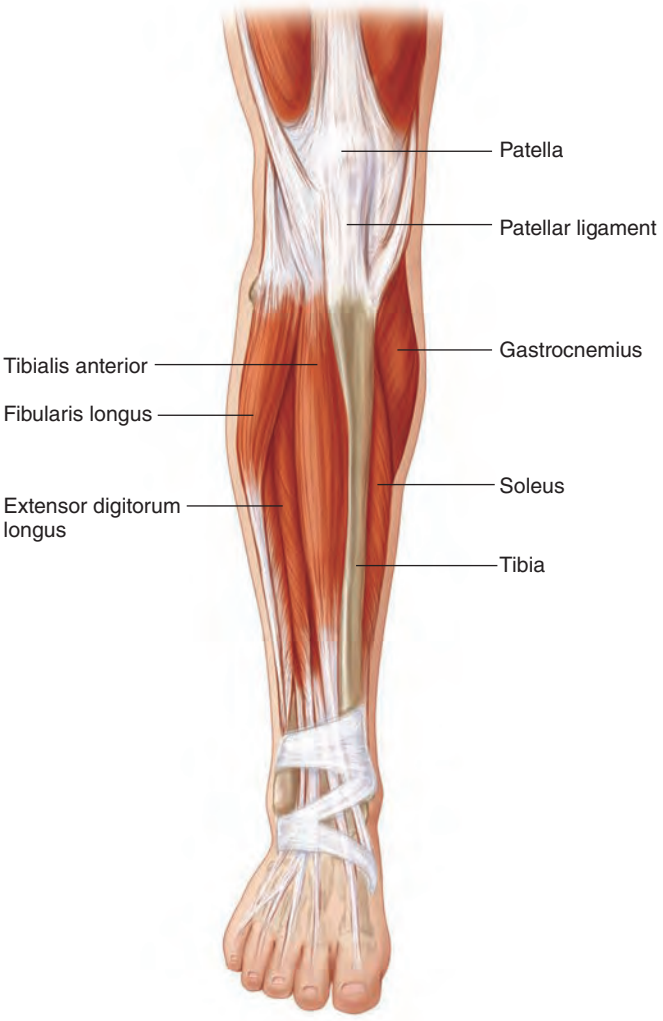


Figure 7.23 Muscles of the anterior right leg.

Fibromyalgia (fī-brō-mi-alj-a) is a painful condition of the muscles and joints with no known cause. Once thought to be a mental disorder, this is actually a musculoskeletal disorder that often leads to depression due to the helpless nature of the chronic symptoms.

Muscular dystrophy (dis′-trō-fē) is a general term for a number of inherited muscular disorders that are characterized by the progressive degeneration of muscles. The affected muscles gradually weaken and atrophy, producing a progressive crippling of the patient. There is no specific drug cure, but patients are encouraged to keep active and are given muscle-strengthening exercises.

Strains, or "pulled muscles," result when a muscle is stretched excessively. This usually occurs when an antagonist has not relaxed quickly enough as an agonist contracts. The hamstrings are a common site of muscle strains. In mild strains, only a few muscle fibers are damaged. In severe strains, both connective and muscle tissues are torn, and muscle function may be severely impaired.

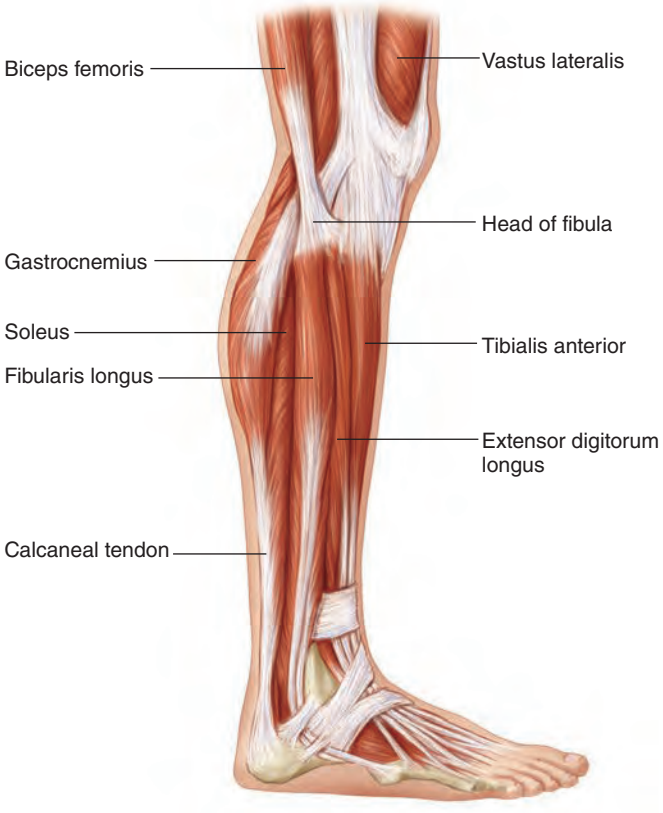


Figure 7.24 Lateral view of muscles of the right leg.

Neurological Disorders Affecting Muscles

Botulism (boch′-ū-lizm) poisoning is caused by a neurotoxin produced by the bacterium *Clostridium botulinum.* The toxin prevents release of ACh from the terminal boutons of somatic motor axons. Without prompt treatment with an antitoxin, death may result from paralysis of breathing muscles. Poisoning results from eating improperly canned vegetables or meats that contain *C. botulinum* and the accumulated toxins.

Myasthenia gravis (mī-as-thē′-nē-ah grav′-i-is) is characterized by extreme muscular weakness caused by improper functioning of the neuromuscular junctions. It is an autoimmune disease in which antibodies are produced that attach to the ACh receptors on the motor end plate and reduce or block the stimulatory effect of ACh. Myasthenia gravis occurs most frequently in women between 20 and 40 years of age. Usually, it first affects ocular muscles and other muscles of the face and neck, which may lead to difficulty in chewing, swallowing, and talking. Other muscles of the body may be involved later. Treatment typically involves the use of acetylcholinesterase inhibitors and immunosuppressive drugs, such as the steroid prednisone.

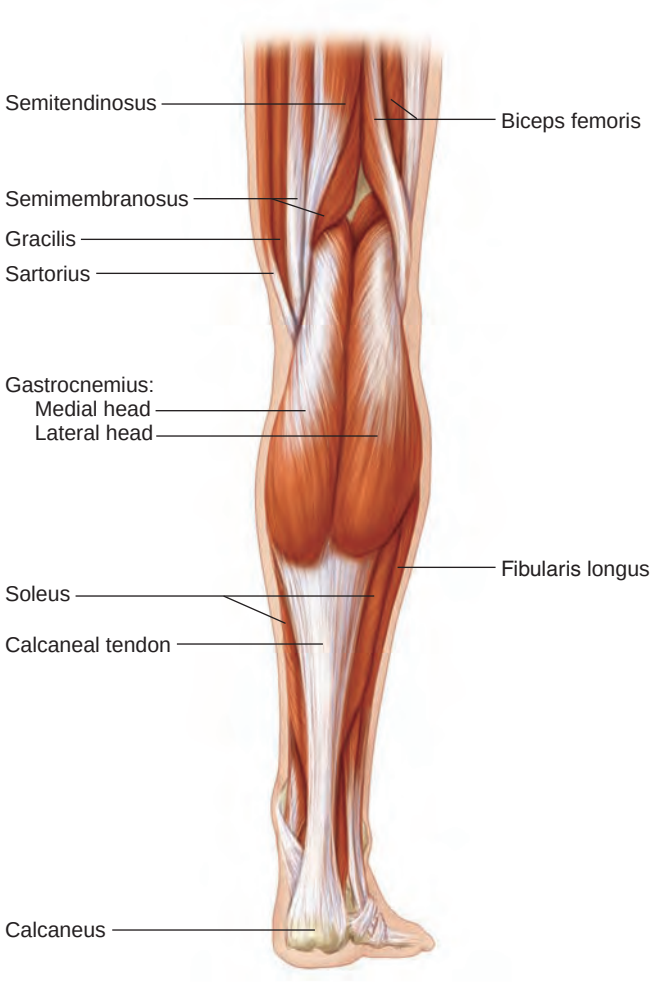


Figure 7.25 Muscles of the posterior right leg.

Poliomyelitis (pō-lē-ō-mī-e-lī´-tis) is a viral disease of somatic motor neurons in the spinal cord. Destruction of the somatic motor neurons leads to paralysis of skeletal muscles. It is now rare in industrialized countries due to the availability of a polio vaccine. Virtually all children in the United States receive this vaccine, which protects them from polio.

Spasms are sudden, involuntary contractions of a muscle or a group of muscles. They may vary from simple twitches to severe convulsions and may be accompanied by pain. Spasms may be caused by irritation of the motor neurons supplying the muscle, emotional stress, or neurological disorders. Spasms of smooth muscle in the walls of the digestive and respiratory tracts, or certain blood vessels can be hazardous. Hiccupping is a spasm of the diaphragm.

Tetanus (tet′-ah-nus) is a disease caused by the anaerobic bacterium *Clostridium tetani*, which is common in soil. Infection usually results from puncture wounds. *C. tetani* produces a neurotoxin that affects somatic motor neurons in the spinal cord, resulting in continuous stimulation and tetany of certain muscles. Because the first muscles affected are those that move the mandible, this disease is often called "lockjaw." Without prompt treatment, mortality is high. Young children usually receive vaccinations of tetanus toxoid to stimulate production of antibodies against the neurotoxin. Booster injections are given at regular intervals to keep the concentration of antibodies at a high level in order to prevent the disease.

Chapter Summary

- The three types of muscle tissue in the body are skeletal, smooth, and cardiac.
- Each type of muscle tissue has unique structural and functional characteristics.

7.1 Structure of Skeletal Muscle

- Each skeletal muscle is formed of many muscle fibers that are arranged in fascicles.
- Connective tissue envelops each muscle fiber, each fascicle, and the entire muscle.
- Muscles are attached to bones or other tissues by either tendons or aponeuroses.
- The sarcolemma is the plasma membrane of a muscle fiber, and the sarcoplasm (cytoplasm) contains the myofibrils, the contractile elements.
- Myofibrils consist of thick and thin myofilaments. The arrangement of the myofilaments produces the striations that are characteristic of muscle fibers.
- Each myofibril consists of many sarcomeres joined end-to-end. A sarcomere is bounded by a Z line at each end.
- I bands are light areas in a muscle tissue micrograph, and A bands are dark areas.
- The H band is the center of a sarcomere and contains only thick myofilaments.
- The terminal bouton of a somatic motor neuron is adjacent to each muscle fiber at the neuromuscular junction. The terminal bouton fits into depressions in the sarcolemma, called motor end plates. The synaptic cleft is the small space between the terminal bouton and motor end plate. The neurotransmitter ACh is contained in tiny vesicles in the terminal bouton.
- Each muscle fiber is innervated and controlled by a somatic motor neuron.
- A motor unit consists of a somatic motor neuron and all muscle fibers it innervates.

7.2 Physiology of Skeletal Muscle Contraction

- An activated terminal bouton releases ACh into the synaptic cleft. ACh attaches to ACh receptors of the motor end

plate, which leads to the release of Ca^{2+} within the sarcoplasm. This, in turn, leads to the formation of cross-bridges between the heads of myosin molecules and the myosin binding sites on actin molecules. A series of ratchetlike movements pulls the thin myofilaments toward the center of the sarcomere, producing contraction.
- Acetylcholinesterase quickly breaks down ACh to prevent continued stimulation and to prepare the muscle fiber for the next stimulus.
- Energy for contraction comes from high-energy phosphate bonds in ATP.
- After cellular respiration has formed a muscle fiber's normal supply of ATP, excess energy is transferred to creatine to form creatine phosphate, which serves as a reserve supply of energy.
- Small amounts of oxygen are stored in combination with myoglobin, which gives muscle fibers a reserve of oxygen for aerobic respiration.
- Vigorous muscular activity quickly exhausts available oxygen, leading to the accumulation of lactic acid and causing excess post-exercise oxygen consumption. Heavy breathing after exercise provides the oxygen required to metabolize lactic acid and restore the pre-exercise state within the muscle fiber.
- Fatigue most likely results primarily from the lack of raw fuel in a muscle fiber.
- Large amounts of heat are produced by the chemical and physical processes of muscle contraction.
- When stimulated by a threshold stimulus, individual muscle fibers exhibit an all-or-none contraction response.
- A simple contraction consists of a latent phase, contraction phase, and relaxation phase.
- Whole muscles provide graded contraction responses, which are enabled by the number of motor units that are recruited.
- A sustained contraction of all motor units is tetany.
- Muscle tone is a state of partial contraction that results from alternating contractions of a few motor units.

7.3 Actions of Skeletal Muscles

- The origin is the immovable attachment, and the insertion is the movable attachment.
- Muscles are arranged in groups with opposing actions: agonists and antagonists.

7.4 Naming of Muscles

- Several criteria are used in naming muscles.
- These criteria include function, shape, relative position, location, site of attachment, origin and insertion, size, and orientation of fibers.

7.5 Major Skeletal Muscles

- Muscles of facial expression originate on skull bones and insert on the dermis of the skin. They include the epicranius, orbicularis oculi, orbicularis oris, buccinator, zygomaticus, and platysma.
- Muscles of mastication originate on fixed skull bones and insert on the mandible. They include the masseter and the temporalis.
- Muscles that move the head occur in the neck and superior back. They include the sternocleidomastoid and splenius capitis.
- Muscles of the abdominal wall connect the pelvic girdle, thoracic cage, and vertebral column. They include the rectus abdominis, external oblique, internal oblique, and transversus abdominis.
- The diaphragm is the major muscle of breathing.
- External intercostals and internal intercostals move the ribs, helping breathing.
- Muscles that move the pectoral girdle originate on the thoracic cage or vertebrae and insert on the pectoral girdle. They include the trapezius, rhomboid major and minor, levator scapulae, pectoralis minor, and serratus anterior.
- Muscles that move the arm originate on the thoracic cage, vertebrae, or pectoral girdle and insert on the humerus. They include the pectoralis major, deltoid, subscapularis, supraspinatus, infraspinatus, latissimus dorsi, teres major, and teres minor.
- Supraspinatus, infraspinatus, teres minor, and subscapularis make up the rotator cuff.
- Muscles that move the forearm originate on the scapula or humerus and insert on the radius or ulna. They include the biceps brachii, brachialis, brachioradialis, and triceps brachii.
- Muscles that move the wrist and fingers are the muscles of the forearm. They include the flexor carpi radialis, flexor carpi ulnaris, palmaris longus, extensor carpi radialis longus, extensor carpi ulnaris, and extensor digitorum.
- Muscles that move the thigh originate on the pelvic girdle and insert on the femur. They include the iliacus, psoas major, gluteus maximus, gluteus medius, tensor fasciae latae, adductor longus, and adductor magnus.
- Muscles that move the leg originate on the pelvic girdle or femur and insert on the tibia or fibula. They include the quadriceps femoris, biceps femoris, semitendinosus, semimembranosus, gracilis, and sartorius.
- Muscles that move the foot and toes are the muscles of the leg. They include the gastrocnemius, soleus, fibularis longus, tibialis anterior, and extensor digitorum longus.

7.6 Disorders of the Muscular System

- Disorders of muscles include cramps, fibrosis, fibromyalgia, muscular dystrophy, and strains.
- Neurological disorders that directly affect muscle action include botulism, myasthenia gravis, poliomyelitis, spasms, and tetanus.

Self-Review

Answers are located in appendix B.

1. A skeletal muscle consists of many _____, which are arranged in fascicles.
2. Muscles are attached to bones by _____.
3. A contractile unit of a myofibril is a _____.
4. A muscle contraction is triggered by _____ binding to its receptors on the motor end plate.
5. Contraction occurs when thick myofilaments pull _____ myofilaments toward the center of a sarcomere.
6. The movable attachment of a muscle is its _____.
7. The mandible is elevated by the contraction of the temporalis and the _____.
8. The abdominal muscle extending from the sternum to the pubis is the _____.
9. The broad muscle of the inferior back is the _____.
10. The shoulder muscle that abducts the arm is the _____.
11. The arm muscle that extends the forearm is the _____.
12. The large muscle that extends and laterally rotates the thigh is the _____.
13. The four-part thigh muscle that extends the leg is the _____.
14. The large superficial calf muscle that plantar flexes the foot is the _____.

Critical Thinking

1. Using what you have learned in chapters 6 and 7, predict what would happen if calcium ions were not sequestered in the sarcoplasmic reticulum and were allowed to mingle with the high levels of Pi in the sarcoplasm.
2. Predict the clinical symptoms of a person with damage to the nerve that supplies the triceps brachii. How would the agonist–antagonist relationship be disturbed?
3. Can the origin and insertion of some muscles be interchanged? Explain.
4. As a cosmetic procedure, Botox is injected in very small doses into specific facial muscles to reduce wrinkles. It is derived from a neurotoxin that prevents the release of ACh at the neuromuscular junction. Explain how Botox works.

6
CHAPTER

Nervous System

Have you ever wondered why you can handle multiple tasks at once? The answer is simple. You have a nervous system designed for rapid multitasking. Think about Bridgette and her typical commute to work. Bridgette is driving to work during the morning rush hour on Interstate 75 with her coworker Adam. The two are chatting about an important meeting later in the day that will outline the next quarter's objectives, while Bridgette continuously tracks the cars in all three lanes and adjusts her speed to match the flow of traffic. She subconsciously coordinates her use of turn signals, mirrors, and steering wheel to change lanes, while listening carefully to Adam's thoughts on an interoffice memo from the day before. Feeling a little bit tired, she begins to take a swig of her coffee but notices quite quickly that it is still too hot to drink. A few minutes later as Bridgette exits the highway, the two laugh hysterically and begin to sing when an old song comes on the radio. Clearly, the speed at which Bridgette's brain processes information and coordinates her body allows her morning commute to be productive, safe, and enjoyable.

CHAPTER OUTLINE

SELECTED KEY TERMS

Autonomic nervous system (auto = self; nom = distribute) The portion of the nervous system that is involved in subconscious activities.
Axon (ax = axis, central) A neuronal process that carries nerve impulses away from the cell body.
Central nervous system The portion of the nervous system composed of the brain and spinal cord.
Dendrite (dendr = tree) A neuronal process that carries impulses toward the cell body or axon.
Ganglion (gangli = a swelling) A group of cell bodies located external to the CNS.
Myelin sheath (myel = marrow) An insulating layer formed by neuroglia that surrounds an axon.
Nerve A bundle of axons in the peripheral nervous system.
Nerve impulse An electrochemical signal created by and conducted along the axon of a neuron.
Neuroglia Supportive and protective cells within the nervous system.
Neuron A cell capable of producing and transmitting a nerve impulse.
Peripheral nervous system (peri = around) Portion of the nervous system composed of cranial and spinal nerves, ganglia, and sensory receptors.
Postsynaptic Pertaining to the cell that is activated by a signal at a synapse.
Presynaptic Pertaining to the neuron that releases a signal at a synapse.
Reflex An involuntary, rapid, and predictable response to a stimulus.
Somatic nervous system The portion of the nervous system that is involved in conscious activities.
Synapse (syn = together) The junction between an axon and another neuron or effector cell.

THE NERVOUS SYSTEM is the primary coordinating and controlling system of the body. Most of the activities of the nervous system occur below the level of consciousness and serve to maintain homeostasis. To maintain homeostasis, the nervous system requires almost instantaneous communication with the body. To achieve communication at this rate of speed, the nervous system uses **nerve impulses** that flow rapidly over and among neurons and between neurons and other body cells.

The general functions of the nervous system can be summarized as:

1. Detection of internal and external changes
2. Analysis of the detected changes
3. Organization of the information for immediate and future use
4. Initiation of the appropriate actions in response to the changes

8.1 Divisions of the Nervous System

Learning Objective

1. Identify the anatomical and functional divisions of the nervous system and their components.

Although the nervous system functions as a coordinated whole, it is divided into anatomical and functional divisions as an aid in understanding this complex organ system.

Anatomical Divisions

The nervous system has two major anatomical divisions. The **central nervous system (CNS)** consists of the brain and spinal cord. The CNS is the body's neural integration center. It receives incoming information (nerve impulses), analyzes and organizes it, and initiates appropriate action. The **peripheral nervous system (PNS)** is located external to the CNS and consists of cranial and spinal nerves, ganglia, and sensory receptors. The PNS carries nerve impulses formed by **sensory receptors,** such as pain and sound receptors, to the CNS. It also carries nerve impulses from the CNS to **effectors,** which are the muscles, glands, and adipose tissue.

Functional Divisions

Similarly, the nervous system is divided into two major functional divisions. The **sensory division** carries nerve impulses from sensory receptors to the CNS. Somatic sensory information is collected by sensory receptors within the skin, skeletal muscles, bones, and joints. Visceral sensory information is collected by sensory receptors in the viscera in the ventral cavity, in the walls of blood vessels, and within the CNS. The **motor division** carries nerve impulses from the CNS to effectors, which perform an action. The motor division is further divided into two subdivisions. The **somatic nervous system (SNS)** is involved in the *voluntary* (conscious) control of skeletal muscles. The **autonomic nervous system (ANS)** provides *involuntary* (subconscious) control of cardiac muscle, smooth muscle, adipose tissue, and glands (figure 8.1).

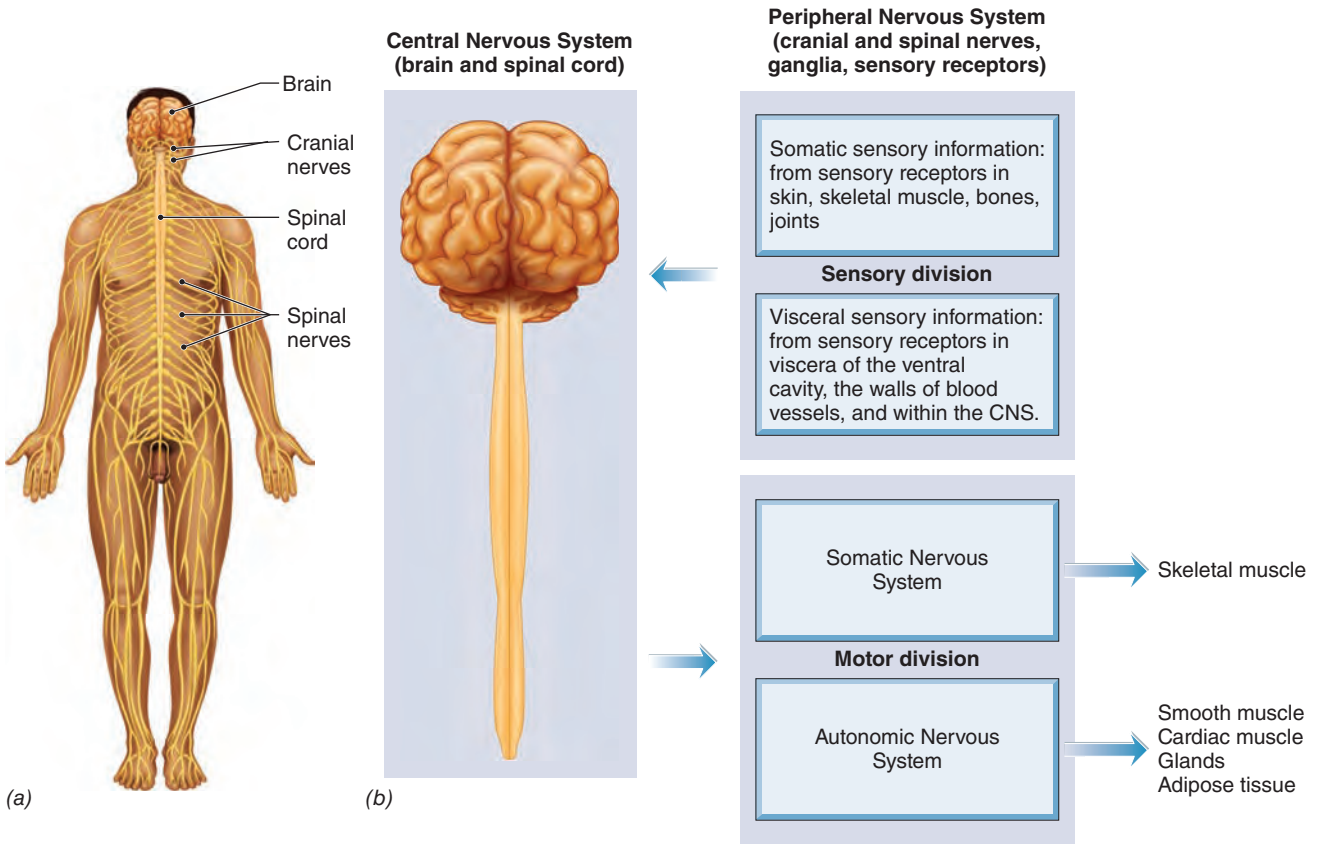


Figure 8.1 Components of the Nervous System.
(a) Anatomically, the nervous system consists of the central nervous system (brain and spinal cord) and the peripheral nervous system (cranial and spinal nerves, ganglia, sensory receptors). *(b)* Functionally, the peripheral nervous system consists of the sensory division and the motor division, which is divided into the somatic nervous system and the autonomic nervous system.

8.2 Nervous Tissue

Learning Objectives

2. Describe the structure of a neuron.
3. Compare the three structural types of neurons.
4. Compare the three functional types of neurons.
5. Explain the functions of the five types of neuroglia.

The nervous system consists of organs composed primarily of nervous tissue supported and protected by connective tissues. As described in chapter 4, there are two types of cells that compose nervous tissue: neurons and neuroglia.

Neurons

Neurons (nū′-rahns), or nerve cells, are the structural and functional units of the nervous system. They are delicate cells that are specialized to generate and transmit nerve impulses. Neurons may vary in size and shape but they have many common features.

As shown in figures 8.2 through 8.4, the **cell body** is the portion of a neuron that contains the large, spherical nucleus. The cell body also contains the usual cytoplasmic organelles. Two types of neuronal processes extend from the cell body: dendrites and axons. A neuron may have many dendrites but it has only one axon.

Dendrites (den′-drits) are usually short, highly-branched, tapering processes that receive impulses (electrochemical signals) from other neurons and sensory receptors. Dendrites carry impulses toward the cell body or axon.

An **axon** (ak′-sahn), or *nerve fiber,* is a long, thin process of a neuron. It may have one or more side branches, called *axon collaterals.* It also forms a number of short, fine branches, the *terminal arborization,* at its distal tip. The slightly enlarged tips of the terminal arborization are the **terminal boutons,** which form junctions (synapses) with other neurons, muscles, adipose tissue, or glands. An axon carries nerve impulses away from the cell body or dendrites.

Some axons are enclosed in an insulating **myelin sheath** formed by special neuroglia. Such axons are referred

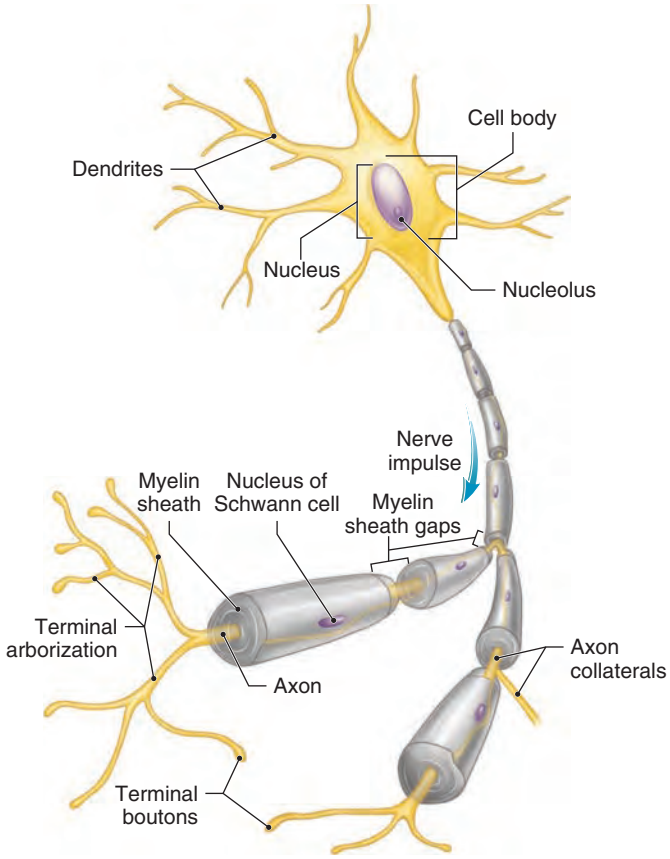


Figure 8.2 Neuron Anatomy.
The cell body contains the nucleus. One or more dendrites and a single axon are extensions from the cell body.

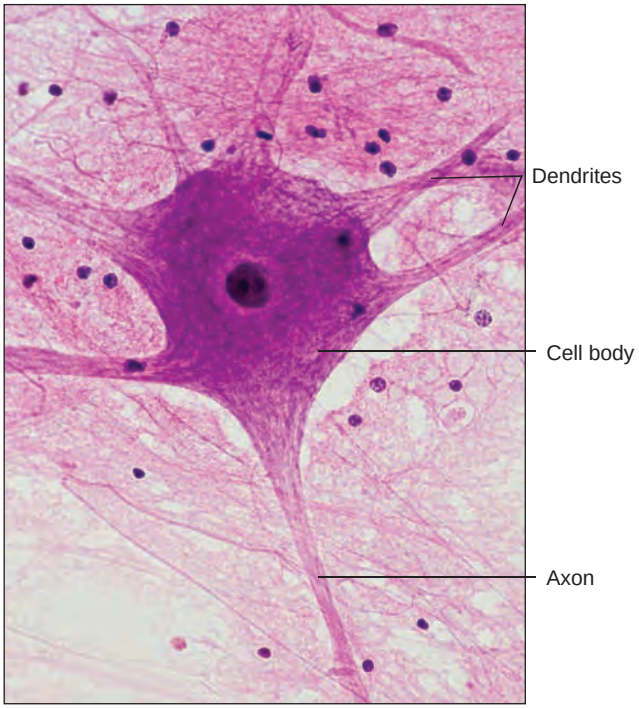


Figure 8.3 Neurons are the structural and functional units of the nervous system (50×). The dark spots in the area surrounding the neuron are nuclei of neuroglia. Note the location of the dendrites and axon.

to as *myelinated* axons. The myelin sheath increases the speed of nerve impulse transmission. The tiny spaces between adjacent myelin-forming cells, where the axon is exposed, are known as **myelin sheath gaps** (or nodes of Ranvier). Axons lacking a myelin sheath are referred to as *unmyelinated* axons and have a much slower speed of nerve impulse transmission.

Types of Neurons

Neurons may be classified according to their anatomy or their function. Structurally, there are three basic types of neurons: multipolar, bipolar, and unipolar neurons (figure 8.4).

Multipolar neurons have several dendrites and a single axon extending from the cell body. Most of the neurons whose cell bodies are located in the brain and spinal cord are multipolar neurons.

Bipolar neurons have only two processes: a dendrite and an axon extending from opposite ends of the cell body. Bipolar neurons occur in the sensory portions of the eyes, ears, and nose.

Unipolar neurons have a single process extending from the cell body. This process quickly divides into two branches extending in opposite directions, with both branches functioning as a single axon. One end of the axon ends in a terminal arborization, while the other ends in dendrites. Unipolar neurons carry nerve impulses from sensory receptors to the CNS. Clusters of cell bodies of unipolar neurons often form **ganglia** (singular, *ganglion*), which are located in the PNS.

Functionally, there are three basic types of neurons: sensory neurons, interneurons, and motor neurons.

Sensory neurons carry nerve impulses from the peripheral parts of the body to the CNS. Their dendrites are associated with sensory receptors or are specialized to detect changes directly. Nerve impulses are carried over an axon within cranial or spinal nerves to the CNS. Cell bodies of sensory neurons are located external to the CNS in ganglia. Structurally, most sensory neurons are unipolar neurons, although bipolar neurons are found in special sense organs.

Interneurons are located entirely within the CNS and synapse with other neurons. They are responsible for the processing and interpretation of nerve impulses by the CNS. Interneurons receive nerve impulses from sensory neurons and transmit them from place to place within the CNS. They also activate motor neurons, which results in a stimulation of effectors. Interneurons are multipolar neurons.

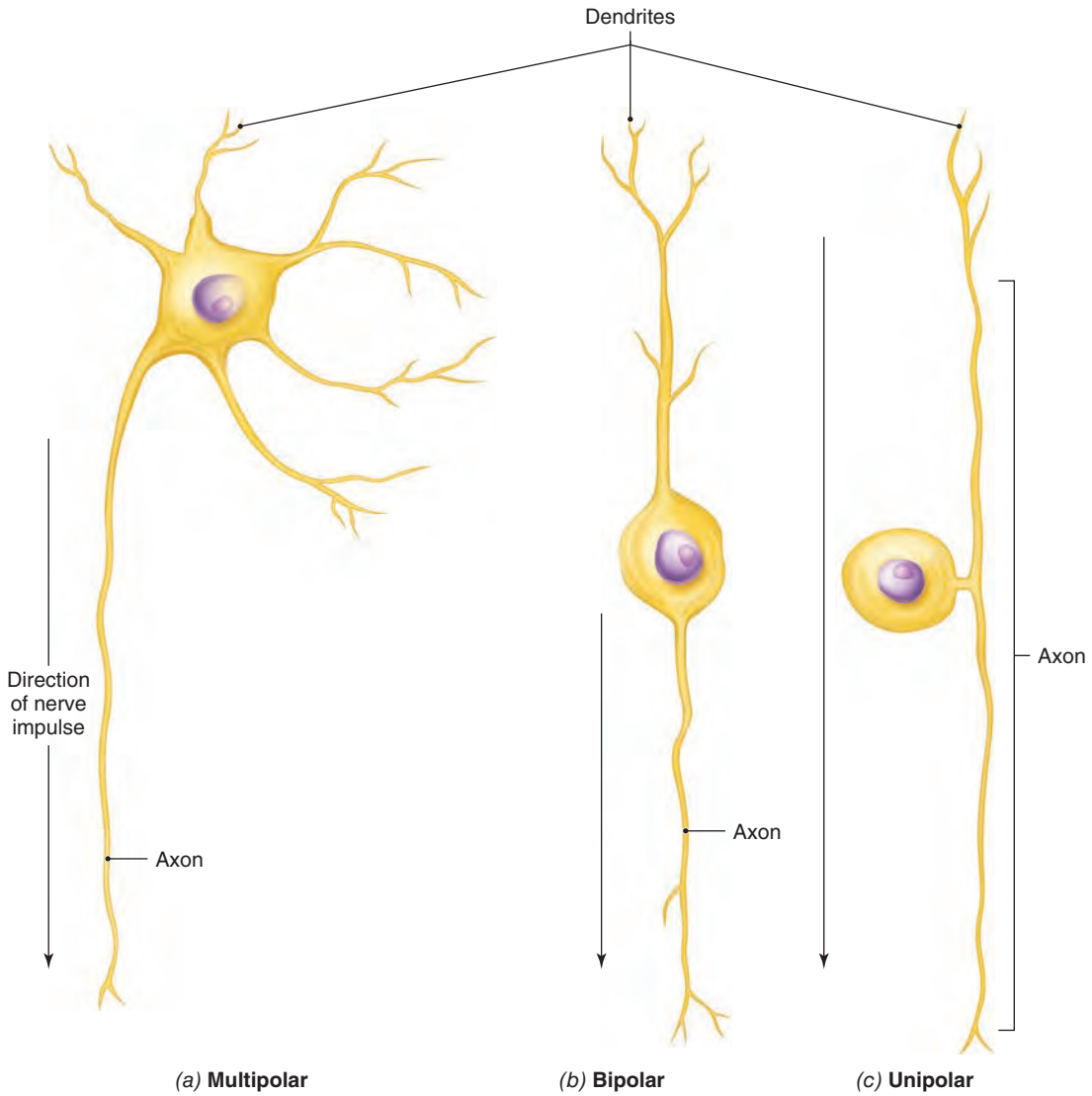


Figure 8.4 Structural Types of Neurons.

Motor neurons carry nerve impulses from the CNS to effectors to produce an action. Their cell bodies and dendrites are located within the CNS, while their axons are located in cranial and spinal nerves. Motor neurons are multipolar neurons (table 8.1).

Neuroglia

The **neuroglia** (nū-rog′-lē-ah) provide support and protection for neurons. One type of neuroglia–Schwann cells–occurs in the PNS. Four types of neuroglia occur in the CNS, where they are even more numerous than neurons (figures 8.5 and 8.6).

Schwann cells form the myelin sheath around PNS myelinated axons. They wrap tightly around an axon many times so that the nucleus and most of the cytoplasm become squeezed into the superficial layer. The deep layers, formed by layers of plasma membrane, constitute the myelin sheath. The most superficial layer forms the **neurilemma,** which is essential for axon regeneration after injury.

Oligodendrocytes (ōl-i-gō-den′-drō-sīt̄z) form the myelin sheath of myelinated axons within the CNS but they do not form a neurilemma. Lack of a neurilemma is one factor that contributes to the inability of axons within the brain and spinal cord to regenerate after injury.

Astrocytes (as′-trō-sīt̄z) are the primary supporting cells for neurons in the CNS. They stimulate the growth of neurons and influence synaptic transmission. Astrocytes also join with the epithelium of blood vessels to

Table 8.1 Functional Types of Neurons

Type	Structure	Function
Sensory neurons	Mostly unipolar, some bipolar	Carry nerve impulses from peripheral sensory receptors to the CNS
Interneurons	Multipolar	Carry nerve impulses between neurons within the CNS
Motor neurons	Multipolar	Carry nerve impulses from the CNS to effectors (muscles, glands, and adipose tissue)

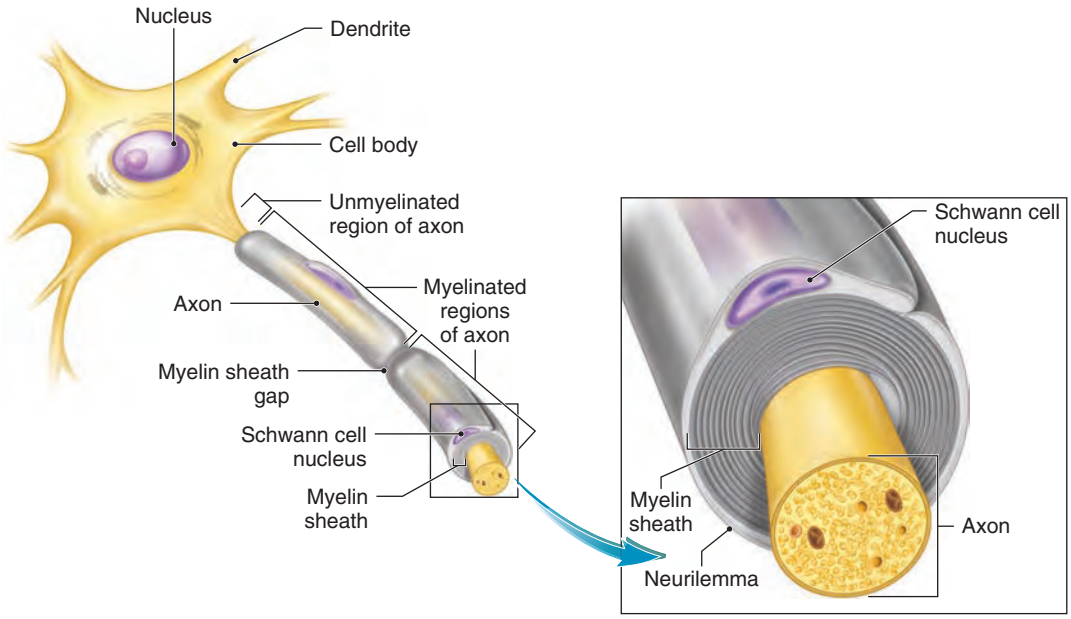


Figure 8.5 The portion of a Schwann cell that winds tightly around an axon forms a myelin sheath, while the cytoplasm and nucleus of the Schwann cell remaining on the surface form the neurilemma.

form the *blood-brain barrier,* which protects neurons by tightly regulating the exchange of materials between the blood and neurons.

Microglial cells are scattered throughout the CNS, where they keep the tissues clean by engulfing and digesting cellular debris and pathogens.

Ependymal (e-pen-dĭ′-mal) **cells** form the epithelial-like lining of cavities in the brain and spinal cord and aid in the production of cerebrospinal fluid, a unique fluid within the CNS that will be discussed later.

Check My Understanding

1. What are the general functions of the nervous system?
2. What are the structural and functional types of neurons?
3. What are the roles of the five types of neuroglia?

8.3 Neuron Physiology

Learning Objectives

6. Explain the formation and conduction of a nerve impulse.
7. Describe how nerve impulses are transmitted across a synapse.

Neurons have two unique functional characteristics: irritability and conductivity. **Irritability** is the ability to respond to a stimulus by forming a nerve impulse. **Conductivity** is the ability to transmit a nerve impulse along an axon to other neurons or effector cells. These characteristics enable the functioning of the nervous system.

Membrane Potential

Most body cell plasma membranes are polarized, meaning there is an electrical charge difference across the plasma membrane. This difference creates a *voltage* that is called

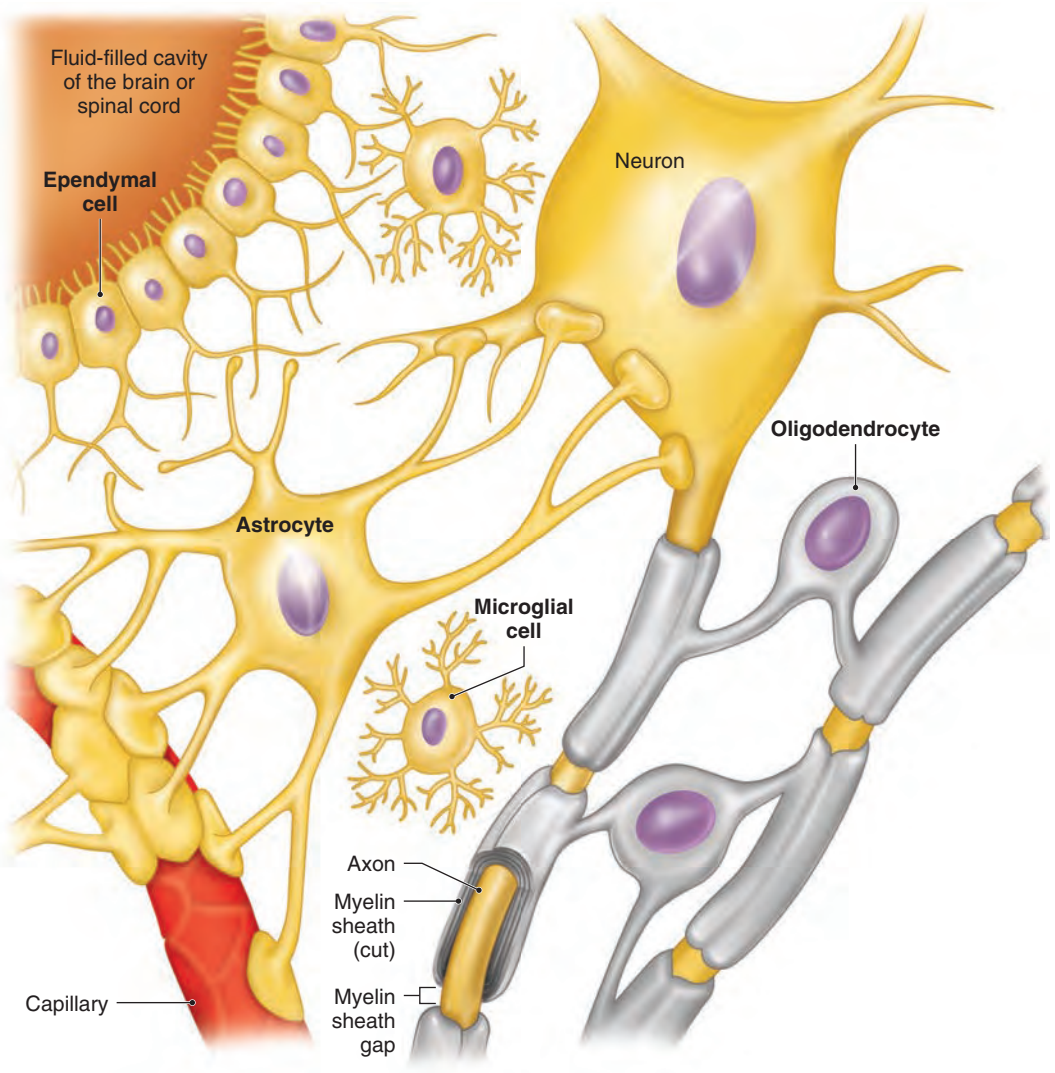


Figure 8.6 Types of Neuroglia in the Central Nervous System.

a **membrane potential.** In neurons and other cells with irritability that are inactive, this voltage is called a **resting membrane potential (RMP).** In neurons, the RMP is maintained at an average around −70mV. The reason for the difference in electrical charge is the unequal distribution of ions and proteins on either side of the plasma membrane (figure 8.7). In a resting neuron, sodium (Na^+) and chloride (Cl^-) ion concentrations are high in the ECF and low in the cytosol, whereas potassium (K^+) ions have the opposite distribution. There are also large, negatively charged proteins and ions, such as phosphates (PO_4^{3-}) and sulfates (SO_4^{2-}), in the cytosol that cannot cross the plasma membranes. These differences polarize the plasma membrane, meaning there are a net excess of positive charges on the ECF-side and a net excess of negative charges on the cytosol-side. The negative RMP indicates that the cytosol-side of the plasma membrane is more negative than the ECF-side.

To establish and maintain the RMP, neurons must be able to compensate for the diffusion of Na^+ and K^+ along their concentration gradients. The plasma membrane is more permeable to K^+, but both ions exhibit movement that is capable of disrupting the RMP. The Na^+/K^+ pump is a carrier protein that uses ATP to move Na^+ and K^+ against their concentration gradient (see Chapter 3). This carrier is continuously active to establish and maintain the RMP and to restore it after nerve impulse formation.

Nerve Impulse Formation

When stimulated, axons exhibit an all-or-none response. They either form a nerve impulse that will travel along the axon or do not respond. The weakest stimulus that will activate a neuron to produce a nerve impulse is called a *threshold stimulus.* Nerve impulses do not vary in their degree of electrical change, meaning every nerve impulse is identical.

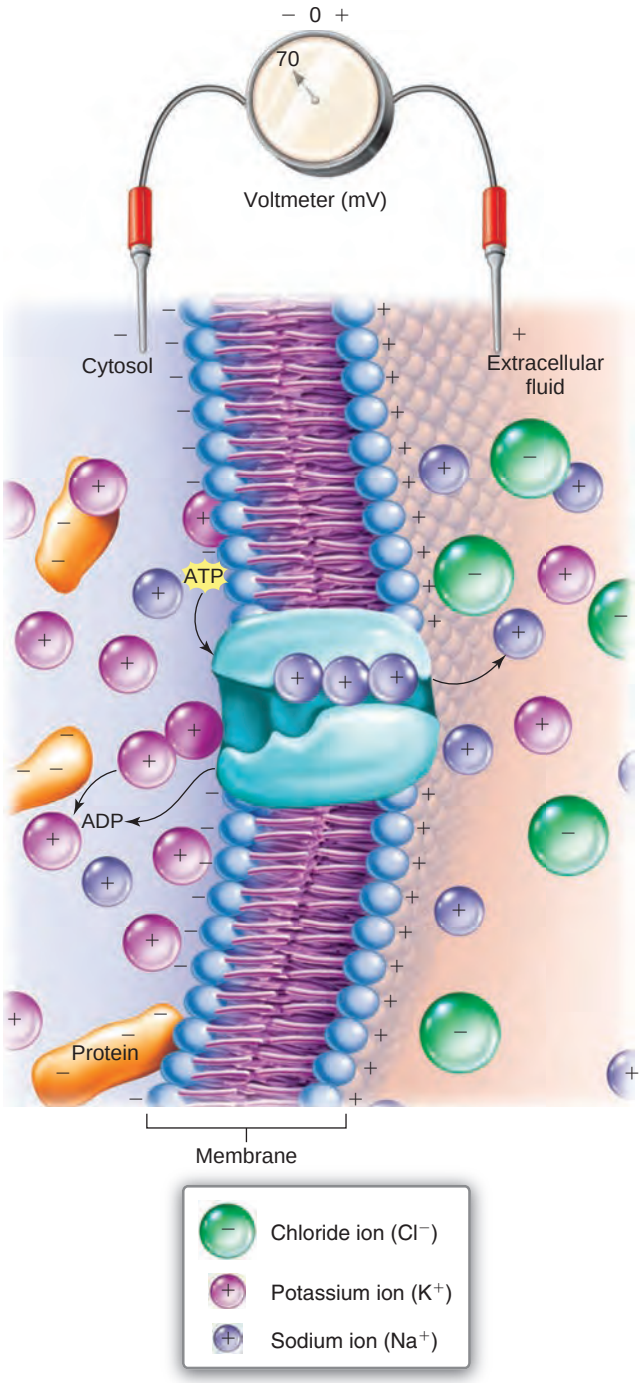


Figure 8.7 Resting Membrane Potential.
At rest, Na^+ and Cl^- ions are in high concentration in the ECF and K^+ ions are in high concentration in the cytosol. The plasma membrane possesses a net + charge on its ECF-side and a net – charge on its cytosol-side. The resulting voltage across the plasma membrane is −70mV. The Na^+/K^+ pump compensates for ion diffusion by moving 3 Na^+ from the cytosol back into the ECF and 2 K^+ from the ECF back into the cytosol.

When a neuron is activated by a threshold stimulus, its plasma membrane becomes permeable to Na^+ as Na^+ channels open, which allows these ions to quickly diffuse into the neuron. The inward flow of Na^+ for a brief instant causes the cytosol along the inside of the plasma membrane to become positively charged (an excess of positive charges) and the ECF along the outside to become negatively charged (an excess of negative charges) at the point of stimulation. The membrane potential changes to +30mV as a result of these changes. This switch in polarity is called *depolarization* and the plasma membrane is now referred to as *depolarized*. This sudden depolarization *is* the nerve impulse, or **action potential** (figure 8.8*b*). The wave of depolarization then flows along the axon. You will see how this happens momentarily.

Repolarization

Immediately after depolarization, K^+ channels open and Na^+ channels close, allowing K^+ to diffuse into the ECF in order to *repolarize* or reestablish the RMP. The loss of K^+ to the ECF creates an excess of positive charges along the ECF-side of the plasma membrane and an excess of negative charges along the cytosol-side. As a result, the membrane voltage changes from +30mV to −70mV (figure 8.8*c*). As described in the previous section, the Na^+/K^+ pump then reestablishes the resting-state distribution of ions (figure 8.8*d*). When this is accomplished, the neuron is ready to respond to another stimulus. Depolarization and repolarization are accomplished in about 1 millisecond.

Nerve Impulse Conduction

When a nerve impulse is formed at one point in an axon, it triggers the depolarization of adjacent portions of the plasma membrane, which, in turn, depolarizes still other regions of the plasma membrane. The result is a wave of depolarization that conducts a nerve impulse along the axon. Repolarization immediately follows a nerve impulse.

Conduction of nerve impulses is more rapid in myelinated axons than in unmyelinated axons. Recall that a myelinated axon is exposed only at myelin sheath gaps. Because of this, a nerve impulse jumps from gap to gap and does not have to depolarize the intervening segments of the axon (figure 8.9).

Synaptic Transmission

A **synapse** (sin′-aps) is a junction of an axon with either another neuron or an effector cell. At a synapse, the terminal bouton of the **presynaptic** neuron fits into a small depression on the **postsynaptic** neuron's dendrite or cell body or on a cell within a muscle, a gland, or adipose tissue. There is a tiny space, the **synaptic cleft,** between the presynaptic and postsynaptic structures, so they are not in physical contact (figure 8.10).

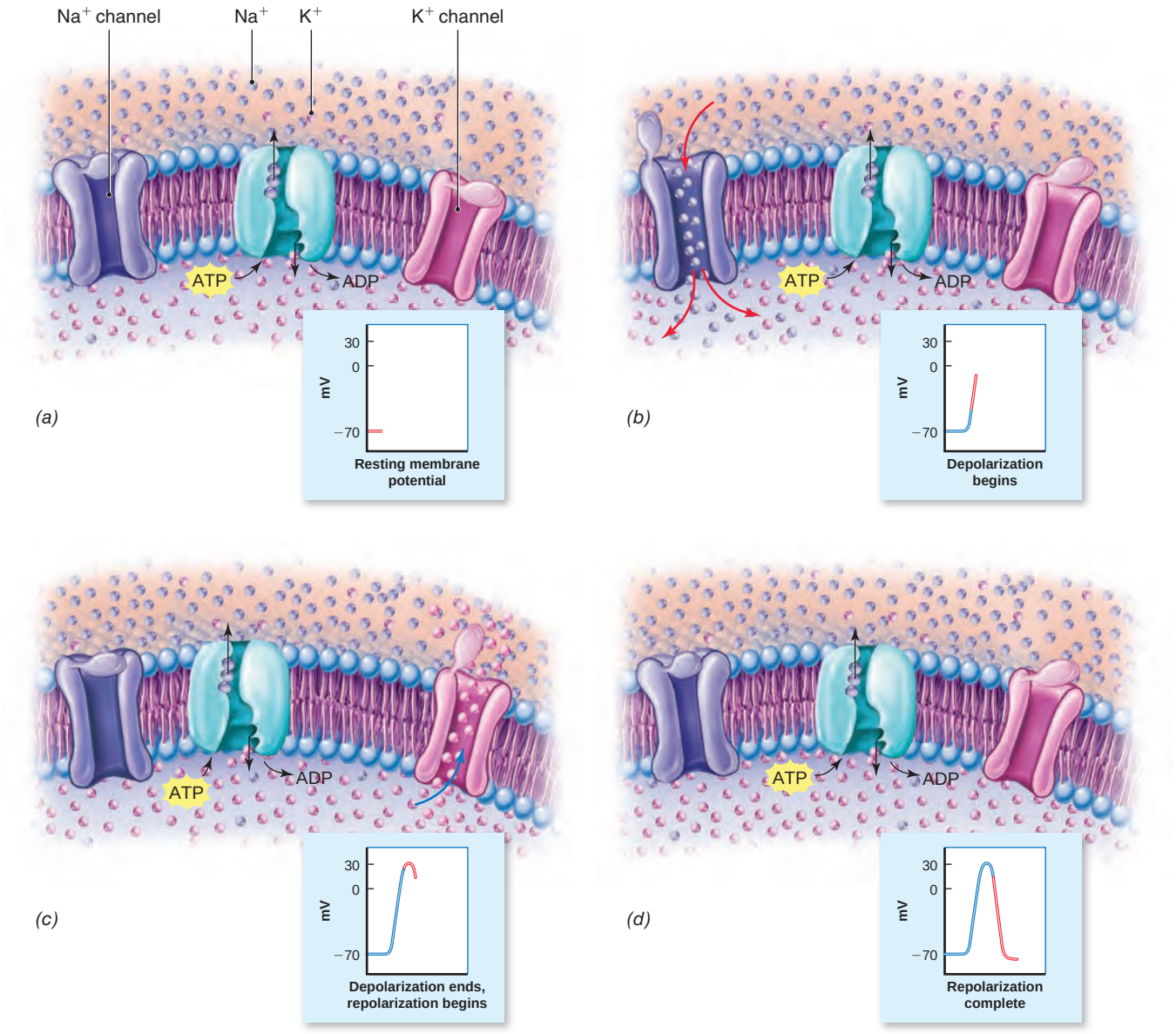


Figure 8.8 Depolarization and Repolarization of a Neuron.
(a) Neuron at rest. Both Na^+ and K^+ channels are closed. *(b)* Na^+ channels open and Na^+ flows into the neuron depolarizing the plasma membrane to +30mV. *(c)* Na^+ channels close. K^+ channels open and K^+ flows out of the neuron repolarizing the plasma membrane to −70mV. *(d)* K^+ channels close and Na^+/K^+ pumps reestablish resting ion distribution.

In neuron-to-neuron synaptic transmission, when a nerve impulse reaches the terminal bouton of the presynaptic neuron, it causes the terminal bouton to secrete **neurotransmitters** into the synaptic cleft. Then, the neurotransmitters bind to receptors on the postsynaptic neuron's plasma membrane, which triggers a response in the postsynaptic neuron. Some neurotransmitters stimulate formation of a nerve impulse in the postsynaptic neuron, while others inhibit nerve impulse formation. If a nerve impulse is formed in the postsynaptic neuron, it is carried along the neuron's axon to the next synapse where synaptic transmission takes place again.

Because only terminal boutons can release neurotransmitters, nerve impulses can pass in only one direction across a synapse–from the presynaptic neuron to the postsynaptic neuron. Thus, nerve impulses always pass in the "correct" direction, which maintains order in the nervous system.

Some neurotransmitters are reabsorbed into the terminal bouton for reuse. Others diffuse out of the synaptic

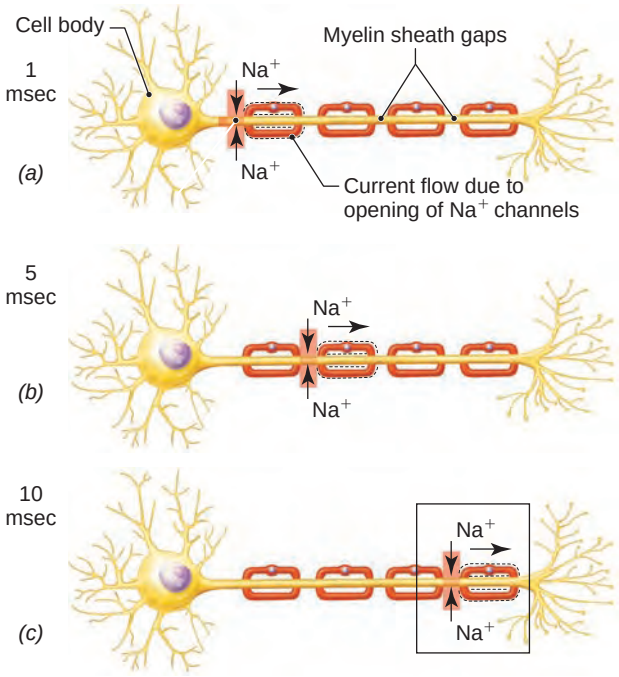


Figure 8.9 Movement of sodium ions during (*a*) nerve impulse formation (depolarization), and (*b*) and (*c*) nerve impulse conduction. Note that repolarization immediately follows depolarization.

cleft or are decomposed by enzymes released into the synaptic cleft. Some of the decomposition products are then reabsorbed into the bouton for reuse, while others diffuse away from the synaptic cleft. Quick removal of a neurotransmitter prevents continuous stimulation or inhibition of the postsynaptic neuron (or cell) and prepares the synapse for another transmission. From start to finish, synaptic transmission takes only a fraction of a second.

Neurotransmitters

Neurotransmitters enable neurons to communicate with each other as well as with other cells throughout the body. Scientific research has identified over 100 neurotransmitters at work within the human nervous system and most likely more will be discovered in the future. When released, neurotransmitters create either excitatory or inhibitory effects on the postsynaptic cell. *Excitatory neurotransmitters* cause the formation of an impulse in the postsynaptic cell, which in turn promotes cell function. *Inhibitory neurotransmitters* inhibit the formation of an impulse in the postsynaptic cell, resulting in an inhibition of cell function. What makes the study of neurotransmitters intriguing is the fact that one neurotransmitter can create both excitatory and inhibitory effects depending upon the postsynaptic cell receiving the signal. For

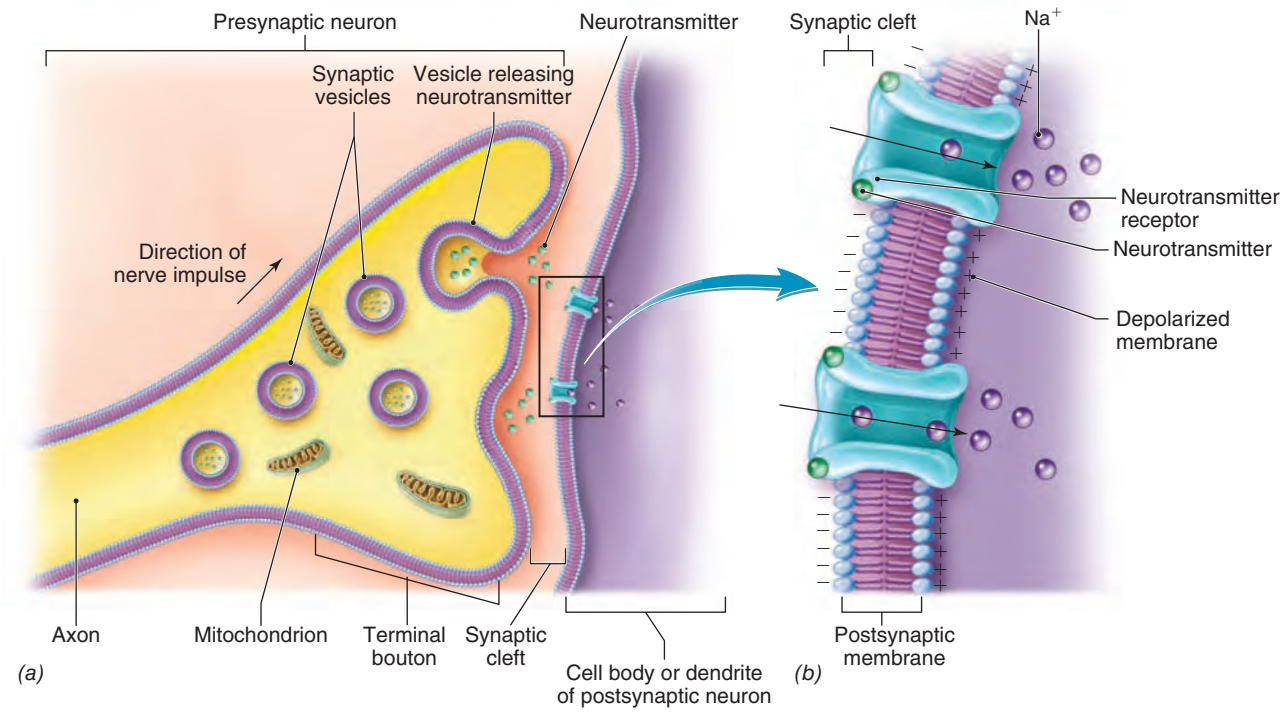


Figure 8.10 Synaptic Transmission from Neuron to Neuron.
(*a*) A terminal bouton of the presynaptic neuron fits into a depression on a dendrite or the cell body of the postsynaptic neuron. When a nerve impulse reaches the terminal bouton, a neurotransmitter is released into the synaptic cleft. (*b*) The neurotransmitter binds with receptors on the plasma membrane of the postsynaptic neuron, causing depolarization of the membrane.

example, acetylcholine acts as an excitatory neurotransmitter in skeletal muscle by promoting contraction of skeletal muscle fibers (see Chapter 7). However, acetylcholine acts as an inhibitory neurotransmitter in cardiac muscle by inhibiting contraction of cardiac muscle cells, resulting in a decrease in heart rate (see Chapter 12).

The cell body and dendrites of a postsynaptic neuron synapse with hundreds of presynaptic neurons. Some of the neurotransmitters released in these synapses exert excitatory effects, while some exert inhibitory effects. Whether or not a nerve impulse is formed in the postsynaptic neuron depends upon whether the excitatory or inhibitory effects are dominating at that time.

Check My Understanding

4. How are nerve impulses formed and conducted?
5. What is the mechanism of synaptic transmission?

Clinical Insight

Inhibitory and stimulatory drugs act by affecting synaptic transmission. Some *tranquilizers* and *anesthetics* inhibit synaptic transmission by increasing the threshold of postsynaptic neurons. *Nicotine, caffeine,* and *benzedrine* promote synaptic transmission by decreasing the threshold of postsynaptic neurons.

8.4 Protection for the Central Nervous System

Learning Objective

8. Describe how the brain and spinal cord are protected from injury.

Both the brain and the spinal cord are soft, delicate organs that would be easily damaged without adequate protection. Surrounding bones and fibrous membranes provide both protection and support. The brain occupies the cranial cavity formed by the cranial bones, and the spinal cord lies within the vertebral canal formed by the vertebrae. Three membranes are located between the CNS and the surrounding bones. These membranes are collectively called the meninges.

Meninges

The **meninges** (me-nin′-jēs; singular *meninx*) consist of three membranes arranged in layers. From deepest to most superficial they are the pia mater, arachnoid mater, and dura mater (figures 8.11 and 8.12).

The **pia mater** (pee-uh mah-ter; "tender mother") is the very thin, deepest membrane. It tightly envelops both the brain and the spinal cord and penetrates into each groove and depression. It contains many blood vessels that nourish the underlying brain and spinal cord.

The **arachnoid** (ah-rak′-noyd) **mater** ("spider mother") is the middle membrane. It is a thin, weblike membrane without blood vessels that does not penetrate into the small

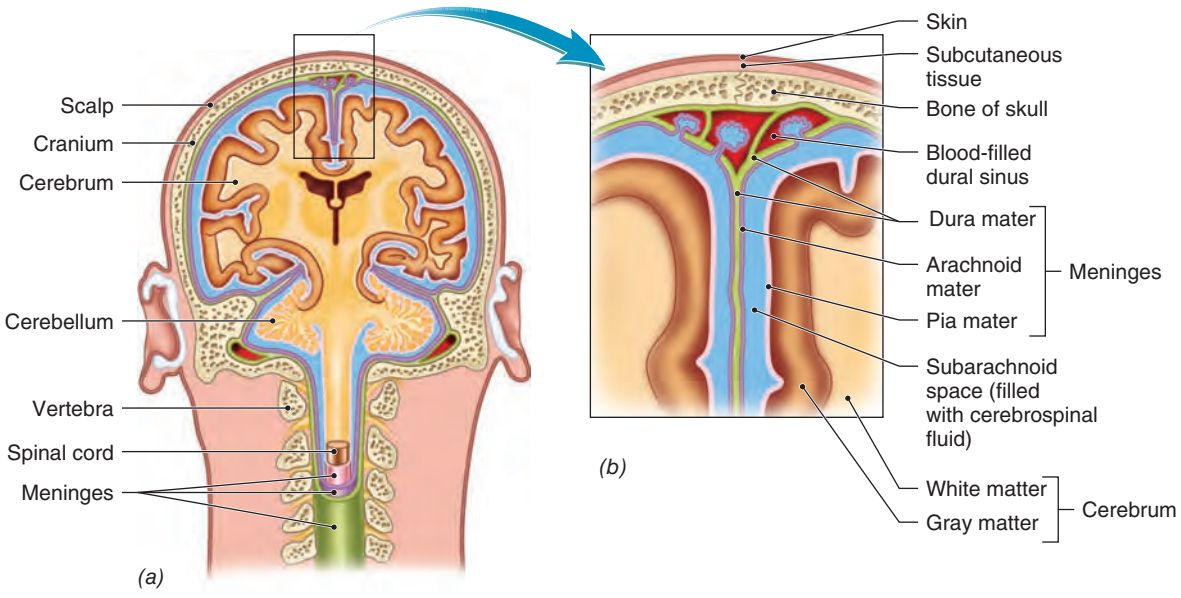


Figure 8.11 (*a*) Membranes called meninges enclose the brain and spinal cord. (*b*) The meninges include three layers: dura mater, arachnoid mater, and pia mater.

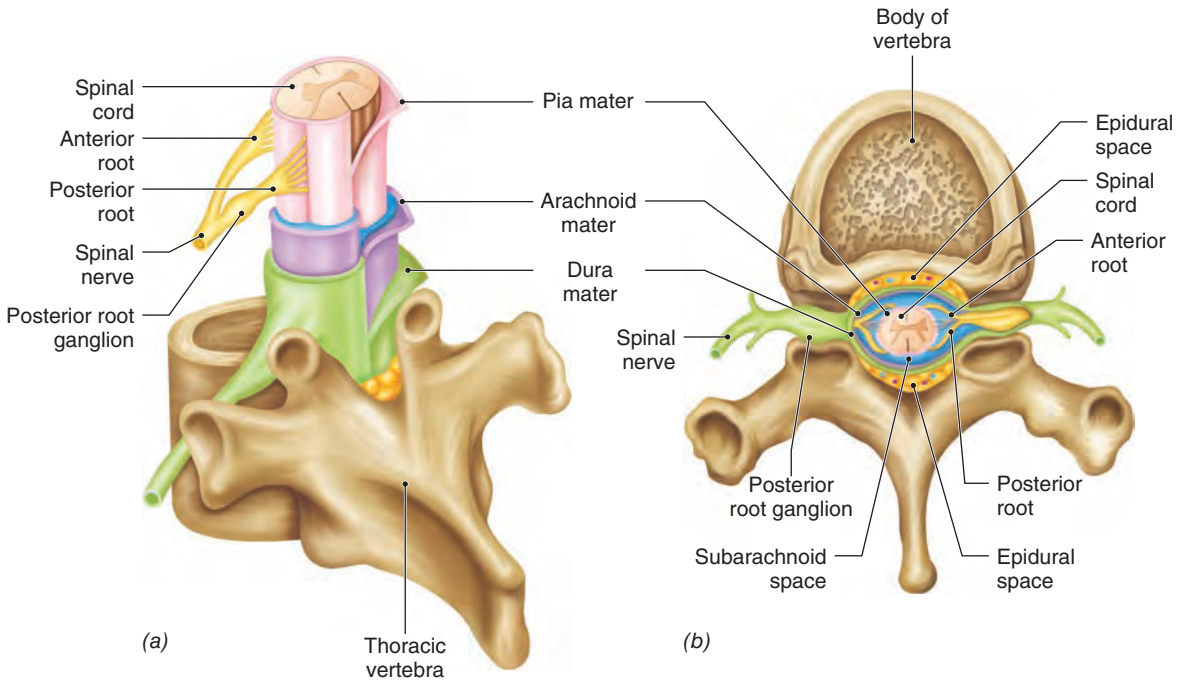


Figure 8.12 Meninges and Spinal Cord.
(*a*) The meninges support and protect the spinal cord. (*b*) Adipose tissue fills the epidural space, providing a protective cushion.

depressions as does the pia mater. Between the pia mater and the arachnoid mater is the *subarachnoid space,* which contains *cerebrospinal fluid.* This clear, watery liquid serves as a shock absorber around the brain and spinal cord.

The **dura** (du′-rah) **mater** ("tough mother") is the tough, fibrous most superficial layer. In the cranial cavity, it is attached to the internal surfaces of the cranial bones and penetrates into *fissures* between some parts of the brain. A fissure is a deep, wide groove that separates brain regions. In the vertebral canal, the dura mater forms a protective tube that extends to the sacrum. It does not attach to the bony surfaces of the vertebral canal but is separated from the bone by an *epidural space.* Adipose tissue fills the epidural space and serves as an additional protective cushion. Physical trauma can cause tearing of blood vessels extending between the dura and arachnoid maters. The pooling of blood between the two meninges, which is called a *subdural hematoma,* creates an artificial space called the *subdural space.*

8.5 Brain

Learning Objectives

9. Describe the major parts of the brain in terms of structure, location, and function.
10. Identify the functions of the lobes of the cerebrum.
11. Describe the formation, circulation, absorption, and functions of cerebrospinal fluid.

The brain is a large, exceedingly complex organ. It contains about 100 billion neurons and innumerable neuronal processes and synapses. The brain consists of four major components: the cerebrum, cerebellum, diencephalon, and brainstem. Locate these structures in figure 8.13.

Cerebrum

The **cerebrum** is the largest portion of the brain. It performs the higher brain functions involved with sensations, voluntary actions, reasoning, planning, and problem solving.

Structure

The cerebrum consists of the left and right **cerebral hemispheres,** which are joined by a mass of myelinated axons called the **corpus callosum.** The cerebral hemispheres are separated by the **longitudinal cerebral fissure,** which lies along the superior midline and extends inferiorly to the corpus callosum.

The surface of the cerebrum has numerous folds or ridges, called *gyri* (jī′-rē; singular, gyrus). The shallow grooves between the gyri are called *sulci* (sul′-sē; singular, sulcus). The superficial layer of the cerebrum is composed of *gray matter* (cell bodies, dendrites, terminal arborizations, and unmyelinated axons) and is called the **cerebral cortex.** *White matter,* composed of myelinated and unmyelinated axons, lies deep to the cortex and composes most of the cerebrum. These axons transmit nerve impulses

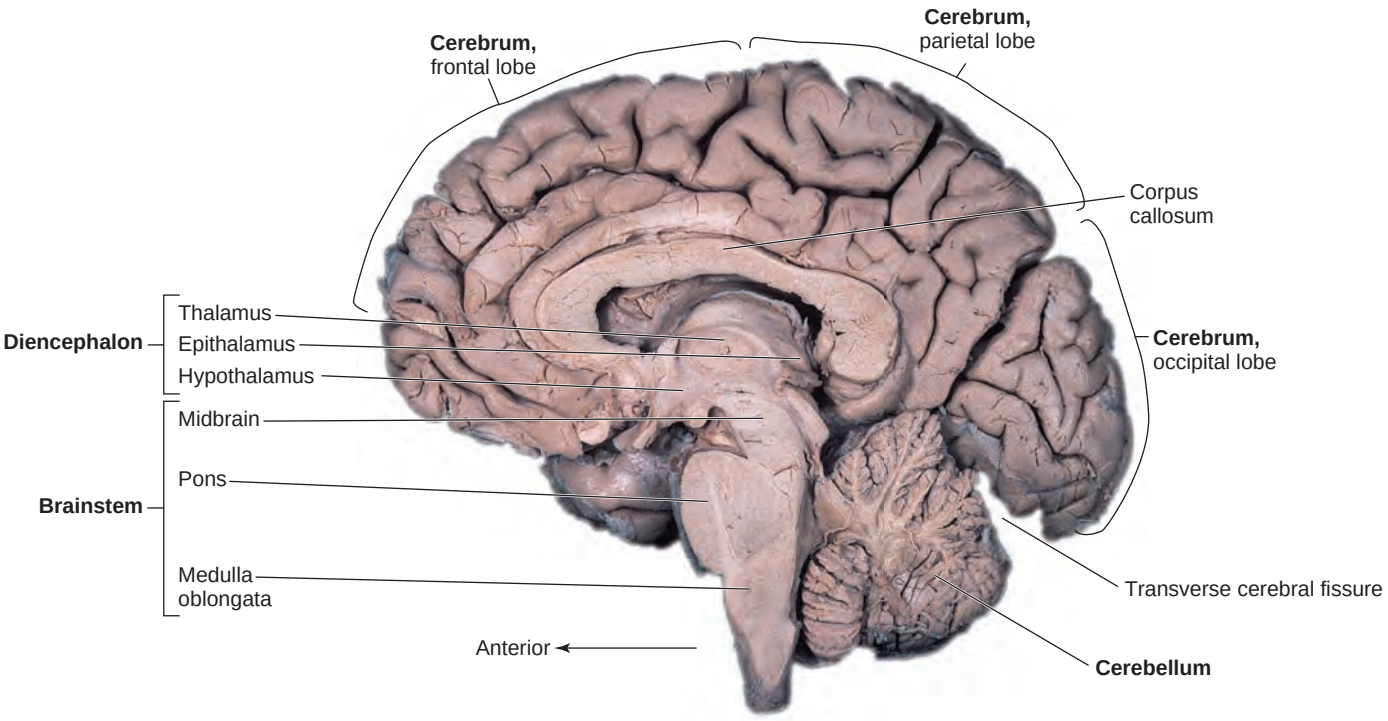


Figure 8.13 The major components of the brain as shown in a median section. Note the unlabeled gyri and sulci of the cerebrum.

between regions within the same cerebral hemisphere, between the cerebral hemispheres via the corpus callosum, and between the cerebral cortex and lower brain centers. Several masses of gray matter, called **nuclei,** are embedded deep within the white matter of each cerebral hemisphere.

Each cerebral hemisphere is divided into five lobes. Four lobes are named for the cranial bones under which they lie. Locate the cerebral lobes in figures 8.13 and 8.14.

1. The **frontal lobe** lies anterior to the *central sulcus* and superior to the *lateral sulcus.*
2. The **parietal lobe** lies posterior to the central sulcus, superior to the temporal lobe, and anterior to the occipital lobe.
3. The **temporal lobe** lies inferior to the frontal and parietal lobes and anterior to the occipital lobe.
4. The **occipital lobe** lies posterior to the parietal and temporal lobes. The boundaries between the parietal, temporal, and occipital lobes are not distinct.
5. The **insula** lies deep to the lateral sulcus. It is the lobe that cannot be viewed superficially.

Functions

The cerebrum is involved in the interpretation of sensory nerve impulses as sensations and in controlling voluntary motor responses, intellectual processes, the will, and many personality traits. The cerebrum has three major types of functional areas: sensory, motor, and association areas (figure 8.14).

Sensory areas receive nerve impulses formed by sensory receptors and interpret them as sensations. These areas occur in several cerebral lobes. For example, the sensory areas for vision are in the occipital lobes and those for hearing are found in the temporal lobes. Areas identifying sensations from skin (cutaneous) stimulation lie along the *postcentral gyri* (gyri just posterior to the central sulci) of the parietal lobes. Sensory areas for taste are located at the inferior end of the postcentral gyri. The sensory areas for smell are located in the inferior part of the frontal lobe and the medial aspect of the temporal lobe.

Ascending sensory axons carrying sensations from the skin cross over from one side to the other prior to reaching the thalamus. Thus, the postcentral gyrus in the left cerebral hemisphere receives nerve impulses from the skin on the right side of the body, and vice versa.

Motor areas are located in the frontal lobe. The *primary motor areas* that control skeletal muscles lie along the *precentral gyri* (gyri just anterior to the central sulci) of the frontal lobes. The region anterior to the primary motor area is the *premotor area.*

The premotor area is involved in complex learned activities, such as writing, tying your shoes, and driving a car. Also in the premotor area is the *frontal eye field,* which controls voluntary eye movements. The *motor speech area* (*Broca*

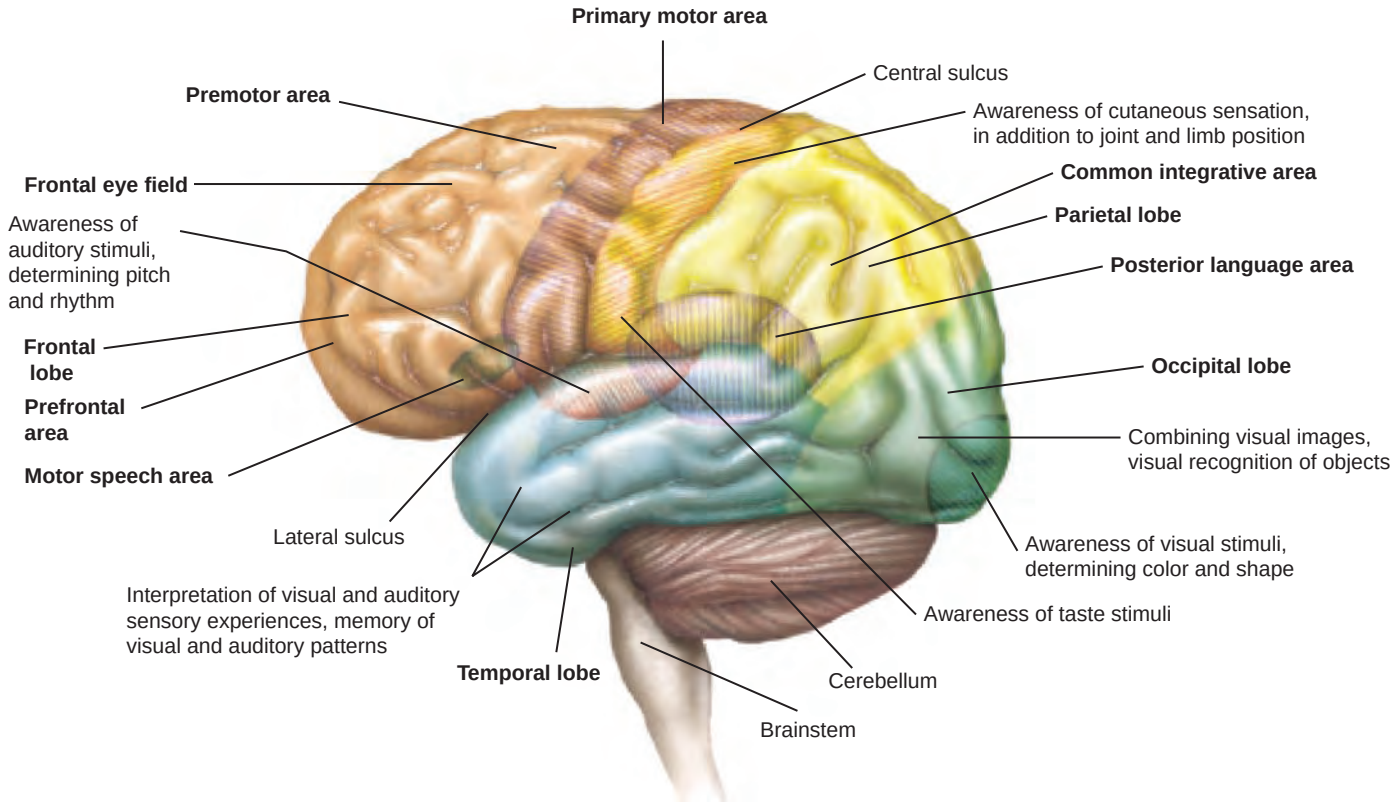


Figure 8.14 A lateral view of the left brain showing the cerebral lobes and their functional areas.

area), which controls the ability to speak, is located near the inferior end of the primary motor area. It is found in only one hemisphere: the left hemisphere in about 90% of people.

Descending motor axons cross over from one side to the other in the brainstem. Thus, the left side of the cerebrum controls skeletal muscles on the right side of the body, and vice versa.

Association areas occur in each cerebral lobe, where they interrelate sensory inputs and motor outputs. They play critical roles in the interrelationships of sensations, memory, will, and the coordination of motor responses. The *common integrative area* is a major association area that is located at the junction of the temporal, parietal, and occipital lobes. It is involved with the interpretation of complex sensory experiences and thought processes. The *posterior language area* (*Wernicke area*), which is an association area located in the temporal and parietal lobes, is used to interpret the meaning of spoken and written language. Like the motor speech area, it is found in only one hemisphere: the left hemisphere in about 90% of people.

The *prefrontal area*, which is located in the anterior portion of the frontal lobe, is involved with functions such as planning, complex behaviors, conscience, generating personality, and executive functions. Executive functions include distinguishing between good and bad, understanding future consequences, social control of urges, and working towards a goal. Portions of the prefrontal area are not fully developed until a person is in his or her 20s, which is why teenagers often have issues with impulse control and poor decision-making.

Clinical Insight

The transmission of nerve impulses by neurons in the brain produces electrical potentials that can be detected and recorded as brain waves. A recording of brain waves is called an *electroencephalogram (EEG)*. The patterns of brain waves are used in the diagnosis of certain brain disorders. The cessation of brain wave production is one criterion of brain death.

Hemisphere Specialization

The two cerebral hemispheres perform different functions in most people, although each performs basic functions of receiving sensory input and initiating voluntary motor

output. In about 90% of the population, the left cerebral hemisphere controls analytical and verbal skills, such as mathematics, reading, writing, and speech. In these persons, the right hemisphere controls musical, artistic and spatial awareness, imagination, and insight. In some persons, this pattern is reversed; in a few, there seems to be no specialization. Men also have greater lateralization than women, which is why damage to a hemisphere can have greater effects in men.

Diencephalon

The **diencephalon** (di-en-sef′-a-lon) is a small but important part of the brain. It lies between the brainstem and the cerebrum of the brain and consists of three major components: the thalamus, hypothalamus, and epithalamus (see figure 8.13).

Thalamus

The **thalamus** (thal′-ah-mus) consists of two lateral masses of nervous tissue that are joined by a narrow isthmus of nervous tissue called the *interthalamic adhesion.* Sensory nerve impulses (except those for smell) coming from lower regions of the brain and the spinal cord are first received by the thalamus before being relayed to the cerebral cortex. The thalamus provides a general but nonspecific awareness of sensations such as pain, pressure, touch, and temperature. It seems to associate sensations with emotions but it is the cerebral cortex that interprets the precise sensation. The thalamus also serves as a relay station for communication between motor areas of the brain.

Hypothalamus

The **hypothalamus** (hī-pō-thal′-ah-mus) is located inferior to the thalamus and anterior to the midbrain. It communicates with the thalamus, cerebrum, and other parts of the brain. The hypothalamus is the major integration center for the autonomic nervous system. In this role, it controls virtually all internal organs. The hypothalamus also is the connecting link between the brain and the endocrine system, which produces chemicals (hormones) that affect most cells in the body. This link results from hypothalamic control of the hypophysis, or pituitary gland, which is suspended from its inferior surface. Although it is small, the hypothalamus exerts a tremendous impact on body functions.

The primary function of the hypothalamus is the maintenance of homeostasis, and this is accomplished through its regulation of

- body temperature;
- mineral and water balance;
- appetite and digestive processes;
- heart rate and blood pressure;
- sleep and wakefulness;
- emotions; and
- secretion of hormones by the pituitary gland.

Epithalamus

The **epithalamus** (ep-i-thal′-ah-mus; epi = above) is a small mass of tissue located superior and posterior to the thalamus forming part of the roof of the third ventricle. The major structure within the epithalamus is the *pineal gland.* The pineal gland is stimulated to produce a hormone called *melatonin* when sunlight levels become low during the evening and overnight hours. This hormone induces sleepiness to initiate the night component of a person's day-night cycle and may assist in regulating the onset of puberty. This hormone will be discussed further in Chapter 10.

Limbic System

The thalamus and hypothalamus are associated with parts of the cerebral cortex and nuclei deep within the cerebrum to form a complex known as the **limbic system.** The limbic system is involved in memory and in emotions such as sadness, happiness, anger, and fear. It seems to regulate emotional behavior, especially behavior that enhances survival. Mood disorders, such as depression, are usually a result of malfunctions of the limbic system. It also is referred to as the "motivational system" because it provides our desire to carry out the commands created by the cerebrum.

Check My Understanding

6. How is the CNS protected from mechanical injuries?
7. What are roles of the functional areas of the cerebrum?
8. What are the functions of the thalamus, hypothalamus, and epithalamus?

Brainstem

The **brainstem** is the stalklike portion of the brain that joins higher brain centers to the spinal cord. It contains several nuclei that are surrounded by white matter. Ascending (sensory) and descending (motor) axons between higher brain centers and the spinal cord pass through the brainstem. The components of the brainstem include the midbrain, pons, and medulla oblongata (see figure 8.13).

Midbrain

The **midbrain** is the most superior portion of the brainstem. It is located posterior to the hypothalamus and superior to the pons. It contains reflex centers for head, eye, and body movements in response to visual and auditory stimuli. For example, reflexively turning the head to enable better vision or better hearing is activated by the midbrain.

Pons

The **pons** lies between the midbrain and the medulla oblongata and is recognizable by its bulblike anterior portion. It consists primarily of axons. Longitudinal axons connect lower and higher brain centers, and transverse axons connect with the cerebellum. The pons also works with the medulla oblongata by controlling the rate and depth of breathing (see chapter 14).

Medulla Oblongata

The **medulla oblongata** (me-dūl′-ah ob-lon-ga′-ta) is the most inferior portion of the brain, and it is the connecting link with the spinal cord. Descending (motor) axons extending between the brain and the spinal cord cross over to the opposite side of the brain within the medulla oblongata. The medulla oblongata contains three integration centers that are vital for homeostasis:

1. The **respiratory rhythmicity center** controls the basic rhythm of breathing by triggering each cycle of inhale and exhale. It is also involved in associated reflexes such as coughing and sneezing.
2. The **cardiac control center** regulates the rate and force of heart contractions.
3. The **vasomotor center** regulates blood pressure and blood flow by controlling the diameter of blood vessels.

Reticular Formation

The **reticular** (re-tik′-ū-lar) **formation** is a network of axons and small nuclei of gray matter that extends from the superior spinal cord, through the brainstem, into the diencephalon. This network generates and transmits nerve impulses that arouse the cerebrum to wakefulness. A decrease in activity results in sleep. Damage to the reticular formation may cause unconsciousness or a coma.

Cerebellum

The **cerebellum** (ser-e-bel′-um) is the second largest portion of the brain. The **transverse cerebral fissure** separates it superiorly from the occipital and temporal lobes of the cerebrum. It is also positioned posterior to the pons and medulla oblongata. It is divided into two lateral hemispheres by a medial constriction, the *vermis* (ver′-mis). Gray matter forms a thin superficial layer covering the deep white matter, which forms most of the cerebellum (see figure 8.13).

The cerebellum is a reflex center that controls and coordinates the interaction of skeletal muscles. It controls posture, balance, and muscle coordination during movement. Damage to the cerebellum may result in a loss of equilibrium, muscle coordination, and muscle tone.

Table 8.2 summarizes the major brain functions.

Table 8.2 Summary of Brain Functions

Part	Function
Cerebrum	Sensory areas interpret nerve impulses as sensations. Motor areas control voluntary skeletal muscle actions. Association areas interrelate various sensory and motor areas and are involved in intellectual processes, will, memory, emotions, and personality traits. The limbic system is involved with motivation and with emotions as they relate to survival behavior.
Diencephalon	
Thalamus	Receives and relays sensory nerve impulses (except smell) to the cerebrum and motor nerve impulses to lower brain centers. Provides a general awareness of pain, touch, pressure, and temperature.
Hypothalamus	Serves as the major integration center the autonomic nervous system. Controls water and mineral balance, heart rate and blood pressure, appetite and digestive activity, body temperature, and sexual response. Is involved in sleep and wakefulness and in emotions of anger and fear. Regulates functions of the pituitary gland.
Epithalamus	Production of the hormone melatonin
Brainstem	
Midbrain	Relays sensory nerve impulses from the spinal cord to the thalamus and motor nerve impulses from the cerebrum to the spinal cord. Contains reflex centers that move the eyeballs, head, and neck in response to visual and auditory stimuli.
Pons	Relays nerve impulses between the midbrain and the medulla oblongata and between the cerebellar hemispheres. Helps medulla oblongata control breathing.
Medulla oblongata	Relays nerve impulses between the brain and spinal cord. Reflex centers control heart rate and contraction force, blood vessel diameter, breathing, swallowing, vomiting, coughing, sneezing, and hiccupping. Motor axons cross over to the opposite side.
Cerebellum	Controls posture, balance, and the coordination of skeletal muscle contractions.

Check My Understanding

9. What are the functions of the medulla oblongata?
10. How is the cerebellum involved in skeletal muscle contractions?

Ventricles and Cerebrospinal Fluid

There are four interconnecting **ventricles,** or cavities, within the brain. Each ventricle is lined by ependymal cells and is filled with **cerebrospinal fluid (CSF).** The largest ventricles are the two *lateral ventricles* (first and second ventricles), which are located within the cerebral hemispheres. The *third ventricle* is a narrow space that lies on the midline between the lateral masses of the thalamus and superior to the hypothalamus. The *fourth ventricle* is located on the midline in the posterior portion of the brainstem just anterior to the cerebellum. It is continuous with the central canal of the spinal cord. Observe the relative positions of the ventricles in figure 8.15.

Each ventricle contains a **choroid** (kō′-royd) **plexus,** a mass of special capillaries and ependymal cells that secrete CSF, but most of the CSF is produced in the lateral ventricles. The flow of CSF is shown in

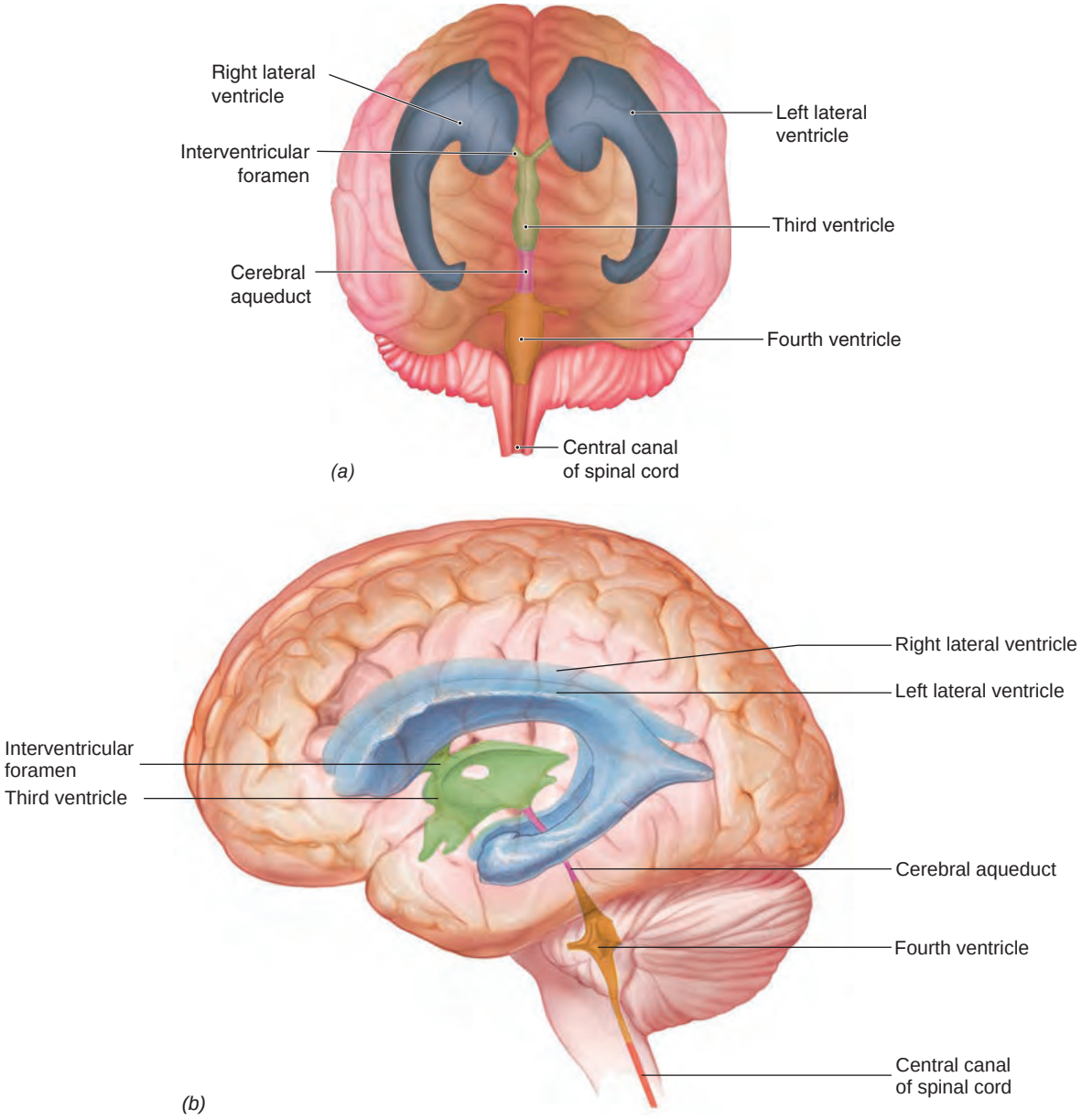


Figure 8.15 Anterior (*a*) and lateral (*b*) views of the ventricles of the brain. Note how they are interconnected.

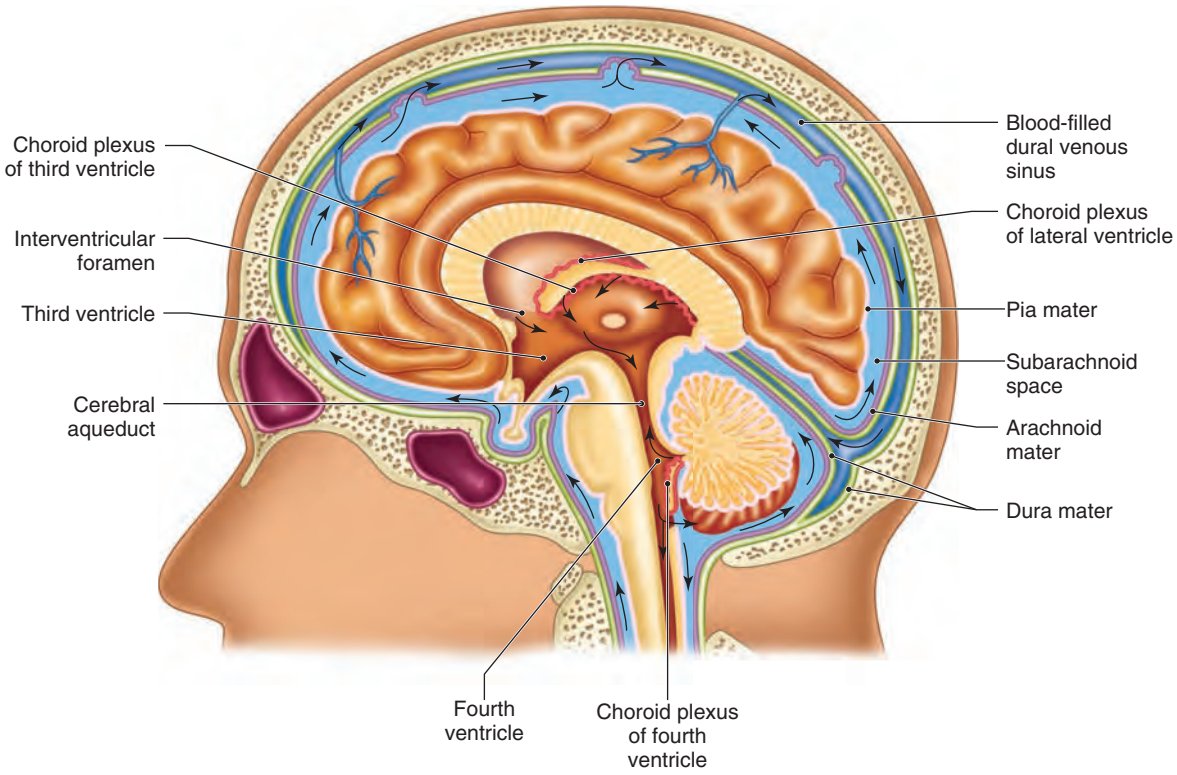


Figure 8.16 Circulation of CSF. Choroid plexuses in ventricle walls secrete CSF. The fluid flows through the ventricles, central canal of the spinal cord, and subarachnoid space. It is reabsorbed into the blood at the dural venous sinus.

figure 8.16. From the lateral ventricles, the CSF flows through the interventricular foramina into the third ventricle and then through the cerebral aqueduct into the fourth ventricle. From the fourth ventricle, some of the fluid flows inferiorly through the central canal of the spinal cord, but most of it passes into the subarachnoid space of the meninges. Within the subarachnoid space, the CSF flows in two directions. Some flows superiorly around the brain. The remainder flows inferiorly along the posterior of the spinal cord, returns superiorly along its anterior surface, and continues superiorly around the brain in the subarachnoid space. CSF is reabsorbed into the blood-filled dural venous sinus that is located along the superior midline within the dura mater (figures 8.11 and 8.16). The secretion and absorption of CSF normally occur at equal rates, which results in a rather constant hydrostatic pressure within the ventricles and subarachnoid space.

As mentioned previously, CSF acts as a protective shock absorber that surrounds the brain and spinal cord. Because it is circulated throughout the CNS, cerebrospinal fluid is used for the transportation of ions, nutrients, and waste products. It also provides the brain with buoyancy, which "floats" the brain within the skull and prevents damaging contact with the cranial floor.

8.6 Spinal Cord

Learning Objective

12. Describe the structure and function of the spinal cord.

The **spinal cord** is continuous with the brain. It descends from the medulla oblongata through the foramen magnum into the vertebral canal and extends to the second lumbar vertebra. Beyond this point, only the roots of the inferior spinal nerves occupy the vertebral canal.

Structure

The spinal cord is cylindrical in shape. It has two small grooves that extend throughout its length: the wider *anterior median fissure* and the narrower *posterior median sulcus*. These grooves divide the spinal cord into left and right portions. Thirty-one pairs of spinal nerves branch from the spinal cord. The spinal cord is divided into four segments–*cervical, thoracic, lumbar,* and *sacral*–based upon where the spinal nerves exit the vertebral column.

The cross-sectional structure of the spinal cord is shown in figures 8.12 and 8.17. Gray matter, shaped like the outstretched wings of a butterfly, is centrally located

and is surrounded by white matter. The *central canal* extends the length of the spinal cord and contains CSF.

The pointed projections of the gray matter, as seen in cross section, are called horns. The *anterior horns* contain the cell bodies of somatic motor neurons whose axons enter spinal nerves and carry nerve impulses to skeletal muscles. The *posterior horns* contain interneurons that receive nerve impulses from sensory axons in the spinal nerves and carry them to sites within the CNS. *Lateral horns*, found only in the thoracic and lumbar segments of the spinal cord, contain the cell bodies of autonomic motor neurons whose axons follow ANS pathways as they carry nerve impulses to cardiac and smooth muscle, glands, and adipose tissue. Interneurons form most of the gray matter in the CNS.

The horns of the gray matter divide the white matter into three regions: the *anterior*, *posterior*, and *lateral funiculi* (singular, funiculus). These funiculi contain **nerve tracts,** which are bundles of myelinated and unmyelinated axons of interneurons that extend superiorly and inferiorly within the spinal cord.

Functions

The spinal cord has two basic functions. It transmits nerve impulses to and from the brain, and it serves as a reflex center for spinal reflexes. Nerve impulses are transmitted to and from the brain by axons composing the nerve tracts. *Ascending* (sensory) *tracts* carry sensory nerve impulses to the brain; *descending* (motor) *tracts* carry motor nerve impulses from the brain.

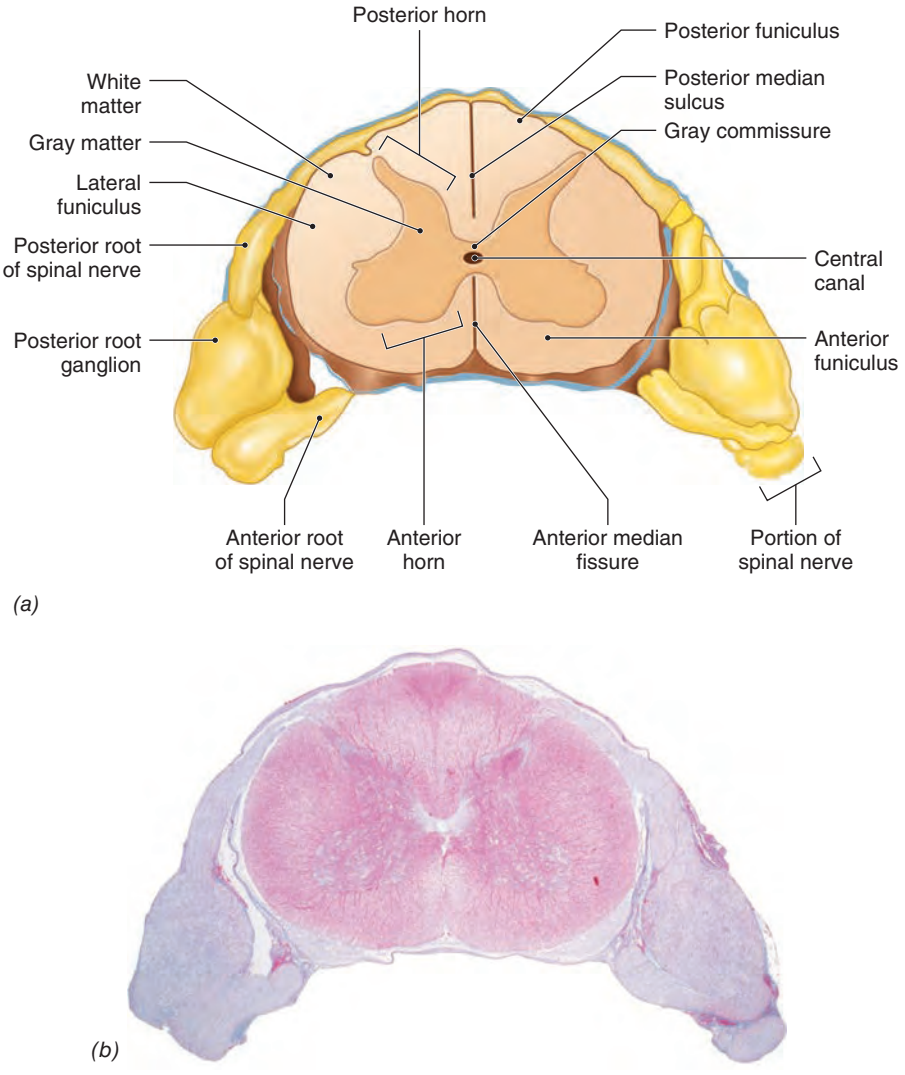


Figure 8.17 A drawing (*a*) and a photomicrograph (*b*) of the spinal cord in cross section show its basic structure.

Clinical Insight

In *hydrocephalus,* a congenital defect restricts the movement of CSF from the ventricles into the subarachnoid space. In severe cases, the buildup of hydrostatic pressure within an infant's brain causes a marked enlargement of the ventricles and brain and widens the fontanelles of the cranium. Without treatment, death usually results within two to three years. Treatment involves surgical insertion of a small tube to drain the excess CSF from a ventricle into the peritoneal cavity, where it is reabsorbed.

Check My Understanding

11. What is the relationship between the ventricles, the meninges, and the cerebrospinal fluid?
12. What are the functions of the spinal cord?

8.7 Peripheral Nervous System (PNS)

Learning Objectives

13. Recall the name, type, and functions for each of the 12 pairs of cranial nerves.
14. Describe the classification of the spinal nerves and the plexuses they form.
15. Explain the functions of the components involved in a reflex.

The *peripheral nervous system (PNS)* consists of cranial and spinal nerves that connect the CNS to other portions of the body, along with sensory receptors and ganglia. A **nerve** consists of axons that are bound together by connective tissue. **Motor nerves** contain mostly axons of motor neurons; **sensory nerves** contain only axons of sensory neurons; and **mixed nerves** contain both motor axons and sensory axons. Most nerves are mixed. Nerves may contain axons of both the somatic nervous system, which is involved with voluntary responses, and the autonomic nervous system, which controls involuntary (automatic) responses.

Cranial Nerves

Twelve pairs of **cranial nerves** arise from the brain and connect the brain with organs and tissues that are primarily located in the head and neck (table 8.3). Most cranial nerves arise from the brainstem. Cranial nerves are identified by both roman numerals and names. The numerals indicate the order in which the nerves arise from the inferior surface of the brain: CN I is most anterior; CN XII is most posterior (figure 8.18).

Five cranial nerves are primarily motor, three are sensory, and four are mixed.

Spinal Nerves

Arising from the spinal cord, there are thirty-one pairs of mixed nerves called **spinal nerves.** Each pair of spinal nerves is named based upon where it exits the vertebral column. The first pair of spinal nerves emerges from the spinal cord between the atlas and the occipital bone. The remaining thirty pairs of spinal nerves emerge through the *intervertebral foramina* between adjacent vertebrae, the *sacral foramina,* and the *sacral hiatus.* There are eight pairs of *cervical nerves* (C1–C8), twelve pairs of *thoracic nerves* (T1–T12), five pairs of *lumbar nerves* (L1–L5), five pairs of *sacral nerves* (S1–S5), and one pair of *coccygeal nerves* (Co) (figure 8.19). Recall from Chapter 6 that there are seven cervical vertebrae. Because the first pair of spinal nerves emerges superior to the atlas, there are eight pairs of cervical nerves instead of seven.

Spinal nerves branch from the spinal cord by two short roots that merge a short distance from the spinal cord to form a spinal nerve. The **anterior root** contains axons of motor neurons whose cell bodies are located within the spinal cord. These neurons carry motor nerve impulses from the spinal cord to effectors. The **posterior root** contains axons of sensory neurons. The swollen region in a posterior root is a **posterior root ganglion,** which contains cell bodies of sensory neurons. The long axons of these neurons carry sensory nerve impulses to the spinal cord. Observe these structures and their relationships in figures 8.12, 8.17, and 8.20.

As shown in figure 8.19, the spinal cord ends at the second lumbar vertebra. The roots of lumbar, sacral, and coccygeal spinal nerves continue inferiorly within the vertebral canal to exit between the appropriate vertebrae. These roots form the *cauda equina,* or horse's tail, in the inferior portion of the vertebral canal.

Spinal Plexuses

After a spinal nerve exits the vertebral canal, it divides into four major parts: the *anterior ramus* (plural, rami), *posterior ramus, meningeal branch,* and *ramus communicans.* The posterior ramus innervates the deep muscles and skin of the posterior trunk. The meningeal branch innervates the vertebrae, meninges, and vertebral ligaments. The ramus communicans passes to the sympathetic chain ganglia and is part of the autonomic system. The anterior rami of many spinal nerves merge to form **spinal plexuses,** networks of nerves, before continuing to the innervated structures. The anterior rami of most thoracic nerves do

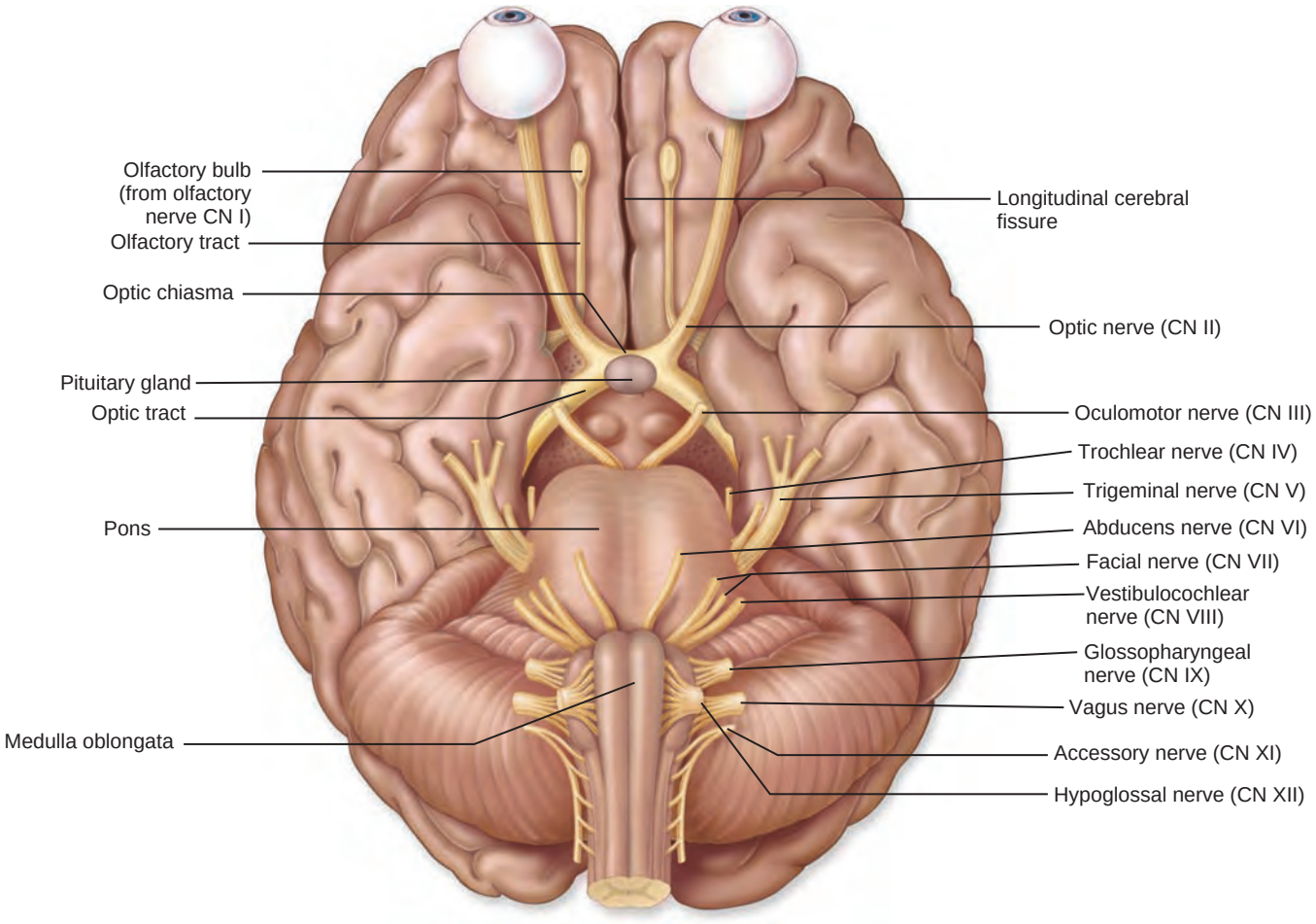


Figure 8.18 Inferior view of the brain showing the roots of the 12 pairs of cranial nerves. Cranial nerves are identified by both roman numerals and names. Most cranial nerves arise from the brainstem.

not form plexuses; rather, they form intercostal nerves. The intercostal nerves innervate the intercostal and abdominal muscles, in addition to overlying skin.

In a plexus, the axons in the anterior rami are sorted and recombined so that axons going to a specific body part are carried in the same peripheral nerve, although they may originate in several different spinal nerves. There are four pairs of plexuses: cervical, brachial, lumbar, and sacral. Because many axons from the lumbar plexus contribute to the sacral plexus, these two plexuses are sometimes called the *lumbosacral plexus* (figure 8.19).

Cervical Plexus The superior cervical nerves merge to form a *cervical plexus* on each side of the neck. The nerves from these plexuses supply the muscles and skin of the neck and portions of the head and shoulders. The paired *phrenic* (fren′-ik) *nerves,* which stimulate the diaphragm to contract and begin inspiration, also arise from the cervical plexus.

Brachial Plexus The inferior cervical nerves and perhaps nerves T1–T2 join to form a *brachial plexus* on each side of the vertebral column in the shoulder region. Nerves that serve skin and muscles of the pectoral girdle and upper limb emerge from the brachial plexuses. The *musculocutaneous, axillary, radial, median,* and *ulnar nerves* arise here.

Lumbar Plexus The last thoracic nerve (T12) and the superior lumbar nerves unite to form a *lumbar plexus* on each side of the vertebral column just superior to the coxal bones. Nerves from the lumbar plexuses supply the skin and muscles of the inferior trunk, external genitalia, and the anterior and medial thighs. The *femoral* and *obturator nerves* arise here.

Sacral Plexus The inferior lumbar nerves and the sacral nerves merge to form a *sacral plexus* on each side of the sacrum within the pelvis. Nerves from the sacral plexuses

Table 8.3 Summary of the Cranial Nerves

Nerve	Type	Function
CN I Olfactory	Sensory	Transmits sensory nerve impulses from olfactory receptors in olfactory epithelium to the brain.
CN II Optic	Sensory	Transmits sensory nerve impulses for vision from the retina of the eye to the brain.
CN III Oculomotor	Motor	Transmits motor nerve impulses to muscles that move the eyes superiorly, inferiorly, and medially; control the eyelids; adjust pupil size; and control the shape of the lens.
CN IV Trochlear	Motor	Transmits motor nerve impulses to muscles that rotate the eyes.
CN V Trigeminal	Mixed	Transmits sensory nerve impulses from scalp, forehead, face, teeth, and gums to the brain. Transmits motor nerve impulses to chewing muscles and muscles in floor of mouth.
CN VI Abducens	Motor	Transmits motor nerve impulses to muscles that move the eyes laterally.
CN VII Facial	Mixed	Transmits sensory nerve impulses from the anterior part of the tongue to the brain. Transmits motor nerve impulses to facial muscles, salivary glands, and tear glands.
CN VIII Vestibulocochlear	Sensory	Transmits sensory nerve impulses from the internal ear associated with hearing and equilibrium.
CN IX Glossopharyngeal	Mixed	Transmits sensory nerve impulses from posterior portion of the tongue, tonsils, pharynx, and carotid arteries to the brain. Transmits motor nerve impulses to salivary glands and pharyngeal muscles used in swallowing.
CN X Vagus	Mixed	Transmits sensory nerve impulses from thoracic and abdominal organs, esophagus, larynx, and pharynx to the brain. Transmits motor nerve impulses to these organs and to muscles of speech and swallowing.
CN XI Accessory	Motor	Transmits motor nerve impulses to muscles of the palate, pharynx, and larynx and to the trapezius and sternocleidomastoid muscles.
CN XII Hypoglossal	Motor	Transmits motor nerve impulses to the muscles of the tongue.

supply the skin and muscles of the buttocks and lower limbs. The *sciatic nerves,* which emerge from the sacral plexuses, are the largest nerves in the body.

Check My Understanding

13. What composes the peripheral nervous system?
14. Identify and describe the functions of the twelve cranial nerves.
15. Name and locate the major spinal plexuses.

Reflexes

Reflexes are rapid, involuntary, and predictable responses to internal and external stimuli. Reflexes maintain homeostasis and enhance chances of survival. A reflex involves either the brain or the spinal cord, a sensory receptor, sensory and motor neurons, and an effector.

Most pathways of nerve impulse transmission within the nervous system are complex and involve many neurons. In contrast, reflexes require few neurons in their pathways and therefore produce very rapid responses to stimuli. Reflex pathways are called **reflex arcs.**

Reflexes are divided into two types–autonomic and somatic–based on the effector(s) involved in the reflex. *Autonomic reflexes* act on smooth muscle, cardiac muscle, adipose tissue, and glands. They are involved in controlling homeostatic processes such as heart rate, blood pressure, and digestion. Autonomic reflexes maintain homeostasis and normal body functions at the unconscious level, which frees the mind to deal with those actions that require conscious decisions. *Somatic reflexes* act on skeletal muscles. They enable quick movements such as moving the hand away from a painful stimulus. A person is usually unaware of autonomic reflexes but is aware of somatic reflexes. Reflexes are also divided into *cranial reflexes* and *spinal reflexes,* depending upon whether the brain or the spinal cord is involved in the reflex.

Figure 8.20 illustrates a somatic spinal reflex, which withdraws the hand after sticking a finger with a tack. Three neurons are involved in this reflex. Pain receptors are stimulated by the sharp pin and form nerve impulses that are carried by a sensory neuron to an interneuron in the spinal cord. Nerve impulses pass along the interneuron to a motor neuron, which carries the nerve impulses to a muscle that contracts to move the hand. Although the brain is not involved in this reflex, it does receive

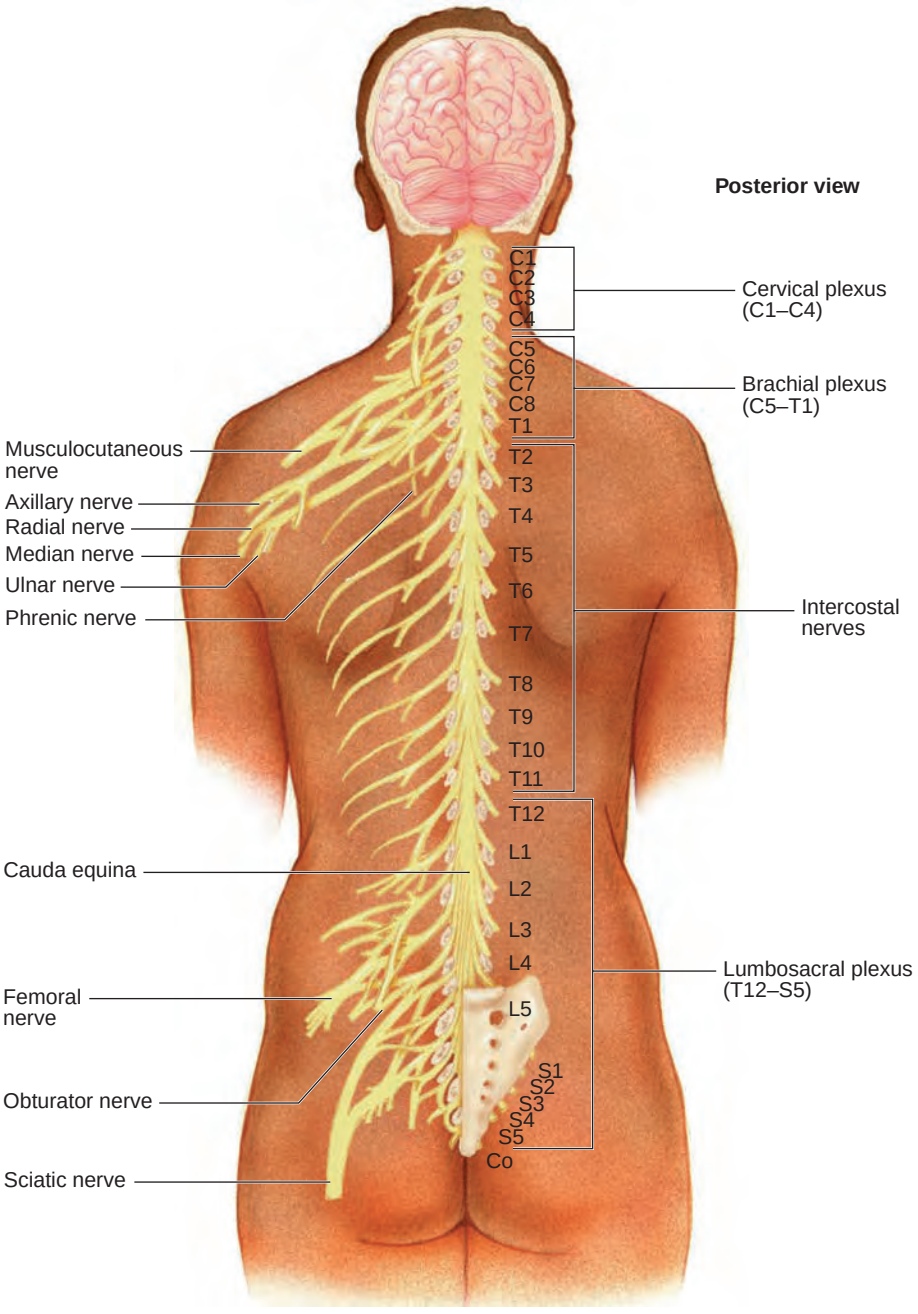


Figure 8.19 Thirty-one pairs of spinal nerves arise from the spinal cord. Anterior rami of spinal nerves in the thoracic region form the intercostal nerves. Those in other segments form nerve networks called spinal plexuses before continuing on to their target tissues.

sensory nerve impulses that make a person aware of a painful stimulus.

Check My Understanding

16. What is a reflex?
17. What are the components of a spinal reflex?

Clinical Insight

Because the responses of reflexes are predictable, physicians usually test a patient's reflexes in order to determine the health of the nervous system. Exaggerated, diminished, or distorted reflexes may indicate a neurological disorder.

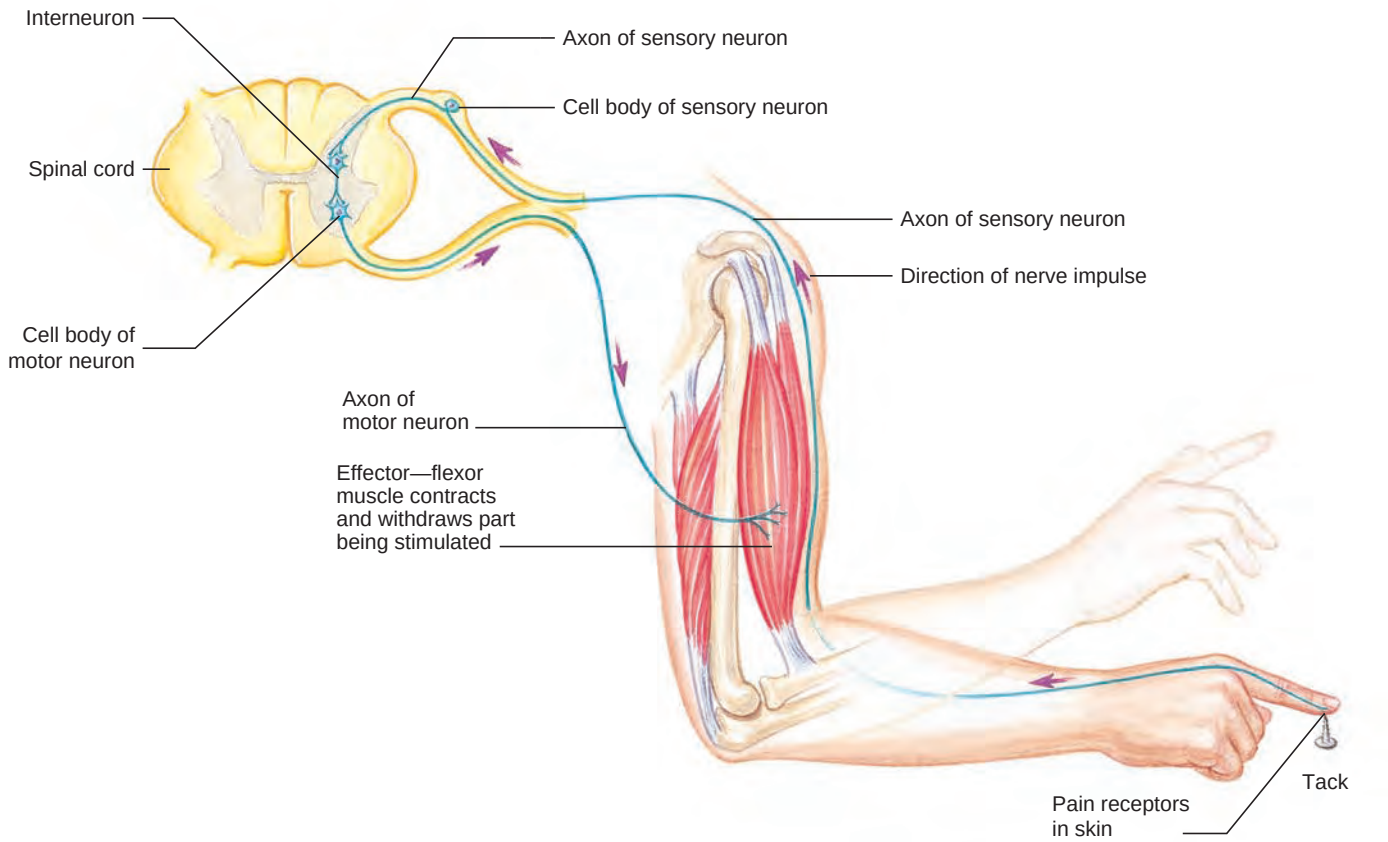


Figure 8.20 A somatic spinal reflex involving a sensory neuron, an interneuron, and a motor neuron.

Clinical Insight

Because the spinal cord ends at the level of the second lumbar vertebra, spinal taps and epidural anesthetics are administered inferior to this point. For these procedures, a patient is placed in a fetal position in order to open the spaces between the posterior margins of the vertebrae. A hypodermic needle is inserted into the vertebral canal either between the third and fourth lumbar vertebrae or between the fourth and fifth lumbar vertebrae. In a *spinal tap* (lumbar puncture), a hypodermic needle is inserted into the subarachnoid space to remove cerebrospinal fluid for diagnostic purposes. An *epidural anesthetic* is given by injecting an anesthetic into the epidural space with a hypodermic syringe. The anesthetic prevents sensory nerve impulses from reaching the spinal cord via posterior roots inferior to the injection. Epidurals are sometimes used to ease pain during childbirth.

8.8 Autonomic Nervous System (ANS)

Learning Objective

16. Compare the structure and functions of the sympathetic and parasympathetic divisions.

The **autonomic** (aw-to-nom′-ik) **nervous system (ANS)** consists of portions of the central and peripheral nervous systems and functions without conscious control. Its role is to maintain homeostasis in response to changing internal conditions. The effectors under autonomic control are cardiac muscle, smooth muscle, adipose tissue, and glands. The ANS functions mostly by involuntary reflexes. Visceral sensory nerve impulses carried to the autonomic reflex centers in the hypothalamus, brainstem, or spinal cord cause visceral motor nerve impulses to be carried to effectors via cranial or spinal nerves. Higher brain centers, such as the limbic system and cerebral cortex, influence the ANS during times of emotional stress.

Table 8.4 compares the somatic and autonomic nervous systems.

Table 8.4 Comparison of Somatic and Autonomic Nervous Systems

	Somatic	Autonomic
Control	Voluntary	Involuntary
Neural Pathway	One motor neuron extends an axon from the CNS to an effector	A preganglionic neuron extends an axon from the CNS to an autonomic ganglion and synapses with a postganglionic neuron that extends an axon to an effector
Neurotransmitters	Acetylcholine	Acetylcholine or norepinephrine
Effectors	Skeletal muscles	Smooth muscle, cardiac muscle, adipose tissue, and glands
Action	Excitatory	Excitatory or inhibitory

Organization

Unlike the somatic nervous system, in which a single motor neuron extends from the CNS to a skeletal muscle, the ANS uses two motor neurons in sequence to carry motor nerve impulses to an effector. The cell body of the first neuron, or *preganglionic neuron,* is located within the brain or spinal cord. It extends an axon from the CNS to an **autonomic ganglion.** The cell body of the second neuron, or *postganglionic neuron,* is located within the autonomic ganglion and it extends an axon from the ganglion to the visceral effector (figure 8.21).

The autonomic nervous system is subdivided into the **sympathetic division** and the **parasympathetic division.** The origin of their motor neurons and the organs innervated are shown in figure 8.22.

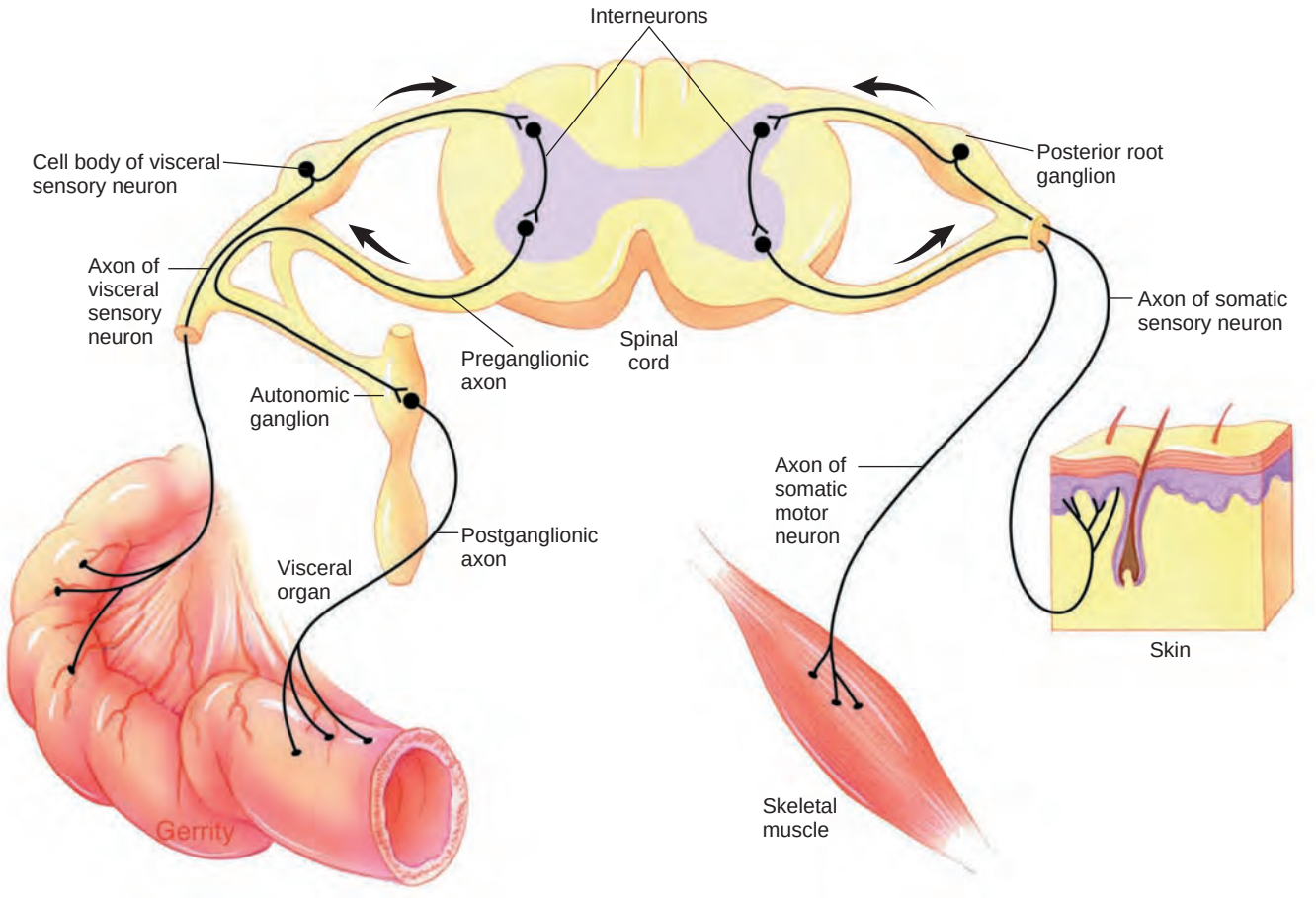


Figure 8.21 Comparison of autonomic and somatic motor pathways in spinal nerves. (*a*) An autonomic pathway involves a preganglionic neuron and a postganglionic neuron that synapse at a ganglion external to the CNS. (*b*) A somatic pathway involves a single motor neuron.

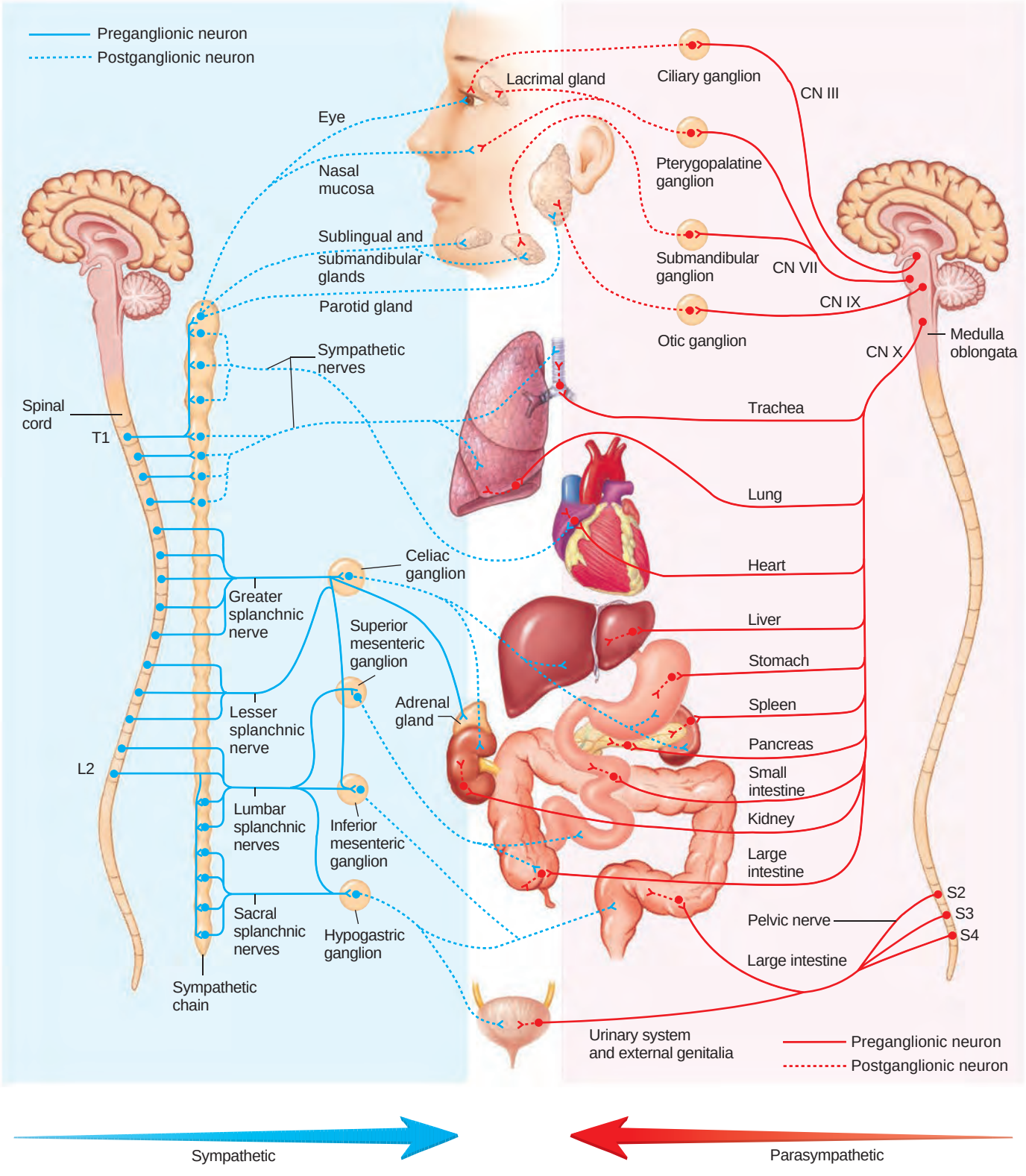


Figure 8.22 Innervation of visceral organs by the autonomic nervous system.

Preganglionic axons of the sympathetic division arise from the thoracic and lumbar segments of the spinal cord–spinal nerves T1–L2. Some preganglionic sympathetic axons branch from the spinal nerves to synapse with postganglionic neurons in autonomic ganglia that are arranged in two chains, one on each side of the vertebral column. These ganglia are called *paravertebral* or *sympathetic chain ganglia*. Other sympathetic preganglionic axons pass through a paravertebral chain ganglion without synapsing and extend to another type of ganglion, a *collateral ganglion*, before synapsing with a postganglionic neuron. Both pathways are shown in figure 8.22.

Preganglionic axons of the parasympathetic division arise from the brainstem and sacral segment (S2–S4) of the spinal cord. They extend through cranial or sacral nerves to synapse with postganglionic neurons within ganglia that are located very near or within visceral organs (figure 8.22).

Most visceral organs receive postganglionic axons of both the sympathetic and the parasympathetic divisions; but a few, such as sweat glands and most blood vessels, receive only sympathetic axons.

Autonomic Neurotransmitters

Preganglionic axons of both the sympathetic and the parasympathetic divisions secrete *acetylcholine* to initiate nerve impulses in postganglionic neurons, but their postganglionic axons secrete different neurotransmitters. Most sympathetic postganglionic axons secrete norepinephrine, a substance similar to adrenaline, which is why they are called *adrenergic axons*. Parasympathetic postganglionic axons secrete acetylcholine and thus are called *cholinergic axons* (figure 8.23).

Functions

Both sympathetic and parasympathetic divisions stimulate some visceral organs and inhibit others. However, their effects on a given organ are opposite. For example, the sympathetic division increases heart rate whereas the parasympathetic division decreases heart rate. The contrasting effects are due to the different neurotransmitters secreted by postganglionic sympathetic and parasympathetic axons and the receptors of the receiving organs.

The sympathetic division prepares the body for physical action to meet emergencies. Its actions have been summarized as preparing the body for *fight or flight*. The parasympathetic division is dominant under the normal, nonstressful conditions of everyday life. Because its actions are usually opposite those of the sympathetic division, it is often viewed as preparing the body for *resting and digesting*. Table 8.5 compares some of the effects of the sympathetic and parasympathetic divisions on visceral organs.

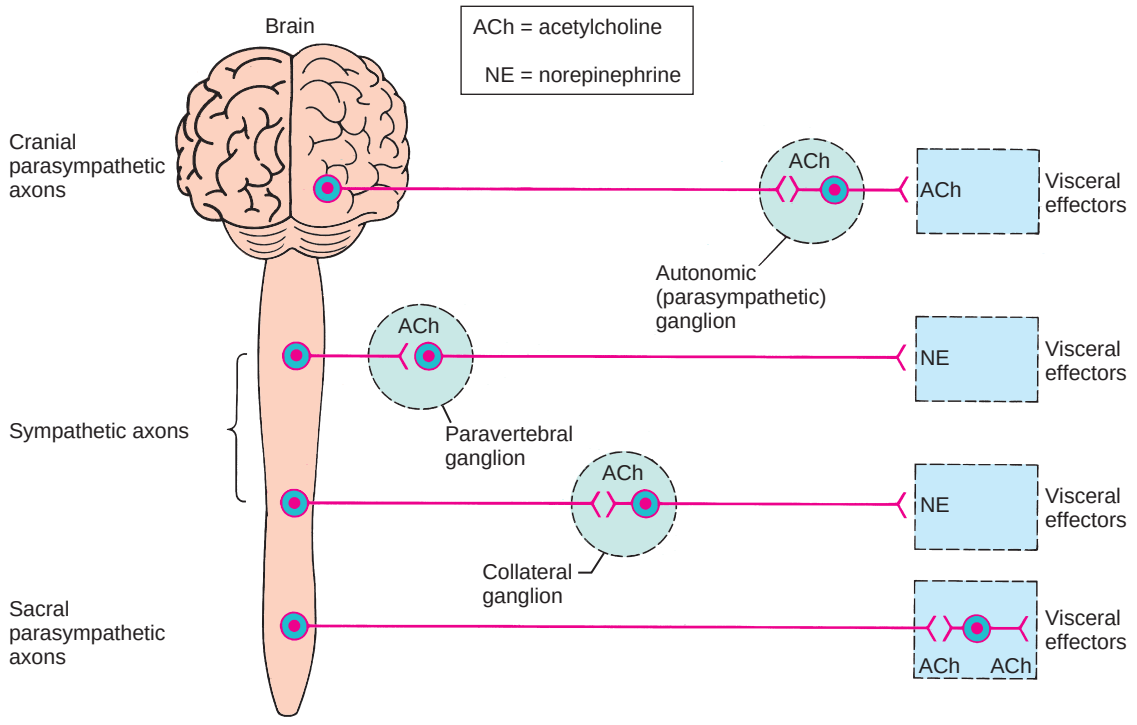


Figure 8.23 Comparison of Neurotransmitters Used in the Autonomic Nervous System.

Table 8.5 Representative Actions of the Autonomic Nervous System

Effector	Sympathetic Stimulation	Parasympathetic Stimulation
Eye	Dilation of pupil; changes lens shape for far vision	Constriction of pupil; changes lens shape for near vision
Heart	Increases rate and strength of contraction	Decreases rate of contraction
Arterioles	Constriction increases blood pressure	No innervation
Blood distribution	Increases supply to skeletal muscles; decreases supply to digestive organs	Decreases supply to skeletal muscles; increases supply to digestive organs
Lungs	Dilates bronchioles	Constricts bronchioles
Digestive tract	Inhibits motility and secretion by glands	Promotes motility and secretion by glands
Liver	Decreases bile production; increases blood glucose	Increases bile production; decreases blood glucose
Gallbladder	Relaxation	Contraction
Kidneys	Decreases urine production	No known action
Pancreas	Decreases secretion of insulin and digestive enzymes	Increases secretion of insulin and digestive enzymes
Spleen	Constriction injects stored blood into circulation	No known action
Urinary bladder	Contraction of external urethral sphincter; relaxation of bladder wall	Relaxation of external urethral sphincter; contraction of bladder wall
Reproductive organs	Vasoconstriction; ejaculation in males; reverse uterine contractions in females; stimulates uterine contractions in labor	Vasodilation; erection in males; vaginal secretion in females

Clinical Insight

Cocaine exerts major effects on the autonomic nervous system. It not only stimulates the sympathetic division but also inhibits the parasympathetic division. In an overdose, this double-barreled action produces an erratic, uncontrollable heartbeat that may result in sudden death.

Check My Understanding

18. How do the somatic and autonomic nervous systems differ in terms of structure?
19. How does the autonomic nervous system maintain homeostasis?

8.9 Disorders of the Nervous System

Learning Objective

17. Describe the common disorders of the nervous system.

Inflammatory Disorders

Meningitis (men-in-jī′-tis) results from a bacterial, fungal, or viral infection of the meninges. Bacterial meningitis cases are the most serious, with about 20% being fatal. If the brain is also involved, the disease is called *encephalitis*. Some viruses causing encephalitis are transmitted by bites of certain mosquitoes.

Neuritis is the inflammation of a nerve or nerves. It may be caused by several factors, such as infection, compression, or trauma. Associated pain may be moderate or severe.

Sciatica (sī-at′-i-kah) is neuritis involving the sciatic nerve. The pain may be severe and often radiates inferiorly through the thigh and leg to the sole of the foot.

Shingles is an infection of one or more nerves. It is caused by the reactivation of the chicken pox virus, which, until that time, has been dormant in the nerve roots. The virus causes painful blisters on the skin at the sensory nerve endings, followed by prolonged pain (figure 8.24*a*).

Noninflammatory Disorders

Alzheimer (alts′-hī-mer) **disease (AD)** is a progressively disabling disease affecting older persons. It is associated with a loss of certain cholinergic neurons in the brain and a reduced ability of neurons to secrete acetylcholine. AD is characterized by a progressive loss of memory, disorientation, and mood swings (figure 8.24*b*).

Cerebral palsy (ser-ē′-bral pawl-zē) is characterized by partial paralysis and sometimes a degree of mental retardation. It may result from damage to the brain during prenatal development, often from viral infections caused by German measles or from trauma during delivery.

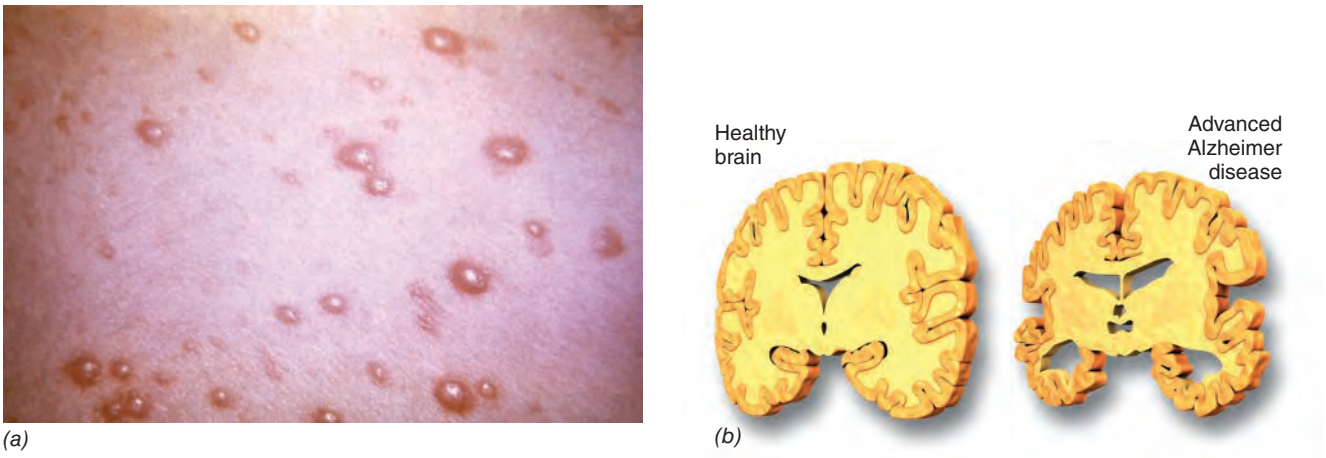


Figure 8.24 Nervous System Disorders. *(a)* Shingles. *(b)* Alzheimer disease.

Cerebrovascular accidents (CVAs) are disorders of blood vessels serving the brain. They result from blood clots, aneurysms (an′-ū-rizms), or hemorrhage. Often called *strokes*, CVAs cause severe damage to the brain due to the loss of oxygen. Response time is crucial after the CVA in order to limit the amount of neural damage. They are a major cause of disability and the third highest cause of death in the United States.

Comas are states of unconsciousness in which the patient cannot be aroused even with vigorous stimulation. Illness or trauma to the brain may alter the functioning of the reticular formation, resulting in a coma.

Concussion results from a severe jarring of the brain caused by a blow to the head. Unconsciousness, confusion, and amnesia may result in severe cases.

Dyslexia (dis-lek′-sē -ah) causes the afflicted person to reverse letters or syllables in words and words within sentences. It results from malfunctioning of the language center of the cerebrum.

Epilepsy (ep′-i-lep″-sē) may have a hereditary basis, or it may be triggered by injuries, infections, or tumors. There are two types of epilepsy. *Grand mal epilepsy* is the more serious form and is characterized by convulsive seizures. *Petit mal epilepsy* is the less serious form and is characterized by momentary loss of contact with reality without unconsciousness or convulsions.

Fainting is a brief loss of consciousness due to a sudden reduction in blood supply to the brain. It may result from either physical or psychological causes.

Headaches are triggered by various physical or psychological factors, but often result from a dilation of blood vessels within the meninges of the brain. Migraine headaches may have visual or digestive side effects and may be triggered by stress, allergies, or fatigue. Sinus headaches may result from inflammation that causes increased pressure within the paranasal sinuses. Some headaches result from tension in muscles of the head and neck.

Mental illnesses may be broadly categorized as either neuroses or psychoses. *Neuroses* are mild maladjustments to life situations that may produce anxiety and interfere with normal behavior. *Psychoses* are serious mental disorders that sometimes cause delusions, hallucinations, or withdrawal from reality.

Multiple sclerosis (MS) is a progressive degeneration of the myelin sheath around axons in the CNS, accompanied by the formation of plaques of scar tissue called *scleroses*. This destruction results in a short-circuiting of neural pathways and an impairment of motor functions.

Neuralgia (nū-ral′-jē-ah) is pain arising from a nerve regardless of the cause of the pain.

Paralysis is the permanent loss of motor control of body parts. It most commonly results from accidental injury to the CNS.

Parkinson disease is caused by an insufficient delivery of the neurotransmitter *dopamine* to neurons in certain nuclei within the cerebrum. It produces tremors and impairs normal skeletal muscle contractions. Parkinson disease is more common among older persons.

Chapter Summary

8.1 Divisions of the Nervous System

- Anatomical divisions are the central nervous system (CNS), composed of the brain and spinal cord, and the peripheral nervous system (PNS), composed of cranial and spinal nerves, ganglia, and sensory receptors.
- Functional divisions are the sensory and motor divisions. The motor division is subdivided into the somatic nervous system (SNS), which is involved in voluntary actions, and the autonomic nervous system (ANS), which is involved in involuntary responses.

8.2 Nervous Tissue

- Nervous tissue consists of neurons and neuroglia.
- A neuron is composed of a cell body, which contains the nucleus; one or more dendrites that conduct impulses toward the cell body or axon; and one axon that conducts nerve impulses away from the cell body or dendrites.
- Myelinated axons are covered by a myelin sheath. Schwann cells form the myelin sheath and neurilemma of peripheral myelinated axons. Oligodendrocytes form the myelin sheath of myelinated axons in the CNS; these axons lack a neurilemma.
- There are three structural types of neurons: multipolar, bipolar, and unipolar.
- There are three functional types of neurons. Sensory neurons carry nerve impulses toward the CNS. Interneurons carry nerve impulses within the CNS. Motor neurons carry nerve impulses from the CNS.
- Schwann cells are neuroglia in the PNS. Four types of neuroglia occur in the CNS: oligodendrocytes, astrocytes, microglial cells, and ependymal cells.

8.3 Neuron Physiology

- Neurons are specialized to form and conduct nerve impulses.
- The plasma membrane of a resting neuron is polarized with an excess of positive charges on the ECF-side and negative charges on the cytosol-side. This difference creates a voltage called the resting membrane potential.
- When a threshold stimulus is applied, the neuron plasma membrane becomes permeable to sodium ions (Na^+), which quickly move into the neuron and cause depolarization of the membrane. This depolarization is the formation of a nerve impulse.
- The depolarized portion of the plasma membrane causes the depolarization of adjacent portions so that a depolarization wave flows along the axon.
- Depolarization makes the neuron plasma membrane permeable to potassium ions (K^+), allowing them to quickly diffuse into the ECF and repolarize the plasma membrane.
- In neuron-to-neuron synaptic transmission, the terminal bouton secretes a neurotransmitter into the synaptic cleft. The neurotransmitter binds to receptors on the postsynaptic neuron, causing either the formation of a nerve impulse or the inhibition of nerve impulse formation. Then, the neurotransmitter is quickly removed by reabsorption into the terminal bouton, an enzymatic reaction or diffusion out of the cleft.
- The most common peripheral neurotransmitters are acetylcholine and norepinephrine. Some neurotransmitters are excitatory, while others are inhibitory.

8.4 Protection for the Central Nervous System

- The brain is encased by the cranial bones, and the spinal cord is surrounded by vertebrae.
- Both the brain and the spinal cord are covered by the meninges: the pia mater, arachnoid mater, and dura mater.
- Cerebrospinal fluid in the subarachnoid space provides buoyancy and serves as a fluid shock absorber surrounding the brain and spinal cord.

8.5 Brain

- The brain consists of the cerebrum, diencephalon, brainstem, and cerebellum.
- The cerebrum consists of two cerebral hemispheres joined by the corpus callosum. Gyri and sulci increase the surface area of the cerebral cortex. Each hemisphere is subdivided into five lobes: frontal, parietal, temporal, occipital, and insula.
- The cerebrum interprets sensations; initiates voluntary motor responses; and is involved in will, personality traits, and intellectual processes. The left cerebral hemisphere is dominant in most people.
- Sensory areas occur in the parietal, temporal, and occipital lobes. Motor areas occur in the frontal lobe. Association areas occur in all lobes of the cerebrum.
- The diencephalon consists of the thalamus, the hypothalamus, and the epithalamus.
- The thalamus is formed of two lateral masses connected by the interthalamic adhesion. It is a relay station for sensory and motor nerve impulses going to and from the cerebrum and provides an uncritical awareness of sensations.
- The hypothalamus is located inferior to the thalamus and forms the floor of the third ventricle. It is a major integration center for the autonomic nervous system. It also regulates several homeostatic processes such as body temperature, mineral and water balance, appetite, digestive processes, and secretion of pituitary gland hormones.

- The epithalamus possesses the pineal gland, which produces the hormone melatonin. Melatonin induces sleepiness in the evenings.
- The limbic system is associated with emotional behavior, memory, and motivation.
- The brainstem consists of the midbrain, pons, and medulla oblongata. Ascending and descending axons between higher brain centers and the spinal cord pass through the brainstem.
- The midbrain is a small, superior portion of the brainstem. It contains reflex centers for movements associated with visual and auditory stimuli.
- The pons is the middle portion of the brainstem. It works with the medulla oblongata to control breathing.
- The medulla oblongata is the most inferior portion of the brainstem and is continuous with the spinal cord. It contains reflexive integration centers that control breathing, heart rate and force of contraction, and blood pressure.
- The reticular formation consists of nuclei and axons that extend from the superior spinal cord and into the diencephalon. It is involved with wakefulness.
- The cerebellum lies posterior to the fourth ventricle. It is composed of two hemispheres separated by the vermis and coordinates skeletal muscle contractions.
- The ventricles of the brain, the central canal of the spinal cord, and the subarachnoid space around the brain and spinal cord are filled with cerebrospinal fluid. Cerebrospinal fluid is secreted by a choroid plexus in each ventricle.
- Cerebrospinal fluid is absorbed into blood of the dural venous sinus in the dura mater.

8.6 Spinal Cord

- The spinal cord extends from the medulla oblongata inferiorly through the vertebral canal to the second lumbar vertebra.
- Gray matter is located internally and is surrounded by white matter. Anterior horns of gray matter contain cell bodies of somatic motor neurons; posterior horns contain interneuron cell bodies that receive incoming sensory nerve impulses; lateral horns contain cell bodies of autonomic motor neurons. White matter contains ascending and descending tracts of myelinated and unmyelinated axons.
- The spinal cord serves as a reflex center and conducting pathway for nerve impulses between the brain and spinal nerves.

8.7 Peripheral Nervous System (PNS)

- The PNS consists of cranial and spinal nerves, in addition to sensory receptors and ganglia. Most nerves are mixed nerves; a few cranial nerves are motor or sensory only. A nerve contains bundles of axons supported by connective tissue.
- The 12 pairs of cranial nerves are identified by roman numeral and name. The 31 pairs of spinal nerves are divided into 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal nerve.
- Anterior rami of many spinal nerves form spinal plexuses where axons are sorted and recombined so that all axons to a particular organ are carried in the same nerve. The four pairs of spinal plexuses are cervical, brachial, lumbar, and sacral plexuses.
- Reflexes are rapid, involuntary, and predictable responses to internal and external stimuli.
- Autonomic reflexes involve smooth muscle, cardiac muscle, adipose tissue, and glands. Somatic reflexes involve skeletal muscles.
- Cranial reflexes involve the brain, while spinal reflexes involve the spinal cord.

8.8 Autonomic Nervous System (ANS)

- The ANS involves portions of the central and peripheral nervous systems that are involved in involuntary maintenance of homeostasis.
- Two ANS motor neurons are used to activate an effector. The axon of the preganglionic neuron arises from the CNS and ends in an autonomic ganglion, where it synapses with a postganglionic neuron. The axon of the postganglionic neuron extends from the ganglion to an effector.
- The ANS is divided into two subdivisions that generally have antagonistic effects. Nerves of the sympathetic division arise from the thoracic and lumbar segments of the spinal cord and prepare the body to meet emergencies. Nerves of the parasympathetic division arise from the brain and the sacral segment of the spinal cord and function mainly in nonstressful situations.

8.9 Disorders of the Nervous System

- Disorders may result from infectious diseases, degeneration from unknown causes, malfunctions, and physical injury.
- Inflammatory neurological disorders include meningitis, neuritis, sciatica, and shingles.
- Noninflammatory neurological disorders include Alzheimer disease, cerebral palsy, CVAs, comas, concussion, dyslexia, epilepsy, fainting, headaches, mental illness, multiple sclerosis, neuralgia, paralysis, and Parkinson disease.

Self-Review

Answers are located in appendix B.

1. Nerve impulses are carried away from the cell body of a neuron by the _____ of the neuron.
2. Neurons that conduct nerve impulses from place to place within the CNS are _____.
3. A nerve impulse is formed by the sudden flow of _____ ions across the plasma membrane into a neuron.
4. Synaptic transmission is dependent upon the secretion of a _____ by an axon's terminal bouton.
5. The _____ is the only lobe of the cerebrum that cannot be seen superficially.
6. Voluntary muscle contractions are controlled by the _____ lobe of the cerebrum.
7. The _____ area of the cerebrum is involved with decision making, conscience, and personality.
8. The _____, a component of the diencephalon, regulates appetite, water balance, and body temperature.
9. The _____, a component of the brainstem, regulates heart and breathing rates.
10. Coordination of body movements is a function of the _____.
11. Cerebrospinal fluid fills the ventricles of the brain and the _____ space of the meninges.
12. The _____ horns of the spinal cord receive incoming sensory nerve impulses.
13. The _____ roots of spinal nerves consist of axons of somatic motor neurons.
14. The _____ nervous system is involved in involuntary responses that maintain homeostasis.
15. The _____ division prepares the body for physical responses to emergencies.

Critical Thinking

1. Predict the cognitive changes that will occur following physical trauma to the anterior portion of the frontal lobe.
2. Explain why damage to the medulla oblongata is life-threatening.
3. Explain the effect of an abnormally high level of potassium ions in the ECF on the ability of a neuron to create a nerve impulse.
4. If you touch a hot stove, a reflexive withdrawal of your hand is triggered at about the same time that you feel the pain. Describe the roles of the PNS and CNS in your response and sensation.
5. Explain how the ANS can both increase and decrease heart rate.

7
CHAPTER

Endocrine System

Katherine, an endocrinologist in Los Angeles, has just finished with her last patient of the day and is headed off to her daily yoga class. An endocrinologist is a doctor who specializes in treating patients with hormonal imbalances. As she drives through traffic, she finds it amusing that the practice of yoga is a good metaphor for the endocrine system. That must be why she enjoys it so much. The ability to successfully maintain and change yoga positions requires focused control and coordination over muscle contraction and relaxation throughout every area of the body. If balance is lost at any time, the yoga position is lost and the person will fall, even possibly become injured. The endocrine system functions in a similar fashion to maintain the body's homeostasis. Many glands work in concert, releasing hormones in precise amounts and with perfect timing, to maintain the health and balance of a human being. If even one of those hormones is produced incorrectly, the entire body can be thrust out of balance. Loss of balance within the body can be debilitating, which is why Katherine knows her medical practice provides such a valuable service.

CHAPTER OUTLINE

JFII

SELECTED KEY TERMS

Endocrine gland (endo = within; crin = secrete) A ductless gland whose secretions diffuse into the blood for distribution.
Gene expression The use of DNA to promote protein synthesis.
Hormone (hormon = to set in motion) A chemical messenger secreted by an endocrine gland.
Hypersecretion (hyper = above) Production of an excessive amount of a secretion.
Hyposecretion (hypo = below) Production of an insufficient amount of secretion.
Negative-feedback mechanism A mechanism that returns a condition to its healthy state, thereby maintaining homeostasis.
Paracrine signal (para = near) Local chemical signal that affects targets cells within the same tissue from which it is produced.
Positive-feedback mechanism A mechanism that amplifies a condition and moves it away from homeostasis.
Prostaglandin A class of chemicals that produce a response in nearby cells.
Second messenger An intracellular substance, activated by a nonsteroid hormone, that produces the specific cellular effect associated with the hormone.
Target cell A cell whose functions are affected by a specific hormone.

TWO INTERRELATED REGULATORY SYSTEMS coordinate body functions and maintain homeostasis: the nervous system and the *endocrine* (en′-do-krin) *system*. Unlike the almost instantaneous coordination by the nervous system, the endocrine system provides slower but longer-lasting coordination. The endocrine system consists of cells, tissues, and organs, collectively called **endocrine glands,** that secrete **hormones** (chemical messengers) into the interstitial fluid. The hormones then pass into the blood for transport to other tissues and organs, where they alter cellular functions (figure 10.1). In contrast, exocrine gland secretions are carried from the gland by a duct (tube) to an internal or external surface.

10.1 The Chemical Nature of Hormones

Learning Objectives

1. Distinguish between endocrine and exocrine glands.
2. Distinguish between neurotransmitters, paracrine signals, and hormones.
3. Explain the three negative-feedback mechanisms that control hormone secretion.
4. Compare the mechanisms of action of steroid and nonsteroid hormones.

There are various modes of communication utilized within the human body (figure 10.2). Neural communication, which was described in chapter 8, uses the release of neurotransmitters at a synapse to transmit a signal from a neuron to another cell. Paracrine communication involves the release of **paracrine signals,** also referred to as "local hormones." Paracrine signals are released within a tissue and are used to affect the function of neighboring cells within that tissue.

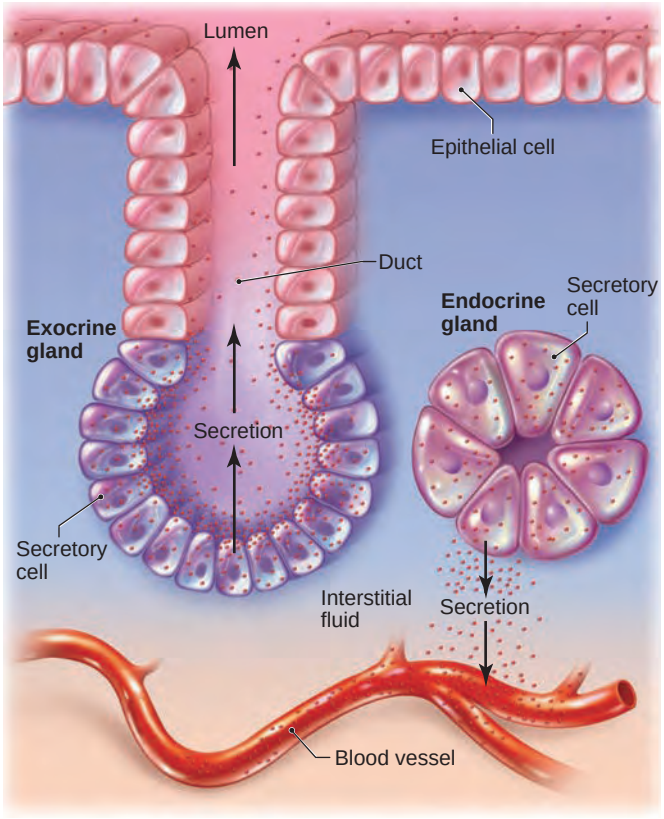


Figure 10.1 Exocrine gland and endocrine gland compared.

Endocrine communication involves the release of hormones into the blood for distribution throughout the body. Because hormones are transported within the blood supply, virtually all body cells are exposed to them. However, a hormone will create a response only in its **target cells,**

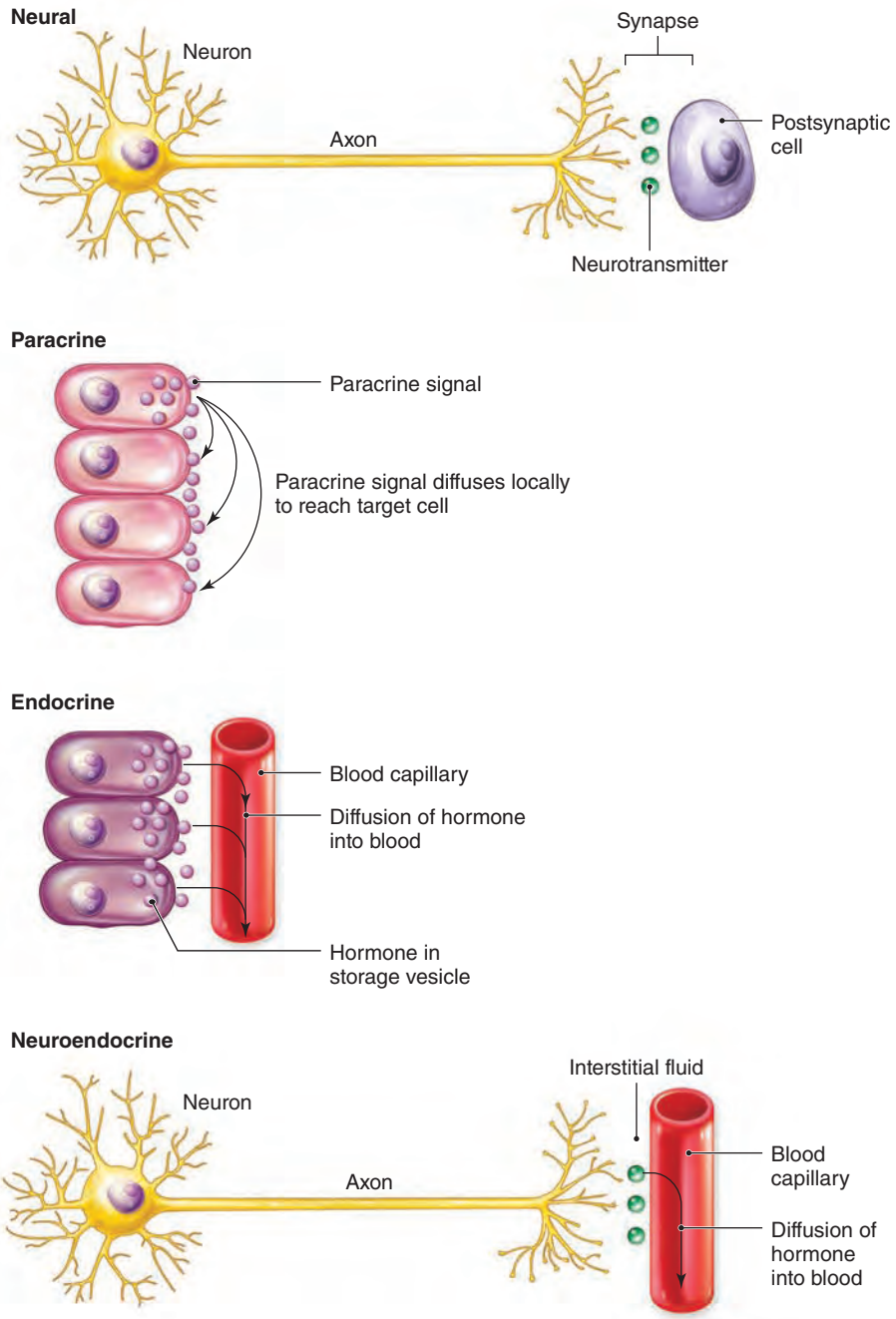


Figure 10.2 Comparison of modes of communication in the human body.

which are cells that possess receptors specific for that hormone. Non-target cells lack these hormone-specific receptors and are unaffected by the hormone. Neuroendocrine communication is a hybrid mechanism in which a neuron releases a hormone that enters a blood vessel. The majority of this chapter focuses on the role of endocrine and neuroendocrine communication in homeostasis.

Hormones are secreted in very small amounts, so their concentrations in the blood are extremely low. However, because they act on cells that have specific receptors for particular hormones, large quantities are not necessary to produce effects. Chemically, hormones may be classified in two broad groups: **steroids,** which are derived from cholesterol, and **nonsteroids,** which are derived from amino acids, peptides, or proteins.

Eicosanoids (i-ko′-sa-noyds) are another group of molecules secreted by cells that cause specific actions in other cells. These lipid molecules act as paracrine signals because they are released into the interstitial fluid and typically affect only nearby cells. Prostaglandins and

Clinical Insight

Aspirin and acetaminophen are widely used pain relievers. They function by inhibiting the synthesis of prostaglandins involved in the inflammatory response, which often is the basis of pain and fever.

leukotrienes are examples. **Prostaglandins** produce a variety of effects ranging from promoting inflammation and blood clotting to increasing uterine contraction in childbirth and raising blood pressure. **Leukotrienes** help regulate the immune response and promote inflammation and some allergic reactions.

Mechanisms of Hormone Action

A hormone produces its effect by binding to a target cell's receptors for that hormone. The more receptors it binds to, the greater is the effect on the target cell. All hormones affect target cells by altering their metabolic activities. For example, they may change the rate of cellular processes in general, or they may promote or inhibit specific cellular processes. The end result is that homeostasis is maintained. Figure 10.3 shows the major endocrine glands.

Steroid and Thyroid Hormones

Steroid hormones and thyroid hormones act on DNA in a cell's nucleus and affect **gene expression** (figure 10.4). (1) Because they are lipid-soluble (see chapter 3), they can easily move through the phospholipid bilayers of plasma membranes to (2) enter the nucleus. (3) After a hormone enters the nucleus, it combines with an intracellular receptor to form a hormone-receptor complex. (4) The hormone-receptor complex interacts with DNA, activating specific genes that synthesize messenger RNA (mRNA). (5) The mRNA exits the nucleus and interacts with ribosomes, which results in the synthesis of specific proteins, usually enzymes. Then the newly formed proteins produce the specific effect that is characteristic of the particular hormone.

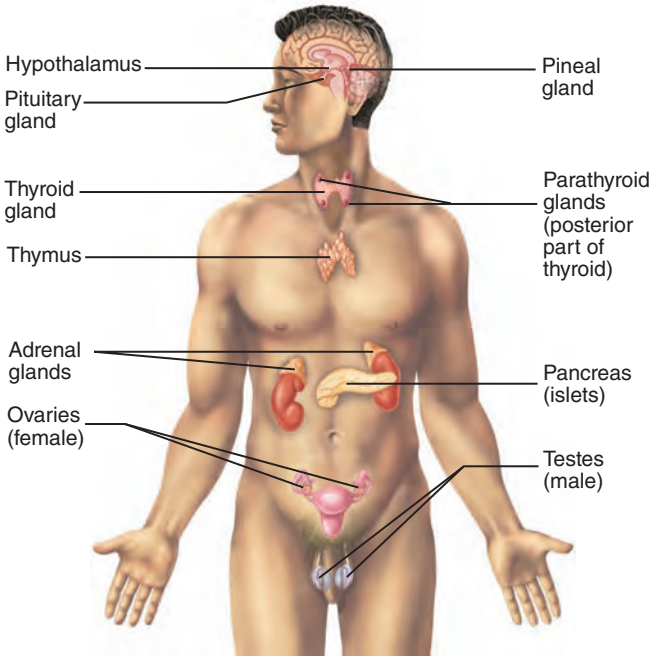


Figure 10.3 The major endocrine glands.

Nonsteroid Hormones

Nonsteroid hormones are proteins, peptides, or modified amino acids that are not lipid-soluble, meaning they cannot pass across the phospholipid bilayer. Two messengers are required for these hormones to produce their effect on a target cell. The *first messenger* is the nonsteroid hormone bound to a receptor on the plasma membrane. The first messenger leads to the formation of a *second messenger* that is often, but not always, *cyclic adenosine monophosphate (cAMP).* The **second messenger** is formed within the cell, and it activates or inactivates enzymes that produce the characteristic effect for the hormone (figure 10.4). When a cAMP is the second messenger, the sequence of events is as follows.

(1) A nonsteroid hormone binds to a receptor on the target cell's plasma membrane to (2) form a hormone-receptor complex. (3) This complex activates a membrane protein (G protein), which, in turn, activates a membrane enzyme (adenylate cyclase), (4) which catalyzes the formation of cyclic adenosine monophosphate (cAMP) from ATP within the cytosol. (5) The cAMP activates enzymes that catalyze the activation or inactivation of cellular enzymes, which produce the cellular changes associated with the specific hormone.

Control of Hormone Production

Most hormone secretion is usually regulated by a **negative-feedback mechanism** that works to maintain homeostasis. When the blood concentration of a regulated substance begins to decrease, the endocrine gland is stimulated to increase the secretion of its hormone. The increased hormone concentration stimulates target cells to raise the blood level of the substance back to normal. When the substance returns to normal levels, the endocrine gland is no longer stimulated to secrete the hormone, and the secretion and concentration of the hormone decrease. Negative feedback keeps hormone levels in the blood relatively stable (figure 10.5). However, there are a few body processes that are hormonally regulated through **positive-feedback mechanisms**. An example that you will see later in this chapter and in chapter 18 is the production of oxytocin during labor and delivery.

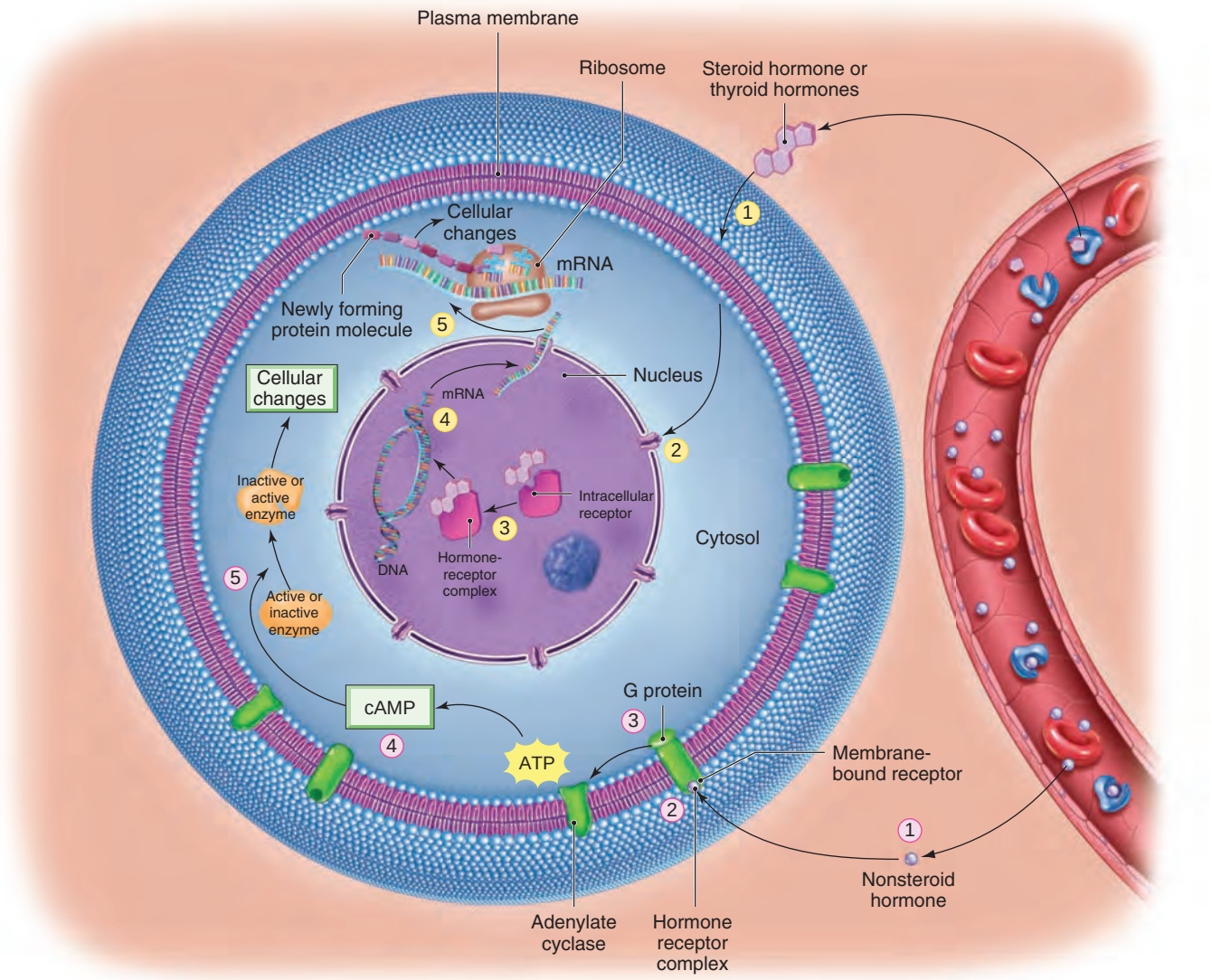


Figure 10.4 Comparison of mechanisms of hormone action. Mechanisms are numbered to match descriptions within text.

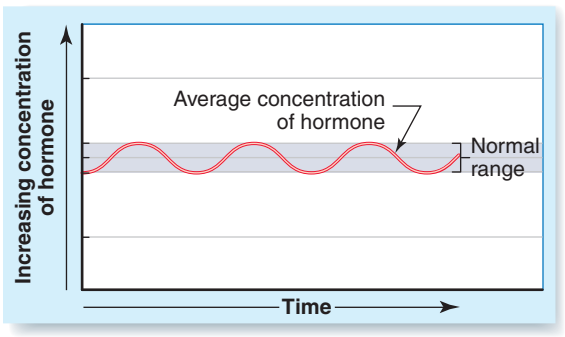


Figure 10.5 Negative-feedback mechanism controls the concentration of a hormone in the blood. The concentration may fluctuate slightly above and below the hormone's average concentration.

As shown in figure 10.6, endocrine glands are controlled by these negative-feedback mechanisms in three ways. (1) In *hormonal control* (figure 10.6*a*), the hypothalamus and anterior lobe of the pituitary gland release hormones that stimulate other endocrine glands to produce hormones. These hormones feedback and affect the function of the hypothalamus and anterior lobe. (2) In *neural control* (figure 10.6*b*), the nervous system stimulates an endocrine gland to produce a hormone, which affects target cells in the body. The actions of the target cells feedback on the nervous system to alter its activity. (3) In *humoral control* (figure 10.6*c*), a chemical change in the blood stimulates an endocrine gland to produce a hormone, which in turn affects target cells. The actions of the target cells then create a change in blood levels of the chemical, which feeds back and alters the activity of the endocrine gland.

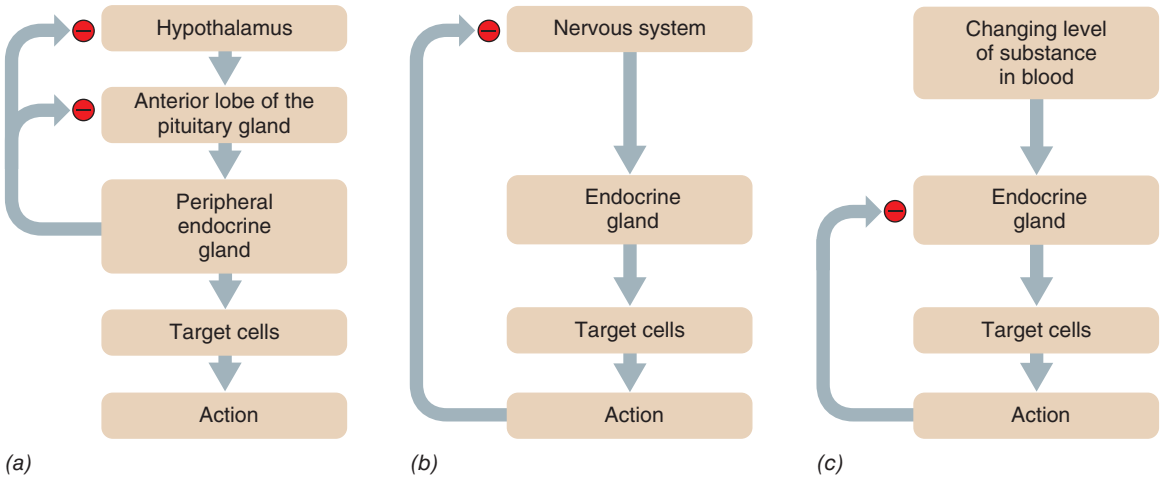


Figure 10.6 Negative-feedback mechanisms used to control the release of various hormones. *(a)* Hormonal control. *(b)* Neural control. *(c)* Humoral control.

These feedback mechanisms may have either stimulatory or inhibitory effects on the hormone production pathway.

The production of hormones is normally precisely regulated so that there is no **hypersecretion** (excessive production) or **hyposecretion** (deficient production). However, hormonal disorders do occur, and they usually result from severe hypersecretion or hyposecretion. Because endocrine disorders are specifically related to individual glands, disorders in this chapter are considered when each gland is discussed rather than at the end of the chapter.

Check My Understanding

1. How do steroid and nonsteroid hormones produce their effects on target cells?
2. How are hormones and prostaglandins similar but different?
3. How is the secretion of hormones regulated?

10.2 Pituitary Gland

Learning Objectives

5. Describe how the production of each of the anterior lobe hormones is controlled.
6. List the actions of hormones of the anterior lobe of the pituitary gland.
7. Describe how the production of each of the posterior lobe hormones is controlled.
8. List the actions of hormones of the posterior lobe of the pituitary gland.
9. Describe the major pituitary gland disorders.

The **pituitary** (pi-tū′-i-tar-ē) **gland,** or **hypophysis** (hī-pof′-i-sis), is attached to the hypothalamus by a short stalk. It rests in a depression of the sphenoid bone, the sella turcica, which provides protection. The pituitary gland consists of two major parts that have different functions: an *anterior lobe* and a *posterior lobe*. Although the pituitary gland is small, it regulates many body functions. The pituitary gland is controlled by neurons and hormones that originate in the **hypothalamus,** as shown in figure 10.7. The hypothalamus serves as a link between the brain and the endocrine system and is itself an endocrine gland. Table 10.1 summarizes the hormones of the pituitary gland and their functions.

Control of the Anterior Lobe

Special neurons (neurosecretory cells) in the hypothalamus regulate the secretion of hormones from the anterior lobe by secreting *releasing* and *inhibiting hormones*. The hypothalamic hormones enter the hypophyseal portal veins, which carry them directly into the anterior lobe without circulating throughout the body. In the anterior lobe, the hormones exert their effects on specific groups of cells. There is a releasing hormone for each hormone produced by the anterior lobe. There are inhibiting hormones for growth hormone and prolactin. As the names imply, releasing hormones stimulate the production and release of hormones from the anterior lobe, while inhibiting hormones have the opposite effect. The secretion of releasing and inhibiting hormones by the hypothalamus is regulated by various hormonal negative-feedback mechanisms.

Control of the Posterior Lobe

The posterior lobe is controlled by the neural negative-feedback mechanism described previously and shown in

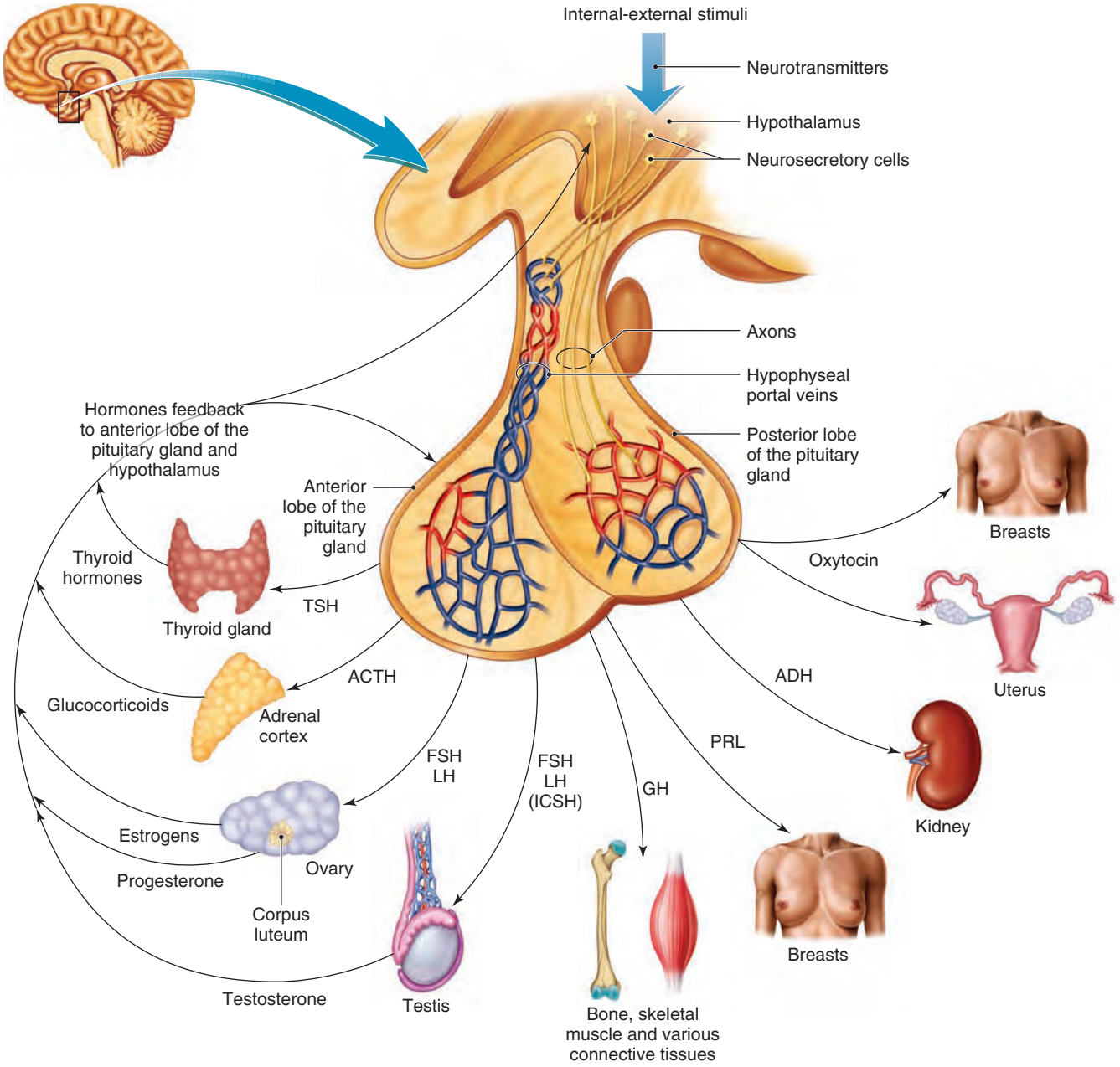


Figure 10.7 Control of pituitary gland secretions. Hypothalamic hormones are secreted by modified neurons and carried by the hypophyseal portal veins to the anterior lobe of the pituitary gland, where they either stimulate or inhibit the secretion of anterior lobe hormones. Nerve impulses stimulate modified neurons in the hypothalamus to secrete hormones that are released from their terminal boutons within the posterior lobe of the pituitary gland.

figure 10.6*b*. Special neurons that originate in the hypothalamus have axons that extend into the posterior lobe of the pituitary gland. Nerve impulses passed along these neurosecretory axons cause the release of hormones from their terminal boutons within the posterior lobe, where they diffuse into the blood. Note that the posterior lobe hormones are formed by neurosecretory cells originating in the hypothalamus and not by cells of the posterior lobe of the pituitary gland. They are only released within the posterior lobe.

Anterior Lobe Hormones

The anterior lobe of the pituitary gland is sometimes called the "master gland" because it affects so many body functions. It produces and secretes six hormones: growth hormone (GH), thyroid-stimulating hormone (TSH), adrenocorticotropic hormone (ACTH), follicle-stimulating hormone (FSH), luteinizing hormone (LH), and prolactin (PRL).

Table 10.1 Hormones of the Pituitary Gland

Hormone	Control	Action	Disorders
Anterior Lobe Hormones			
Growth hormone (GH)	Growth-hormone-releasing hormone (GHRH); growth-hormone-inhibiting hormone (GHIH)	Promotes growth of body cells and cell division; promotes protein synthesis; increases the use of fat and glucose for ATP	Hyposecretion in childhood causes pituitary dwarfism. Hypersecretion in childhood causes gigantism; in adults, it causes acromegaly.
Thyroid-stimulating hormone (TSH)	Thyrotropin-releasing hormone (TRH)	Stimulates thyroid gland to produce thyroid hormones	Hyposecretion leads to secondary hypothyroidism. Hypersecretion leads to secondary hyperthyroidism.
Adrenocorticotropic hormone (ACTH)	Corticotropin-releasing hormone (CRH)	Stimulates adrenal cortex to secrete glucocorticoids and androgens	
Follicle-stimulating hormone (FSH)	Gonadotropin-releasing hormone (GnRH)	In ovaries, stimulates development of ovarian follicles and secretion of estrogens; in testes, stimulates the production of sperm	
Luteinizing hormone (LH)	Gonadotropin-releasing hormone (GnRH)	In females, promotes ovulation, development of the corpus luteum, which leads to the production and secretion of progesterone, preparation of uterus to receive embryo, and preparation of mammary glands for milk secretion; in males, stimulates testes to secrete testosterone	
Prolactin (PRL)	Prolactin-releasing hormone (PRH); prolactin-inhibiting hormone (PIH)	Stimulates milk secretion and maintains milk production by mammary glands	
Posterior Lobe Hormones			
Antidiuretic hormone (ADH)	Concentration of water in body fluids	Promotes retention of water by kidneys	Hyposecretion causes diabetes insipidus.
Oxytocin (OT)	Stretching of uterus; stimulation of nipples	Stimulates contractions of uterus in childbirth and contraction of milk glands when nursing infant	
		In both sexes, promotes parental caretaking and involved in feeling of pleasure associated with sexual experiences	

Growth Hormone

As the name implies, **growth hormone (GH)** stimulates the division and growth of body cells. Increased growth results because GH promotes the synthesis of proteins and other complex organic compounds. GH also increases available energy for these synthesis reactions by promoting the release of fat from adipose tissue, the use of fat in cellular respiration, and the conversion of glycogen to glucose. Although GH is more abundant during childhood and puberty, it is secreted throughout life.

Regulation of growth hormone secretion is by two hypothalamic hormones with antagonistic functions. GH-releasing hormone (GHRH) stimulates GH secretion, and GH-inhibiting hormone (GHIH) inhibits GH secretion. Whether the hypothalamus releases GHRH or GHIH depends upon changes in blood chemistry. For example, following strenuous exercise, a low level of blood sugar (hypoglycemia), and an excess of amino acids in the blood trigger the secretion of GHRH. Conversely, high levels of blood sugar (hyperglycemia) stimulate the secretion of GHIH.

Disorders If hypersecretion of GH occurs during the growing years, the individual becomes very tall—sometimes nearly 2.5 m (8 ft) in height. This condition is known as **gigantism.** If the hypersecretion of GH occurs in an adult after full growth in height has been attained, it produces a condition known as **acromegaly** (ak-rō-meg′-ah-lē). Because the growth of long bones has been completed, only the bones of the face, hands, and feet continue to grow. Over time, the individual develops heavy,

protruding brow ridges, a jutting mandible, and enlarged hands and feet. Both gigantism and acromegaly may result from tumors of the anterior lobe. Affected persons may have other health problems due to hypersecretion of other anterior lobe hormones.

If hyposecretion of GH occurs during childhood, body growth is limited. In extreme cases, this results in **pituitary dwarfism.** Affected persons have well-proportioned body parts but may be less than 1 m (3 ft) in height. They may suffer from other maladies due to a deficient supply of other anterior lobe hormones.

Thyroid-Stimulating Hormone

Thyroid-stimulating hormone (TSH) stimulates the thyroid gland to produce thyroid hormones. Blood concentrations of thyroid hormones control the negative-feedback mechanism for TSH production. Low levels of thyroid hormones activate the hypothalamus to secrete *thyrotropin-releasing hormone (TRH),* which stimulates release of TSH by the anterior lobe. Conversely, high concentrations of thyroid hormones inhibit the secretion of TRH, which decreases production of TSH. Because TSH controls the thyroid gland, disorders of TSH secretion lead to thyroid disorders.

Adrenocorticotropic Hormone

Adrenocorticotropic (ad-re-nō-kor-ti-kō-trō-p′-ik) **hormone (ACTH)** controls the secretion of hormones produced by the adrenal cortex (the superficial portion of the adrenal gland). ACTH production is controlled by *corticotropin-releasing hormone (CRH)* from the hypothalamus. CRH release is controlled by blood levels of ACTH and glucocorticoids from the adrenal cortex through negative-feedback mechanisms. Low levels of ACTH in the blood trigger the production and release of CRH. High blood levels of ACTH inhibit the production of CRH. Low levels of glucocorticoids from the adrenal cortex activate the hypothalamus to secrete CRH, which stimulates the release of ACTH from the anterior lobe. High levels of glucocorticoids inhibit CRH secretion, and thus inhibit the production and secretion of ACTH. Excessive stress may stimulate the production of excessive amounts of ACTH by overriding the negative-feedback control.

Gonadotropins

The **follicle-stimulating hormone (FSH)** and **luteinizing** (lū-tē-in-īz-ing) **hormone (LH)** affect the gonads (testes and ovaries). Their release is stimulated by *gonadotropin-releasing hormone (GnRH)* from the hypothalamus. The onset of puberty in both sexes is caused by the start of FSH secretion. In females, FSH acts on the ovaries to promote the development of ovarian follicles, which contain ova and produce estrogens, the primary female sex hormones. In males, FSH acts on testes to promote sperm production. In females, LH stimulates ovulation and the development of the corpus luteum, a temporary gland in the ovary that produces progesterone, another female sex hormone. In males LH is often referred to as *interstitial cell stimulating hormone (ICSH)* because it affects the interstitial cells of the testes, where it stimulates the secretion of testosterone. Further discussion of FSH and LH can be found in chapter 17.

Prolactin

Prolactin (prō-lak′-tin) **(PRL)** helps to initiate and maintain milk production by the mammary glands after the birth of an infant. Prolactin stimulates milk secretion after the mammary glands have been prepared for milk production by other hormones, including female sex hormones. In males, PRL increases the activity of LH in the testes, thus increasing testosterone production. Prolactin secretion is regulated by the antagonistic actions of *prolactin-releasing hormone (PRH)* and *prolactin-inhibiting hormone (PIH)* produced by the hypothalamus.

Posterior Lobe Hormones

Posterior lobe hormones are good examples of neuroendocrine secretion. The posterior lobe stores and releases two hormones: the antidiuretic hormone and oxytocin. Both of these hormones are secreted by neurons that originate in the hypothalamus and extend into the posterior lobe. The hormones are released into the blood within the posterior lobe and are distributed throughout the body (see figure 10.7).

Antidiuretic Hormone

The **antidiuretic** (an-ti-dī-ū-ret′-ik) **hormone (ADH)** promotes water retention by the kidneys to reduce the volume of water that is excreted in urine. ADH secretion is regulated by special neurons that detect changes in the water concentration of the blood. If water concentration decreases, secretion of ADH increases to promote water retention by the kidneys. If water concentration increases, secretion of ADH decreases, causing more water to be excreted in urine. By controlling the water concentration of blood, ADH helps to control blood volume and blood pressure. Further discussion of ADH can be found in chapter 16.

Disorders A severe hyposecretion of ADH results in the production of excessive quantities (20–30 liters per day) of dilute urine, a condition called **diabetes insipidus** (dī-ah-bē′-tēz in-sip′-i-dus). Diabetes means "overflow," and insipidus means "tasteless." Thus, diabetes insipidus essentially means to have overflow of tasteless urine. Conversely, mellitus means "sweet," so diabetes mellitus is an overflow of sweet urine. In diabetes insipidus, the affected person is always thirsty and must drink water almost constantly.

Clinical Insight

Pitocin, a synthetic oxytocin, is one of several drugs that is used to clinically induce labor. After delivery, these drugs may also be used to increase the muscle tone of the uterus and to control uterine bleeding.

This condition may be caused by injuries or tumors that affect any part of the ADH regulatory mechanism, such as the hypothalamus or posterior lobe of the pituitary gland, or nonfunctional ADH receptors in the kidneys.

Oxytocin

Oxytocin (ok-sē-tō′-sin) **(OT)** is released in large amounts during childbirth. It stimulates and strengthens contraction of the smooth muscles of the uterus, which culminates in the birth of the infant. It also has an effect on the mammary glands. Stimulation of a nipple by a suckling infant causes the release of OT, which, in turn, contracts the milk glands of the breast, forcing milk into the milk ducts, where it can be removed by the suckling infant.

Unlike other hormones, oxytocin secretion is controlled by a positive-feedback mechanism. For example, the greater the nipple stimulation by a suckling infant, the more OT released and the more milk available for the infant. When suckling ceases, OT production ceases.

OT is also produced in males and nonpregnant females, where it plays a role in creating parental caretaking behaviors and feelings of pleasure associated with sexual intercourse.

Check My Understanding

4. How does the hypothalamus control the secretions of the pituitary gland?
5. What are the functions of anterior lobe and posterior lobe hormones?

10.3 Thyroid Gland

Learning Objectives

10. Describe how the production of thyroid hormones is controlled.
11. List the actions of thyroid hormones.
12. Describe how the production of calcitonin is controlled.
13. List the actions of calcitonin.
14. Describe the major thyroid disorders.

The **thyroid gland** is located just inferior to the larynx. It consists of two lobes, each one lateral to the trachea, that are connected by an anterior isthmus (figure 10.8). Table 10.2 summarizes the control, action, and disorders of the thyroid gland.

Thyroxine and Triiodothyronine

Iodine atoms are essential for the formation and functioning of two similar thyroid hormones, produced by groups of cells forming *thyroid follicles* that respond to TSH. **Thyroxine** is the primary hormone. It is also known as $\mathbf{T_4}$ because each molecule contains four iodine atoms. The other hormone, **triiodothyronine** (tri″i-o″do-thi′ro-nen) or $\mathbf{T_3}$, contains three iodine atoms in each molecule. Both T_4 and T_3 exert their effect on body cells, and they have similar functions. They increase the metabolic rate, promote protein synthesis, and enhance neuron function. T_3 and T_4 are the primary factors that determine the basal metabolic rate (BMR), the number of calories required at rest to maintain life. Thyroid hormones are also important during infancy and childhood for normal development of the nervous, skeletal, and muscular systems. Secretion of these hormones is stimulated by TSH from the anterior lobe of the pituitary gland, and TSH, in turn, is regulated by a negative-feedback mechanism as described in the discussion of the anterior lobe of the pituitary gland.

Disorders Hypersecretion, hyposecretion, and iodine deficiencies are involved in the thyroid disorders: Graves disease, simple goiter, cretinism, and myxedema.

Graves disease results from the hypersecretion of thyroid hormones. It is thought to be an autoimmune disorder in which antibodies bind to TSH receptors, stimulating excessive hormone production. It is characterized by restlessness and increased metabolic rate with possible weight loss. Usually, the thyroid gland is somewhat enlarged, which is called a **goiter** (goy-ter), and eyes bulge due to the swelling of tissues posterior to the eyes, producing what is called an *exophthalmic* (ek-sof-thal-mik) *goiter*.

Simple goiter is an enlargement of the thyroid gland that results from a deficiency of iodine in the diet. Without adequate iodine, hyposecretion of thyroid hormones occurs and the thyroid gland enlarges due to overstimulation with TSH in an attempt to produce more thyroid hormones. In some cases, the thyroid gland may become the size of an orange. Goiter can be prevented by including very small amounts of iodine in the diet. For this reason, salt manufacturers produce "iodized salt," which contains sufficient iodine to prevent simple goiter.

Cretinism (kre′-tin-izm) is caused by a severe hyposecretion of thyroid hormones in infants. Without treatment, it produces severe mental and physical retardation. Cretinism is characterized by stunted growth, abnormal bone formation, mental retardation, sluggishness, and goiter.

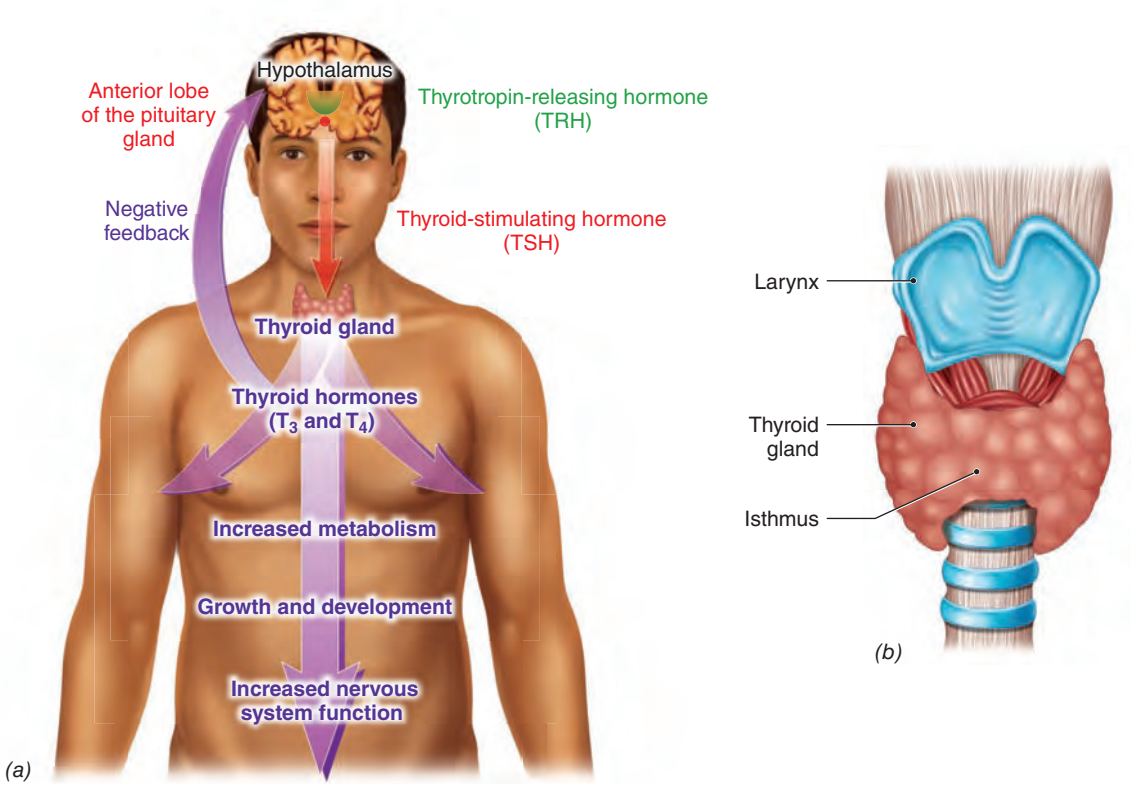


Figure 10.8 Anatomy and Physiology of the Thyroid Gland.
(a) Negative-feedback mechanism of thyroid control. *(b)* The thyroid gland consists of two lobes connected anteriorly at the isthmus.

Table 10.2 Hormones of the Thyroid Gland

Hormone	Control	Action	Disorders
Thyroxine (T_4) and triiodothyronine (T_3)	TSH from anterior lobe of the pituitary gland	Increase metabolic rate; accelerate growth; stimulate neural activity	Hyposecretion in infants and children causes cretinism; in adults, it causes myxedema. Hypersecretion causes Graves disease. Iodine deficiency causes simple goiter.
Calcitonin (CT)	Blood Ca^{2+} level	Decreases blood Ca^{2+} levels by promoting Ca^{2+} deposition in bones, inhibiting removal of Ca^{2+} from bones, promoting excretion of Ca^{2+} by kidneys	

Myxedema (mik-se-de′-mah) is caused by severe hyposecretion of thyroid hormones in adults. It is characterized by sluggishness, weight gain, weakness, dry skin, goiter, and puffiness of the face.

Calcitonin

The thyroid gland produces a third hormone, **calcitonin** (kal-si-to′-nin) **(CT)**, from cells called *C cells* that are located between thyroid follicles. C cells do not respond to the hormonal mechanism the same as thyroid follicles do but respond to a humoral negative-feedback mechanism linked to blood Ca^{2+} levels. Calcitonin decreases blood Ca^{2+} by inhibiting the bone-resorbing action of osteoclasts, increasing the rate of Ca^{2+} deposition by osteoblasts, and promoting Ca^{2+} excretion by the kidneys. An excess of Ca^{2+} in the blood stimulates the thyroid gland to secrete calcitonin. The concentration of Ca^{2+} in the blood is important because it plays vital roles in metabolism, including maintenance of healthy bones, conduction of nerve impulses, muscle contraction, and clotting of blood. The function of calcitonin is antagonistic to parathyroid hormone, which is discussed in the next section.

10.4 Parathyroid Glands

Learning Objectives

15. Describe how the production of parathyroid hormone is controlled.
16. List the actions of parathyroid hormone.
17. Describe the major parathyroid disorders.

The **parathyroid glands** are small glands that are located on the posterior surface of the thyroid gland. There are usually four parathyroid glands, two glands on each lobe of the thyroid (figure 10.9).

Parathyroid Hormone

Parathyroid glands secrete **parathyroid hormone (PTH),** the most important regulator of blood Ca^{2+} levels. PTH increases the concentration of blood Ca^{2+} by promoting the removal of Ca^{2+} from bones by osteoclasts and by inhibiting Ca^{2+} deposition by osteoblasts. PTH acts in the kidneys to inhibit excretion of Ca^{2+} into urine and trigger the activation of vitamin D (also a hormone). Both PTH and vitamin D increase Ca^{2+} absorption by the small intestine. The antagonistic actions of PTH and calcitonin maintain blood Ca^{2+} homeostasis (figure 10.10 and table 10.3).

Disorders **Hypoparathyroidism,** the hyposecretion of PTH, can produce devastating effects. Without treatment, the concentration of blood Ca^{2+} may drop to levels that impair neural and muscular activity. The effect on cardiac muscle may result in cardiac arrest and sudden death. Tetany of skeletal muscles may occur, and death may result from a lack of oxygen due to the inability of breathing muscles to function normally.

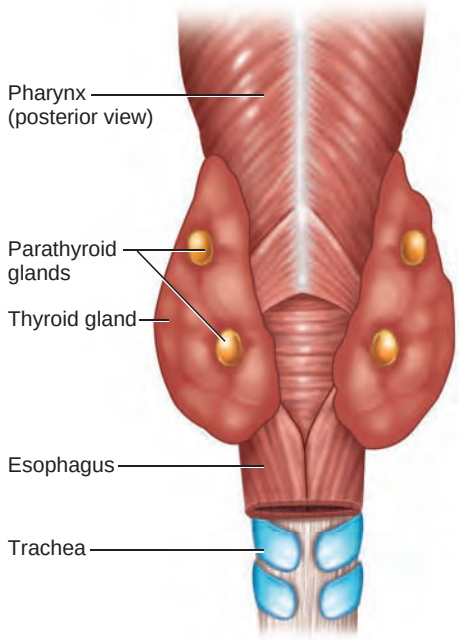


Figure 10.9 Two small parathyroid glands are located on the posterior surface of each lobe of the thyroid gland.

Hyperparathyroidism, the hypersecretion of PTH, causes too much Ca^{2+} to be removed from bones and raises blood Ca^{2+} to abnormally high levels. Without treatment, Ca^{2+} loss results in soft, weak bones that are prone to spontaneous fractures. The excess Ca^{2+} in the blood may lead to the formation of kidney stones or may be deposited in abnormal locations creating bone spurs (abnormal bony growths).

Check My Understanding

6. What are the actions of thyroid hormones?
7. How is the level of blood Ca^{2+} regulated?

10.5 Adrenal Glands

Learning Objectives

18. Describe how the production of adrenal hormones is controlled.
19. List the actions of adrenal hormones.
20. Describe the major adrenal disorders.

There are two **adrenal glands;** one is located on top of each kidney. Each adrenal gland consists of two portions that are distinct endocrine glands: the deep adrenal medulla and the superficial adrenal cortex (figure 10.11). Table 10.4 summarizes the control, action, and disorders of the adrenal gland.

Hormones of the Adrenal Medulla

The **adrenal medulla** secretes **epinephrine** (adrenaline) and **norepinephrine** (noradrenaline), two closely related hormones that have very similar actions on target cells. Epinephrine forms about 80% of the secretions.

The sympathetic division of the autonomic nervous system regulates the secretion of adrenal medullary hormones. They are secreted whenever the body is under stress, and they duplicate the action of the sympathetic division on a bodywide scale. The medullary hormones have a stronger and longer-lasting effect in preparing the body for "fight or flight." The effects of epinephrine and norepinephrine include (1) a decrease in blood flow to the viscera and skin; (2) an increase in blood flow to the skeletal muscles, lungs, and nervous system; (3) conversion of glycogen to glucose to raise the glucose level in the blood; and (4) an increase in the rate of cellular respiration. Epinephrine and norepinephrine are particularly important in short-term stress situations. In times of chronic stress the adrenal cortex makes further adjustment as will be discussed in the next section.

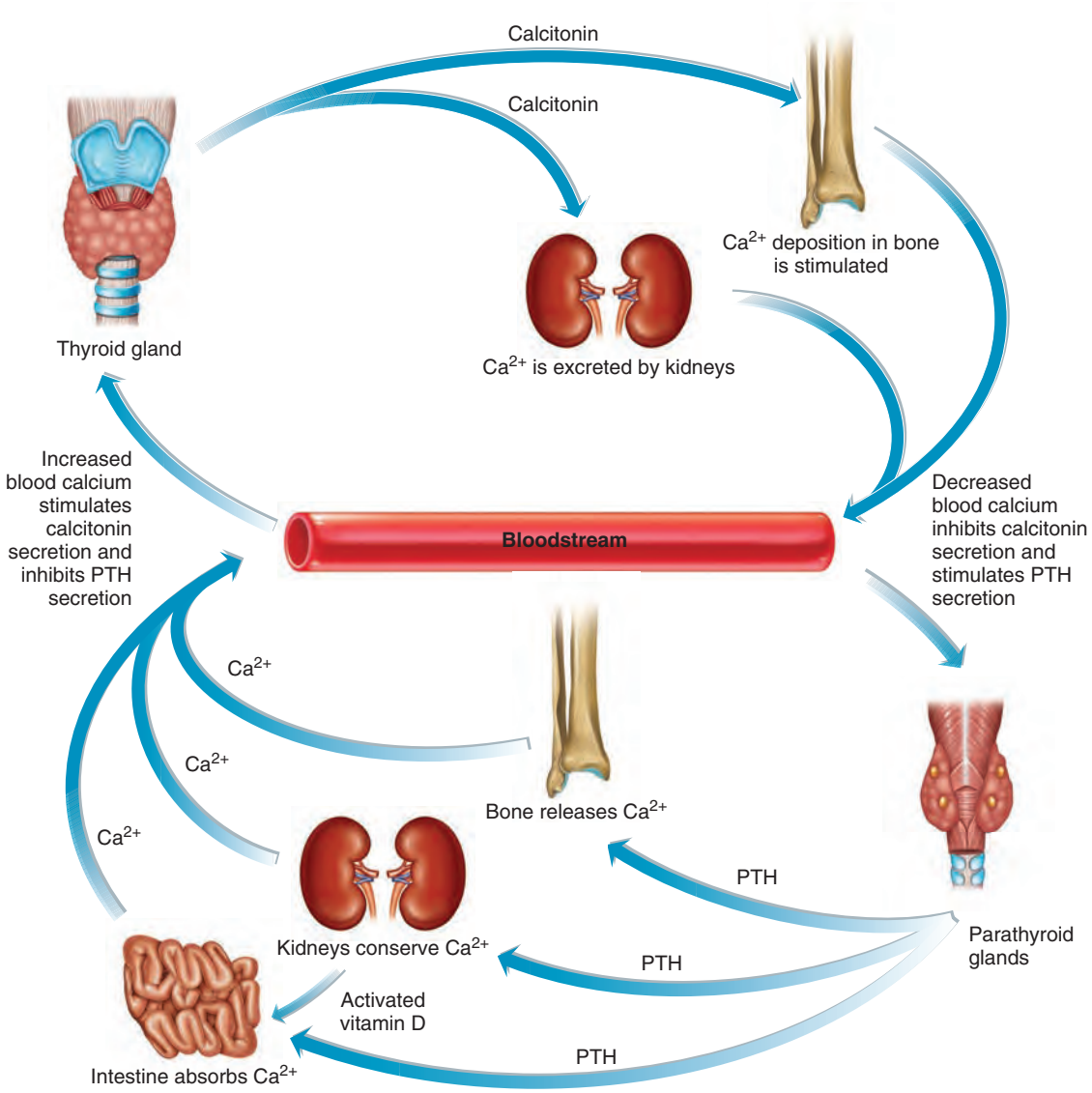


Figure 10.10 Calcium Homeostasis.
The concentration of Ca^{2+} in the blood controls the secretion of calcitonin and PTH.

Table 10.3 Parathyroid Hormone

Hormone	Control	Action	Disorders
Parathyroid hormone (PTH)	Blood Ca^{2+} level	Increases blood Ca^{2+} level by promoting Ca^{2+} removal from bones and Ca^{2+} reabsorption by kidneys	Hyposecretion causes tetany, which may result in death. Hypersecretion causes weak, deformed bones that may fracture spontaneously.

Hormones of the Adrenal Cortex

Several different steroid hormones are produced by the **adrenal cortex,** but the most important ones are aldosterone, cortisol, and the sex hormones.

Aldosterone (al-dō-ster′-ōn) is the most important mineralocorticoid secreted by the adrenal cortex. **Mineralocorticoids** regulate the concentration of electrolytes (mineral ions) in body fluids. Aldosterone stimulates the kidneys to retain sodium ions (Na^+) and to excrete potassium ions (K^+). This action not only maintains the normal balance of Na^+ and K^+ in body fluids but also maintains blood volume and blood pressure. The reabsorption of Na^+ into the blood causes anions, such as chloride (Cl^-) and bicarbonate (HCO_3^-), to be reabsorbed due to their opposing

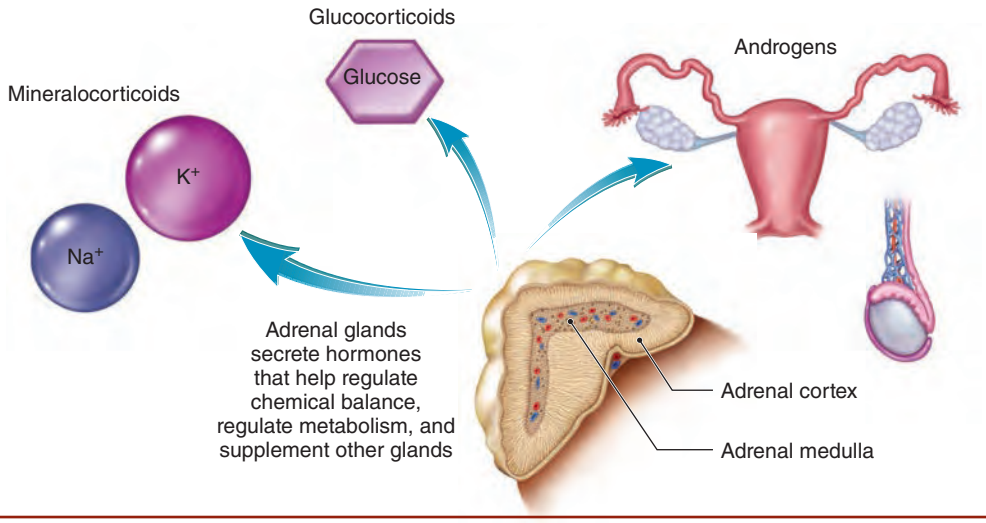


Figure 10.11 An adrenal gland consists of a superficial adrenal cortex and a deep adrenal medulla.

Table 10.4 Hormones of the Adrenal Glands

Hormone	Control	Action	Disorders
Adrenal Medulla			
Epinephrine and norepinephrine	Sympathetic division of the autonomic nervous system	Prepare body to meet emergencies; increase heart rate, cardiac output, blood pressure, and metabolic rate; increase blood sugar by converting glycogen to glucose; dilate respiratory passages	Hypersecretion causes prolonged responses. Hyposecretion causes no major disorders.
Adrenal Cortex			
Aldosterone	Blood electrolyte levels, angiotensin II	Increases blood levels of sodium and water, which decreases blood levels of potassium; increases blood pressure	Hypersecretion inhibits neural and muscular activity, and also causes edema.
Cortisol	ACTH from anterior lobe of the pituitary gland	Promotes formation of glucose from noncarbohydrate nutrients; provides resistance to stress and inhibits inflammation	Hyposecretion causes Addison disease. Hypersecretion causes Cushing syndrome.
Androgens	ACTH from anterior lobe of the pituitary gland	Effects are insignificant in normal adult males; contribute to the sex drive in females.	Hypersecretion as a result of tumors; causes masculinization in females.

charges. And it causes water to be reabsorbed by osmosis, which maintains blood volume and blood pressure. Aldosterone secretion is stimulated by several factors, including (1) a decrease in blood level of Na^+, (2) an increase in blood level of K^+, or (3) a decrease in blood pressure, which leads to angiotensin II production, as will be discussed in chapter 16.

Glucocorticoids are so named because they affect glucose metabolism. There are three major actions of glucocorticoids. (1) In response to chronic stress, glucocorticoids ensure a constant fuel supply by promoting the conversion of noncarbohydrate nutrients into glucose. This is important because carbohydrate sources, such as glycogen, may be exhausted after several hours without food or strenuous exercise. (2) They facilitate the utilization of glucose by cells. (3) They reduce inflammation.

Cortisol (kor′-ti-sol) is the most important of several glucocorticoids that are secreted by the adrenal cortex under the stimulation of ACTH. The blood levels of glucocorticoids are kept in balance because they exert a negative-feedback control on the secretion of CRH and ACTH, as described in the section of this chapter discussing the anterior lobe of the pituitary gland.

The adrenal cortex also secretes small amounts of **androgens** (male sex hormones) and estrogens in response to ACTH from the anterior lobe of the pituitary gland. The estrogens have little significant function. The

Clinical Insight

Everyone experiences stressful situations. Stress may be caused by physical or psychological stimuli that are perceived as threatening. Whereas mild stress can stimulate creativity and productivity, severe and prolonged stress can have serious consequences.

The hypothalamus is the initiator of the stress response. When stress occurs, the hypothalamus activates the sympathetic division of the autonomic nervous system and the secretion of epinephrine and norepinephrine by the adrenal medulla. Thus, both neural and hormonal activity prepare the body to meet the stressful situation by increasing blood glucose, heart rate, breathing rate, blood pressure, and blood flow to the muscular and nervous systems.

Simultaneously, the hypothalamus stimulates the release of ACTH from the anterior lobe of the pituitary gland. ACTH, in turn, causes the secretion of glucocorticoids by the adrenal cortex. Glucocorticoids increase the levels of amino acids and fatty acids in the blood and promote the formation of additional glucose from noncarbohydrate nutrients.

All of these responses prepare the body for an immediate response to cope with a stressful situation.

Prolonged stress may cause several undesirable side effects from the constant secretion of large amounts of epinephrine and glucocorticoids, such as decreased immunity and high blood pressure—problems that are common in our society.

androgens promote the early development of male reproductive organs, but in adult males their effects are masked by sex hormones produced by testes. In females, adrenal androgens contribute to the female sex drive. In both sexes, excessive production results in exaggerated male characteristics.

Disorders **Cushing syndrome** results from hypersecretion by the adrenal cortex. It may be caused by an adrenal tumor or by excessive production of ACTH by the anterior lobe of the pituitary gland. This syndrome is characterized by high blood pressure, an abnormally high blood glucose level, protein loss, osteoporosis, fat accumulation on the trunk, fatigue, edema, and decreased immunity. A person with this condition tends to have a full, round face and an enlarged abdomen.

Addison disease results from a severe hyposecretion by the adrenal cortex. It is characterized by low blood pressure, low blood glucose and sodium levels, an increase in the blood potassium level, dehydration, muscle weakness, and increased skin pigmentation. Without treatment to control blood electrolytes, death may occur in a few days.

Check My Understanding

8. How do secretions of the adrenal medulla prepare the body to react in emergencies?
9. How does the adrenal cortex help to maintain blood pressure?

10.6 Pancreas

Learning Objectives

21. Describe the control of pancreatic hormones.
22. List the actions of pancreatic hormones.
23. Describe the major pancreatic disorders.

The **pancreas** (pan′-krē-as) is an elongate organ that is located posterior to the stomach (figure 10.12). It is both an exocrine gland and an endocrine gland. Its exocrine functions are performed by secretory cells that secrete digestive enzymes into tiny ducts within the gland. These ducts merge to form the pancreatic duct, which carries the secretions into the small intestine. Its endocrine functions are performed by secretory cells that are arranged in clusters or clumps called the **pancreatic islets.** Their secretions diffuse into the blood. The islets contain alpha cells and beta cells. Alpha cells produce the hormone glucagon; beta cells form the hormone insulin. Table 10.5 summarizes the control, action, and disorders of the pancreas.

Glucagon

Glucagon (glū′-kah-gon) increases the concentration of glucose in the blood. It does this by activating the liver to convert glycogen and certain noncarbohydrates, such as amino acids, into glucose. Glucagon helps to maintain the blood level of glucose within normal limits even when carbohydrates are depleted due to long intervals between meals. Epinephrine stimulates a similar action, but glucagon is more effective. Glucagon secretion is controlled by the blood level of glucose via a negative-feedback mechanism. A low level of blood glucose stimulates glucagon secretion, and a high level of blood glucose inhibits glucagon secretion.

Clinical Insight

Persons with inflamed joints often receive injections of *cortisone,* a glucocorticoid, to temporarily reduce inflammation and the associated pain. Such a procedure is fairly common in sports medicine.

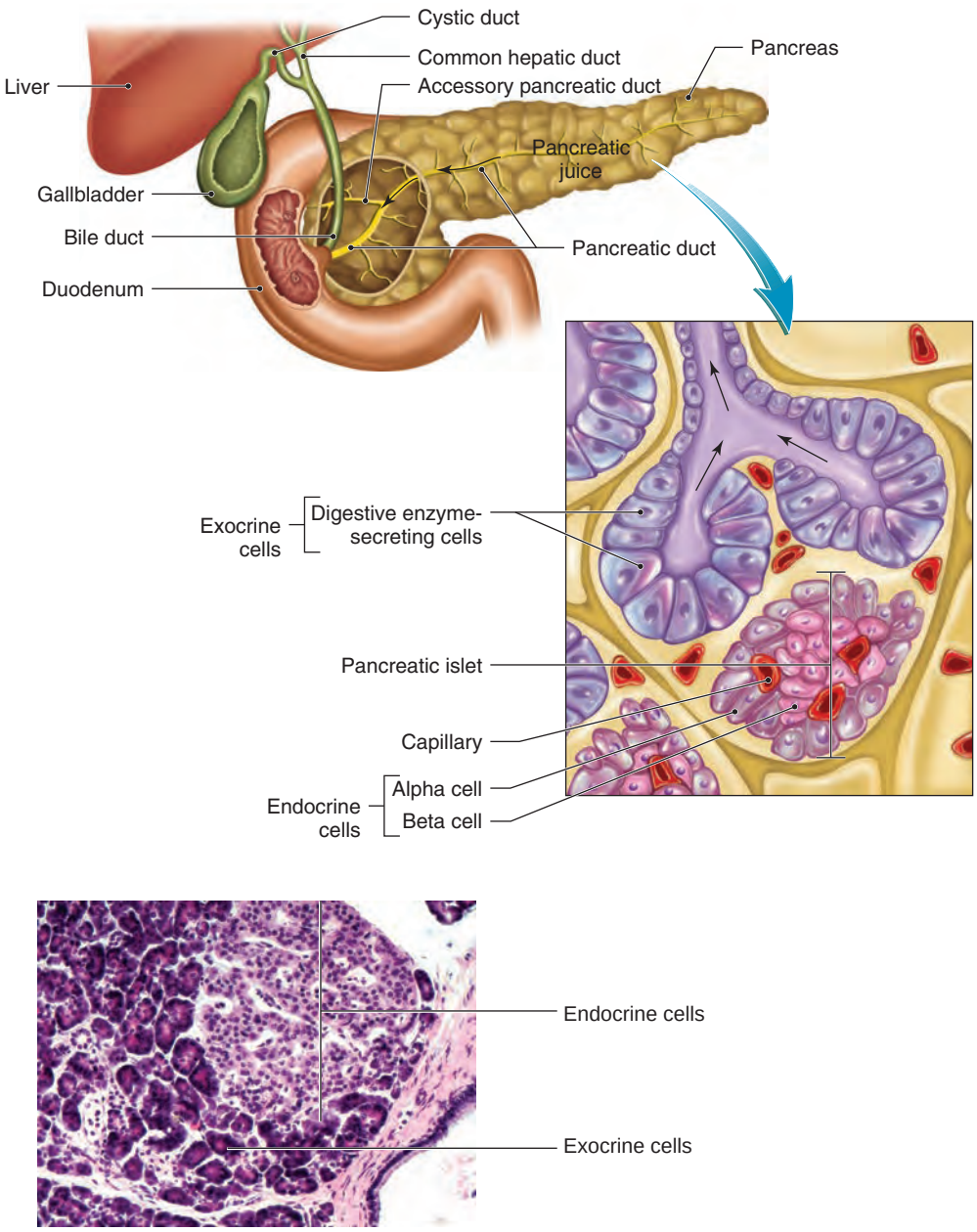


Figure 10.12 The pancreas is both an endocrine and an exocrine gland. The hormone-secreting alpha and beta cells are grouped in clusters, called pancreatic islets. Other pancreatic cells secrete digestive enzymes.

Table 10.5 Hormones of the Pancreas

Hormone	Control	Action	Disorders
Glucagon	Blood glucose level	Increases blood glucose by stimulating the liver to convert glycogen and other nutrients into glucose	
Insulin	Blood glucose level	Decreases blood glucose by aiding movement of glucose into cells and promoting the conversion of glucose into glycogen	Hyposecretion causes type I diabetes mellitus. Hypersecretion may cause hypoglycemia.

Insulin

The effect of **insulin** on the level of blood glucose is opposite that of glucagon. Insulin decreases blood glucose by aiding the movement of glucose into body cells, where it can be used as a source of energy. Without insulin, glucose is not readily available to most cells for cellular respiration. Insulin also stimulates the liver to convert glucose into glycogen for storage. Figure 10.13 shows how the antagonistic functions of glucagon and insulin maintain the concentration of glucose in the blood within normal limits. Like glucagon, the level of blood glucose regulates the secretion of insulin. High blood glucose levels stimulate insulin secretion; low levels inhibit insulin secretion.

Disorders **Diabetes mellitus** (dī-ah-bē′-tēz mel-lī′-tus) is caused by the hyposecretion of insulin or the inability of target cells to recognize it due to a loss of insulin receptors. *Type I* or *insulin-dependent diabetes* is an autoimmune metabolic disorder that usually appears in persons less than 20 years of age. For this reason, it is sometimes called juvenile diabetes, although the condition persists for life. Type I diabetes results when the immune response destroys the beta cells in pancreatic islets. Because the metabolism of carbohydrates, fats, and proteins is affected, persons with type I diabetes must follow a restrictive diet. They must also check their blood glucose level several times a day and inject themselves with insulin, or receive insulin from an implanted insulin pump, to keep their blood glucose concentration within normal limits.

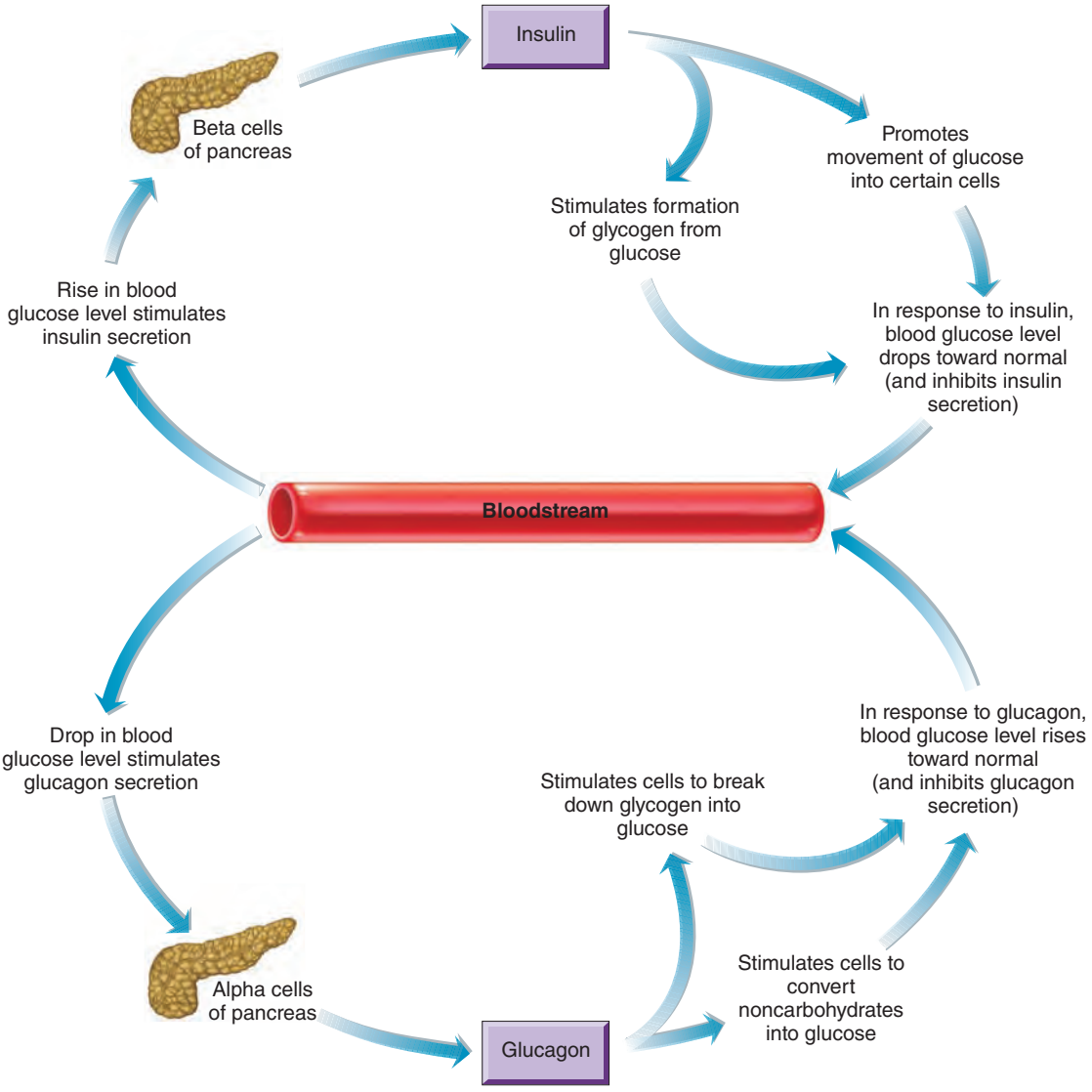


Figure 10.13 Insulin and glucagon function together to help maintain a relatively stable blood glucose level. Negative-feedback mechanism responding to blood glucose level controls the secretion of both hormones.

The vast majority of diabetics have *type II* or *insulin-independent diabetes,* which is caused by a reduction of the insulin receptors on target cells. This form of diabetes, also called adult-onset diabetes, usually appears after 40 years of age in persons who are overweight. The symptoms are less severe than in type I diabetes and can be controlled by a careful diet and oral medications that help regulate blood levels of glucose. The current increase in obesity among children and young adults is of concern because it may lead to an increase in type II diabetes. In either case, the result is **hyperglycemia,** excessively high levels of glucose in the blood. With insufficient insulin or a reduction in target insulin receptors, glucose cannot get into cells easily, and cells must rely more heavily on triglycerides as an energy source for cellular respiration. The products of this reaction tend to decrease blood pH (acidosis), which can inactivate vital enzymes and may lead to death.

An excessive production of insulin, or overdose of insulin, may lead to **hypoglycemia,** a condition characterized by excessively low blood glucose levels. Symptoms include acute fatigue, weakness, increased irritability, and restlessness. In extreme conditions, it may lead to an insulin-triggered coma.

Check My Understanding

10. How does the pancreas regulate the level of blood glucose?

10.7 Gonads

Learning Objectives

24. Describe how the production of female sex hormones is controlled.
25. List the actions of female sex hormones.
26. Describe how the production of male sex hormones is controlled.
27. List the actions of male sex hormones.

The gonads are the sex glands: the ovaries and testes. They not only produce oocytes and sperm, respectively, but also secrete the sex hormones. Table 10.6 summarizes the actions of the sex hormones. The gonads and their hormones are covered in more detail in chapter 17.

Female Sex Hormones

The **ovaries** are the female gonads. They are small, almond-shaped organs located in the pelvic cavity. The ovaries begin to function at the onset of puberty when the gonadotropins (FSH and LH) are released from the anterior lobe of the pituitary gland. Subsequently, ovarian hormones, FSH, and LH interact in an approximately 28-day *ovarian cycle* in which their concentrations increase and decrease in a rhythmic pattern.

Estrogens (es′-trō-jens), the primary female sex hormones, are several related compounds that are secreted by developing ovarian follicles that also contain an oocyte (developing egg). Estrogens stimulate the development and maturation of the female reproductive organs and the secondary sex characteristics (e.g., female fat distribution, breasts, and broad hips). They also help to grow and maintain the uterine lining (endometrium) to support a pregnancy.

Progesterone (prō-jes′-te-rōn) is secreted by the corpus luteum, a gland that forms from the empty ovarian follicle after the oocyte has been released by ovulation. It helps prepare the uterus for receiving a preembryo and maintains the pregnancy. It also helps to prepare the mammary glands for milk production.

Male Sex Hormone

The **testes** are paired, ovoid organs located inferior to the pelvic cavity in the scrotum, a sac of skin located posterior to the penis. The seminiferous tubules of the testes produce sperm, the male sex cell; and the interstitial cells (cells between the tubules) secrete the male hormone **testosterone** (tes-tos′-te-rōn). Testosterone stimulates the development and maturation of the male reproductive organs, the secondary sex characteristics (e.g., growth of facial and body hair, low voice, narrow hips, and heavy muscles and bones), the male sex drive, and helps stimulate sperm production.

Table 10.6 Hormones of Ovaries and Testes

Hormone	Control	Action
Ovaries		
Estrogens	FSH	Development of female reproductive organs, secondary sex characteristics, and sex drive; prepares uterus to receive a preembryo and helps maintain pregnancy
Progesterone	LH	Prepares uterus to receive a preembryo and maintains pregnancy; prepares mammary glands for milk production
Testes		
Testosterone	LH (ICSH)	Development of male reproductive organs, secondary sex characteristics, and sex drive

10.8 Other Endocrine Glands and Tissues

Learning Objectives

28. Describe the actions of melatonin.
29. Describe the action of the thymus.

There are a few other glands and tissues of the body that secrete hormones and are part of the endocrine system. These include the pineal gland, the thymus, the kidneys, the heart, and certain small glands in the lining of the stomach and small intestine. Hormones released from the kidneys, heart, and digestive system will be covered in their respective chapters. In addition, the placenta is an important temporary endocrine organ during pregnancy. It is considered in chapter 18.

Pineal Gland

The **pineal** (pin′-ē-al) **gland** is a small, cone-shaped nodule of endocrine tissue that is located in the epithalamus of the brain near the roof of the third ventricle. It secretes the hormone **melatonin** (mel-ah-tō′-nin), which seems to inhibit the secretion of gonadotropins and may help control the onset of puberty. Melatonin seems to regulate wake-sleep cycles and other biorhythms associated with the cycling of day and night. The secretion of melatonin is regulated by exposure to light and darkness. When exposed to light, nerve impulses from the retinas of the eyes are sent to the pineal gland, causing a decrease in melatonin production. During darkness, these nerve impulses decrease, and melatonin secretion is increased. Secretion is greatest at night and lowest in the day, which keeps our sleep–wakefulness cycle in harmony with the day–night cycle.

As frequent fliers know, jet lag results when the sleep–wakefulness cycles are out of sync with the day–night cycle. Jet lag can be more quickly reversed by exposure to bright light with wavelengths similar to sunlight, because the melatonin cycle is resynchronized to the new day–night cycle.

Thymus

The **thymus** is located in the mediastinum superior to the heart. It is large in infants and children but it shrinks with age and is greatly reduced in adults. It plays a crucial role in the development of immunity, which is discussed in chapter 13. The thymus produces several hormones, collectively called **thymosins** (thi-mo′-sins), which are involved in the maturation of T lymphocytes, a type of white blood cell. Thymosins also seem to have some anti-aging effects. Hence, after the thymus shrinks, we age.

Chapter Summary

- The endocrine system is composed of hormone-secreting cells, tissues, and organs.
- Exocrine glands have a duct; endocrine glands are ductless.
- Hormones are chemical messengers that are carried by the blood throughout the body, where they modify cellular functions of target cells.

10.1 The Chemical Nature of Hormones

- There are four major types of communication in the body: 1) neural, 2) paracrine, 3) endocrine, 4) neuroendocrine. All target cells have receptors for chemical messengers that affect them.
- Prostaglandins are not secreted by endocrine glands. They are formed by most body cells and have a distinctly local (paracrine) effect.
- The major endocrine glands are the adrenal glands, gonads, pancreas, parathyroid glands, pineal gland, pituitary gland, thymus, and thyroid gland. In addition, the hypothalamus functions like an endocrine gland in some ways.
- Hormones may be classified chemically as either steroid hormones or nonsteroid hormones.
- Steroid hormones and thyroid hormones combine with a receptor within the target cell and interact with DNA to affect production of mRNA. All other nonsteroid hormones combine with a receptor in the plasma membrane of the target cell, which activates a membrane enzyme that promotes synthesis of cyclic AMP (cAMP), a second messenger. Cyclic AMP, in turn, activates other enzymes that bring about cellular changes.
- Production of most hormones is controlled by a negative-feedback mechanism.
- The negative-feedback mechanisms of hormone production work one of three ways: (1) hormonal, (2) neural, and (3) humoral.
- Endocrine disorders are associated with severe hyposecretion or hypersecretion of various hormones. Hyposecretion may result from injury. Hypersecretion is sometimes caused by a tumor.

10.2 Pituitary Gland

- The pituitary gland is attached to the hypothalamus by a short stalk. It consists of an anterior lobe and a posterior lobe.
- The hypothalamus secretes releasing hormones and inhibiting hormones that are carried to the anterior lobe by the hypophyseal portal veins. The releasing and inhibiting hormones regulate the secretion of anterior lobe hormones.
- Anterior lobe hormones are
  a. growth hormone (GH), which stimulates growth and division of body cells;
  b. thyroid-stimulating hormone (TSH), which activates the thyroid gland to secrete thyroid hormones;
  c. adrenocorticotropic hormone (ACTH), which stimulates the secretion of hormones by the adrenal cortex;

d. follicle-stimulating hormone (FSH) and luteinizing hormone (LH), which affect the gonads (in females, FSH stimulates production of estrogens by the ovaries, and the development of the ovarian follicles, leading to oocyte production; in males, it activates sperm production by the testes; in females, LH promotes ovulation and stimulates development of the corpus luteum, which produces progesterone; in males, it stimulates testosterone production); and
e. prolactin (PRL), which initiates and maintains milk production by the mammary glands.

- Hyposecretion of GH in childhood causes pituitary dwarfism. Hypersecretion of GH in childhood causes gigantism, while during adulthood it causes acromegaly.
- Hyposecretion and hypersecretion of TSH leads to secondary thyroid disorders.
- Hormones of the posterior lobe are formed by neurons in the hypothalamus and are released within the posterior lobe.
- There are two posterior lobe hormones:
  a. antidiuretic hormone (ADH) promotes retention of water by the kidneys;
  b. oxytocin stimulates contraction of the uterus during childbirth, contractions of mammary glands in breast-feeding, and parental caretaking behaviors and sexual pleasure in both genders.
- Hyposecretion of ADH causes diabetes insipidus.

10.3 Thyroid Gland

- The thyroid gland is located just inferior to the larynx, with two lobes lateral to the trachea.
- TSH stimulates the secretion of thyroxine (T_4) and triiodothyronine (T_3), which increase cellular metabolism, protein synthesis, and neural activity.
- Iodine is an essential component of the T_4 and T_3 molecules.
- Calcitonin decreases the level of blood Ca^{2+} by promoting Ca^{2+} deposition in bones. It also promotes the excretion of Ca^{2+} by the kidneys. Its secretion is controlled humorally by the level of Ca^{2+} in the blood.
- Hypersecretion of thyroid hormones causes Graves disease. Iodine deficiency causes simple goiter.
- Hyposecretion of thyroid hormones in infants and children causes cretinism; in adults, it causes myxedema.

10.4 Parathyroid Glands

- The parathyroid glands are embedded in the posterior surface of the thyroid gland.
- Parathyroid hormone increases the level of blood Ca^{2+} by promoting Ca^{2+} removal from bones, Ca^{2+} absorption from the intestine, and Ca^{2+} retention by the kidneys. PTH also activates vitamin D, which helps stimulate Ca^{2+} absorption by intestine.
- Parathyroid secretion is controlled humorally by the level of blood Ca^{2+}.
- Parathyroid hormone and calcitonin work antagonistically to regulate blood Ca^{2+} levels.
- Hyposecretion of PTH causes tetany, which may result in death. Hypersecretion causes weak, soft, deformed bones that may fracture spontaneously.

10.5 Adrenal Glands

- An adrenal gland is located superior to each kidney. Each gland consists of two parts: a deep adrenal medulla and a superficial adrenal cortex.
- The adrenal medulla secretes epinephrine and norepinephrine, which prepare the body to deal with emergency situations. They increase the heart rate, circulation to nervous and muscular systems, and glucose level in the blood.
- The adrenal cortex secretes a number of hormones that are classified as mineralocorticoids, glucocorticoids, and androgens.
- Aldosterone is the most important mineralocorticoid. It helps to regulate the concentration of electrolytes in the blood, especially sodium and potassium ions, which increases blood pressure.
- Cortisol is the most important glucocorticoid. It promotes the formation of glucose from noncarbohydrate sources and inhibits inflammation. Its secretion is regulated by ACTH.
- Cortisol is involved in the response to chronic stress.
- Small amounts of androgens are secreted. They have little effect in adult males but contribute to the sex drive in adult females.
- Hyposecretion of cortisol causes Addison disease. Hypersecretion causes Cushing syndrome.

10.6 Pancreas

- The pancreas is both an exocrine and an endocrine gland. Its hormones are formed by the pancreatic islets, and their secretions are controlled by the level of blood glucose.
- Glucagon, from the alpha cells, increases the level of blood glucose by stimulating the liver to form glucose from glycogen and some noncarbohydrate sources.
- Insulin, from the beta cells, decreases the level of blood glucose by aiding the movement of glucose into cells.
- The antagonistic functions of glucagon and insulin keep the level of blood glucose within normal limits.
- Hyposecretion of insulin or a decrease in the number of insulin receptors causes diabetes mellitus. Hypersecretion may cause hypoglycemia.

10.7 Gonads

- Gonads are the sex glands: the ovaries in females and the testes in males. They secrete sex hormones, in addition to producing sex cells. The secretion of these hormones is controlled by FSH and LH.
- Estrogens are secreted by ovarian follicles and they stimulate development of female reproductive organs and secondary sex characteristics. Estrogens also help to prepare the uterus for a preembryo and help to maintain pregnancy.
- Progesterone is secreted mostly by the corpus luteum of the ovary after ovulation. It prepares the uterus for the preembryo, maintains pregnancy, and prepares the mammary glands for milk production.
- The testes secrete testosterone, the male sex hormone that stimulates the development of the male reproductive organs and secondary sex characteristics.

10.8 Other Endocrine Glands and Tissues

- The pineal gland is located near the roof of the third ventricle of the brain. It secretes melatonin, which seems to lead to the inhibition of secretion of FSH and LH by the anterior lobe of the pituitary gland. The pineal gland also seems to be involved in biorhythms.
- The thymus is located in the thoracic cavity superior to the heart. It secretes thymosins, which are involved in the maturation of white blood cells called T lymphocytes.
- Thymosins also seem to have anti-aging effects.

Self-Review

Answers are located in appendix B.

1. Chemical coordination of body functions is the function of the _____ system, whose glands secrete _____ that serve as chemical messengers.
2. A particular hormone affects only those cells that have _____ for that hormone.
3. _____ hormones use a second messenger to produce their characteristic effects on cells.
4. The secretion of most hormones is regulated by a _____ mechanism.
5. The secretion of pituitary hormones is regulated by a part of the brain called the _____.
6. The pituitary gland secretes four hormones that regulate secretion of other endocrine glands. _____ acts on the thyroid gland; ACTH acts on the _____; _____ and _____ act on the gonads.
7. Metabolic rate is regulated by _____ secreted by the _____.
8. The concentration of Ca^{2+} in the blood is regulated by two hormones with antagonistic actions: _____ promotes Ca^{2+} deposition in bones; _____ promotes Ca^{2+} removal from bones.
9. Secretions of the adrenal _____ prepare the body to react in emergencies.
10. The primary hormone regulating the concentration of mineral ions in the blood is _____.
11. The pancreatic hormone that increases the concentration of blood glucose is _____.
12. The primary sex hormones in females are _____ and _____; the male sex hormone is _____.

Critical Thinking

1. Some hormones affect many widely distributed cells in the body but others affect relatively few, localized cells. Explain how this occurs.
2. A blood test indicates that a patient has a low level of thyroxine. What are three possible causes of this condition? Explain.
3. A tumor in the parathyroid gland causes hypersecretion of PTH. Predict (1) the effects of this hormone on the skeletal system and (2) the effects on calcitonin production.
4. Using what you have learned about the endocrine system, explain why individuals who work the "night shift" have such a hard time staying awake.

8
CHAPTER

The Cardiovascular System

A two-alarm fire is called in and the alarm begins to sound in the local fire station. Charlie, a veteran firefighter, begins shout directions as he and the others in his unit don their gear. As they travel to the site of the blaze, Charlie is so focused on the task at hand that he is barely aware of the cardiovascular changes occurring within his body. His heart rate increases in order to increase his blood pressure, which in turn increases blood flow through his body. Changes within his blood vessels allow blood flow to be prioritized to organs that will be called upon once he arrives at the scene. Increasing activity in his skeletal muscle tissue, cardiac muscle tissue, and nervous tissue requires elevated rates of ATP production, which in turn require an increase in the delivery of oxygen, glucose, and fatty acids. Increased blood flow to the lungs, liver, and adipose tissue is needed to maintain sufficient levels of these vital chemicals. By the time the fire truck reaches the scene, Charlie is physically prepared to rush into the burning building to rescue trapped inhabitants, thanks in part to the actions of his cardiovascular system.

CHAPTER OUTLINE

SELECTED KEY TERMS

Arteries Blood vessels that carry blood away from the heart.
Atrium (atrium = vestibule) A heart chamber that receives blood returned to the heart by veins.
Capillaries Tiny blood vessels in tissues where exchange of materials between the blood and interstitial fluid occurs.
Cardiac output The volume of blood pumped from each ventricle in one minute.
Cardiac cycle The sequence of events that occur during one heartbeat.
Diastole The relaxation phase of the cardiac cycle.
Pulmonary circuit (pulmo = lung) The blood pathway that transports blood to and from the lungs.
Stroke volume The volume of blood pumped from each ventricle per heartbeat.
Systemic circuit The blood pathway that transports blood to and from all parts of the body except the lungs.
Systole The contraction phase of the cardiac cycle.
Vasoconstriction (vas = vessel) Contraction of vessel smooth muscle to decrease the diameter of the blood vessel.
Vasodilation Relaxation of vessel smooth muscle to increase the diameter of the blood vessel.
Veins Blood vessels that carry blood toward the heart.
Ventricle (ventr = underside) A heart chamber that pumps blood into an artery.

THE HEART AND BLOOD VESSELS form the *cardiovascular* (kar-dē-ō-vas′-kū-lar) *system.* The heart pumps blood through a closed system of blood vessels. Figure 12.1 shows the general scheme of circulation of blood in the body. Blood vessels colored blue carry deoxygenated (oxygen-poor) blood; those colored red carry oxygenated (oxygen-rich) blood. Large arteries carry blood away from the heart and branch into smaller and smaller arteries that open into capillaries, the smallest blood vessels, where materials are exchanged with body tissues. Capillaries open into small veins that merge to form larger and larger veins, and the largest veins return blood to the heart.

12.1 Anatomy of the Heart

Learning Objectives

1. Identify the protective coverings of the heart.
2. Describe the parts of the heart and their functions.
3. Trace the flow of blood through the heart.
4. Describe the blood supply to the heart.

The heart is a four-chambered muscular pump that is located within the mediastinum in the thoracic cavity. It lies between the lungs and just superior to the diaphragm. The *apex* of the heart is the inferior pointed end, which extends toward the left side of the thoracic cavity at the level of the fifth rib. The *base* of the heart is the superior portion, which is attached to several large blood vessels at the level of the second rib. The heart is about the size of a closed fist. Note the relationship of the heart with the surrounding organs in figure 12.2.

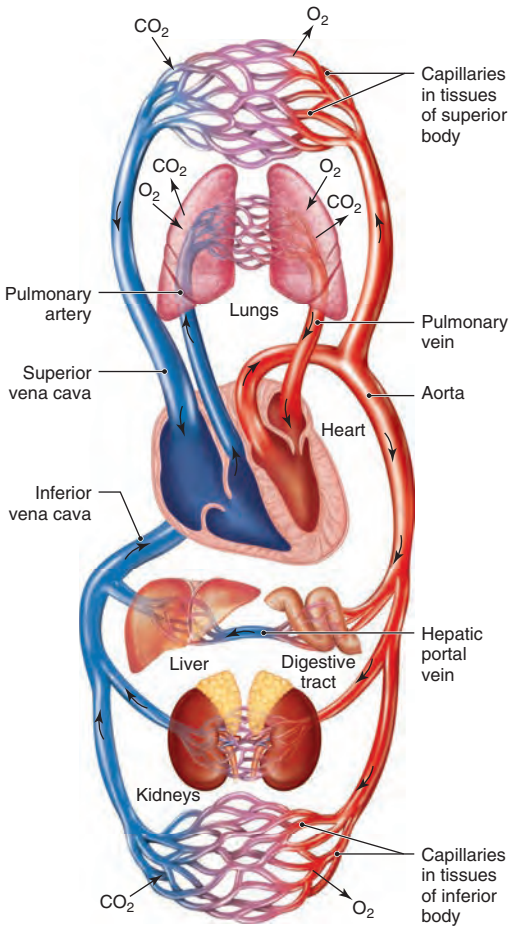


Figure 12.1 The general scheme of the cardiovascular system. Blood vessels carrying oxygenated blood are colored red; those carrying deoxygenated blood are colored blue.

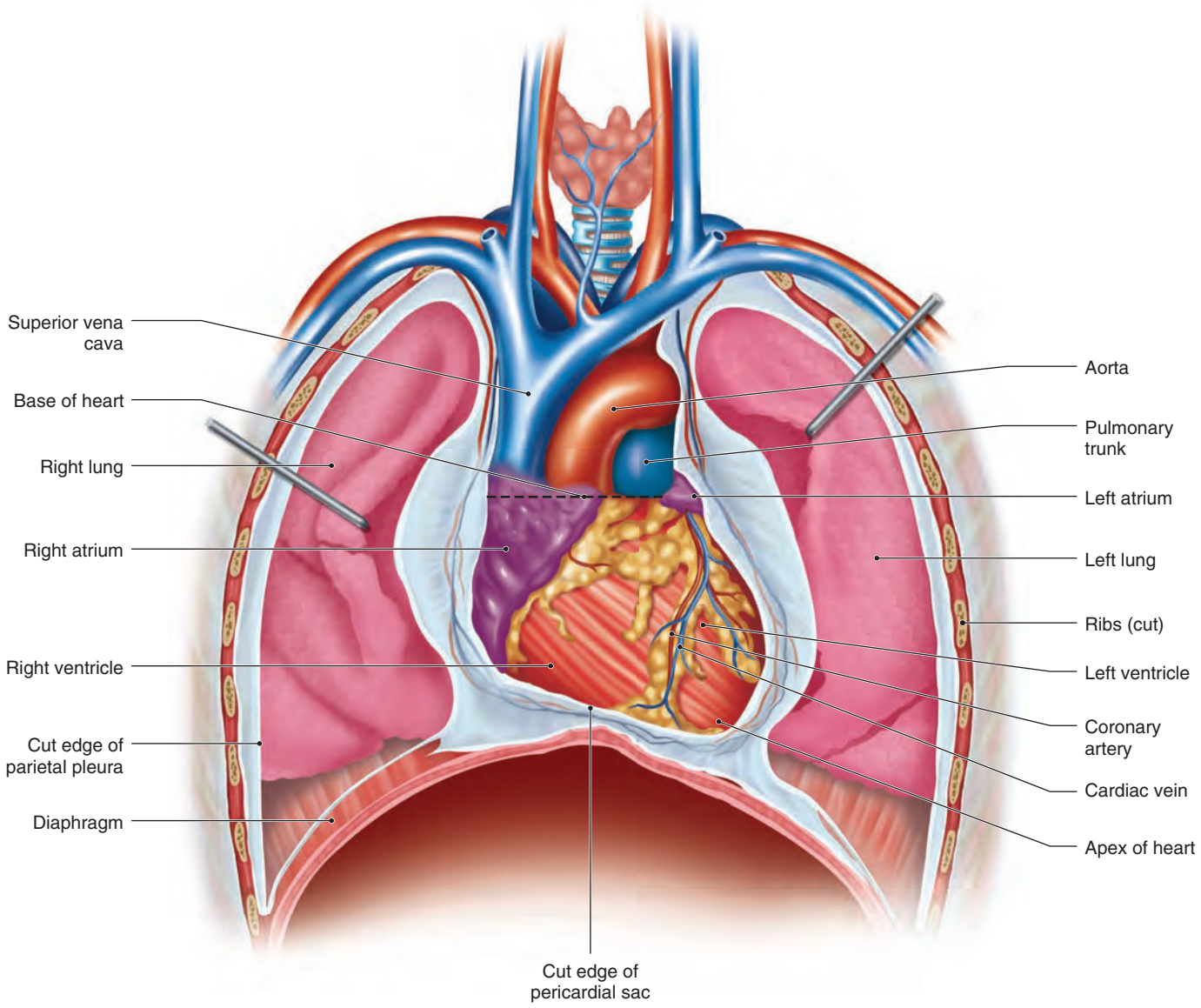


Figure 12.2 The heart is located within the mediastinum in the thoracic cavity.

Protective Coverings

The heart and the bases of the attached blood vessels are enveloped by membranes that are collectively called the **pericardium** (per-i-kar′-dē-um). An external, loosely fitting *pericardial sac* separates the heart from surrounding tissues and allows space for the heart to expand and contract as it pumps blood. The pericardial sac consists of two membranes: an external *fibrous pericardium* and an internal **parietal layer** of **serous pericardium.** The fibrous pericardium is a tough, unyielding membrane composed of dense irregular connective tissue. It is attached to the diaphragm, internal surfaces of the sternum and thoracic vertebrae, and to adjacent connective tissues (figure 12.2). The delicate parietal pericardium lines the internal surface of the fibrous pericardium. At the bases of the large vessels (base of the heart), the parietal layer of serous pericardium folds back to form the **epicardium** (**visceral layer** of **serous pericardium**), which forms the thin membrane that tightly adheres to the surface of the heart. The potential space between the parietal pericardium and the epicardium is the **pericardial cavity** (figure 12.3). This cavity is filled with pericardial fluid, which reduces the friction between the two layers of the pericardium when the heart contracts and expands.

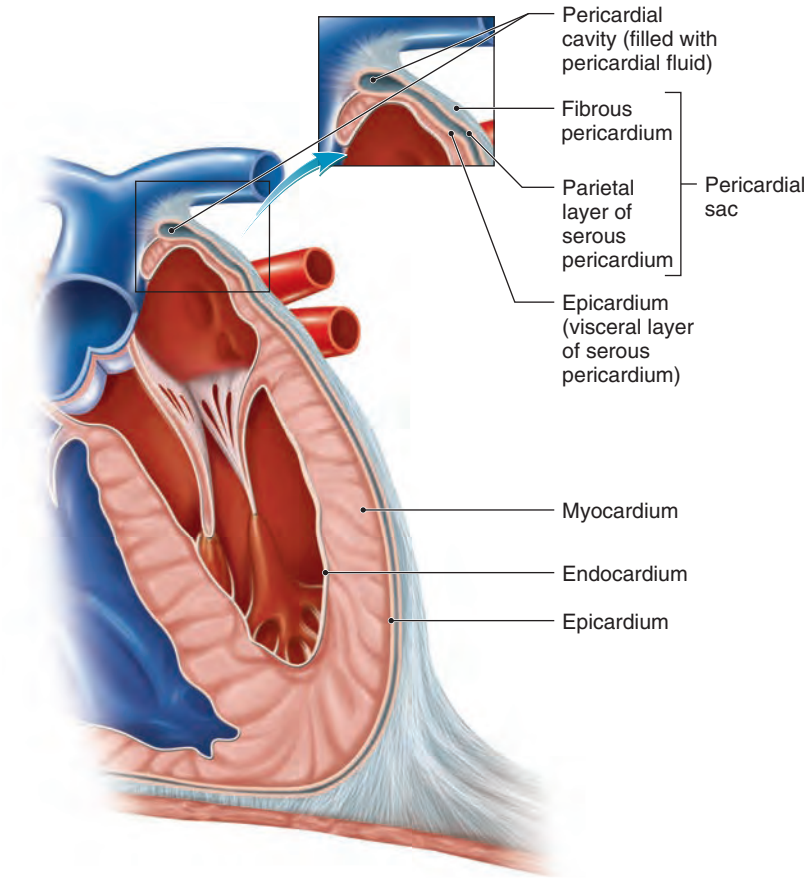


Figure 12.3 The pericardium and heart wall. The inset shows that the fibrous pericardium is lined by the parietal layer of serous pericardium, which folds back to form the epicardium.

The Heart Wall

The wall of the heart consists of a thick layer of cardiac muscle tissue, the **myocardium** (mī-ō-kar′-dē-um), sandwiched between two thin membranes. Contractions of the myocardium provide the force that pumps the blood through the blood vessels. The epicardium is the thin membrane that is firmly attached to the external surface of the myocardium. Blood vessels that nourish the heart itself are located within the epicardium. The internal surface of the myocardium is covered with a simple squamous epithelium called the **endocardium.** The endocardium not only lines the chambers and valves of the heart, but also is continuous with the internal lining of the blood vessels attached to the heart (figure 12.3).

Heart Chambers

The two superior chambers are the **atria** (ā′-trē-ah) (singular, *atrium*), which receive blood being returned to the heart by the veins. The two inferior chambers are the **ventricles** (ven′-tri-kuls), which pump blood into the arteries. There is no opening between the two atria or between the two ventricles. The atria are separated from each other by a partition called the *interatrial septum.* The ventricles are separated by the *interventricular septum,* a thick partition of cardiac muscle tissue (figure 12.4). The heart is a double pump. The right atrium and right ventricle compose the right pump. The left atrium and left ventricle compose the left pump.

The walls of the atria are much thinner than the walls of the ventricles. Differences in thickness are due to differences in the amount of cardiac muscle tissue that is present, which in turn reflects the work required of each chamber. Atrial walls possess less cardiac muscle tissue because blood movement from atria to ventricles is mostly passive, so that force from contraction is not as essential. The ventricles have more cardiac muscle tissue in order to create enough force to push blood superiorly out of the heart. The left ventricle has a thicker, more muscular wall than the right ventricle because it must pump blood throughout the entire body, except the lungs, whereas the right ventricle pumps blood only to the lungs. Locate the atria and ventricles in figure 12.4, and also in figures 12.2 and 12.5, which show external views of the heart. Table 12.1 summarizes the functions of the heart chambers.

Heart Valves

Like all pumps, the heart contains valves that allow the blood to flow in only one direction through the heart. The two types of heart valves are atrioventricular valves (AV valves) and semilunar valves. Observe the location and structure of the heart valves in figures 12.4 and 12.6.

Atrioventricular Valves

The opening between each atrium and its corresponding ventricle is guarded by an **atrioventricular** (ā-trē-ō-ven-trik′-ū-lar) **valve** that is formed of dense irregular connective tissue. Each valve allows blood to flow from the atrium into the ventricle but prevents a backflow of blood from the ventricle into the atrium. The AV valve between the right atrium and the right ventricle is the **tricuspid** (trī-kus′-pid), or **right atrioventricular, valve.** Its name indicates that it is composed of three cusps, or flaps, of tissue. The **mitral** (mī′-tral), or **left atrioventricular, valve** consists of two cusps and is located between the left atrium and the left ventricle.

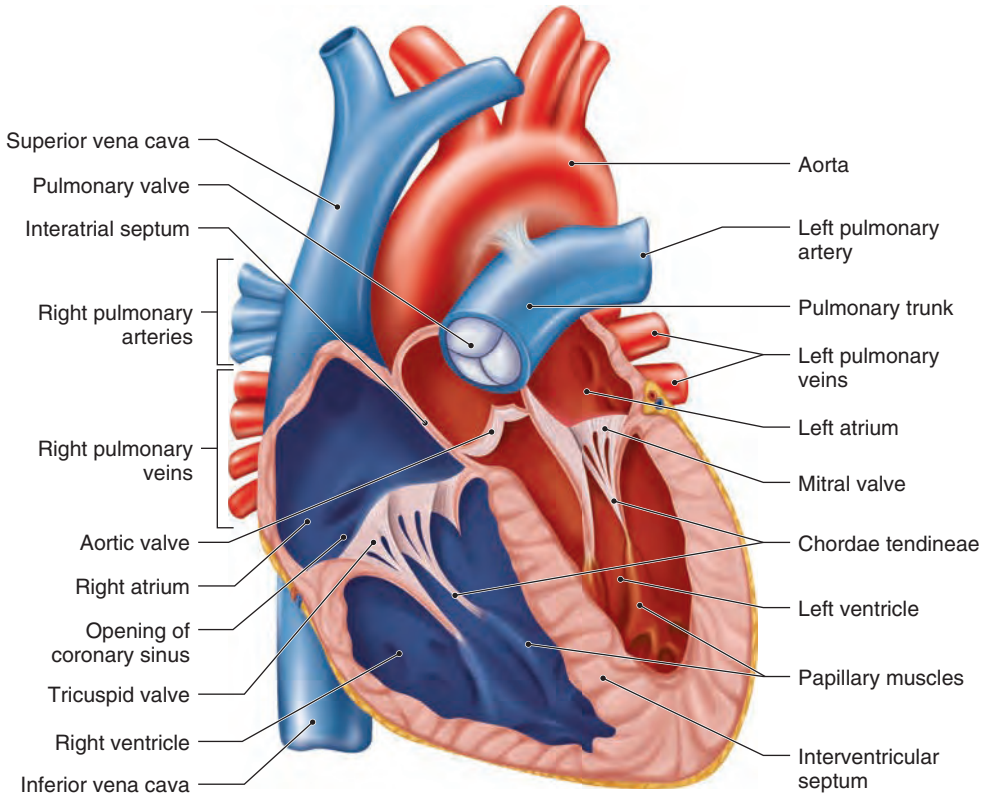


Figure 12.4 The internal structure of the heart is shown in frontal section.

Table 12.1 Functions of the Heart Chambers

Chamber	Function
Right atrium	Receives deoxygenated blood from the superior and inferior venae cavae and the coronary sinus, and passes this blood through the tricuspid valve to the right ventricle
Right ventricle	Receives deoxygenated blood from the right atrium and pumps this blood through the pulmonary valve into the pulmonary trunk
Left atrium	Receives oxygenated blood from the pulmonary veins and passes this blood through the mitral valve to the left ventricle
Left ventricle	Receives oxygenated blood from the left atrium and pumps this blood through the aortic valve into the aorta

The AV valves originate from rings of thick, dense irregular connective tissue that support the junction of the ventricles with the atria and the large arteries attached to the ventricles. This supporting dense irregular tissue is called the *fibrous skeleton* of the heart (figure 12.6). The fibrous skeleton not only provides structural support but also serves as insulation separating the electrical activity of the atria and ventricles. This insulation enables the atria and ventricles to contract independently.

Thin strands of dense irregular connective tissue, the **chordae tendineae** (kor′-de- ten′-di-ne-ee), extend from the valve cusps to the **papillary muscles,** small mounds of cardiac muscle tissue that project from the internal walls of the ventricles (see figure 12.4). The chordae tendineae prevent the valve cusps from being forced into the atria during ventricular contraction. In fact, they are normally just the right length to allow the cusps to press against each other and tightly close the opening during ventricular contraction. Table 12.2 summarizes the functions of the heart valves.

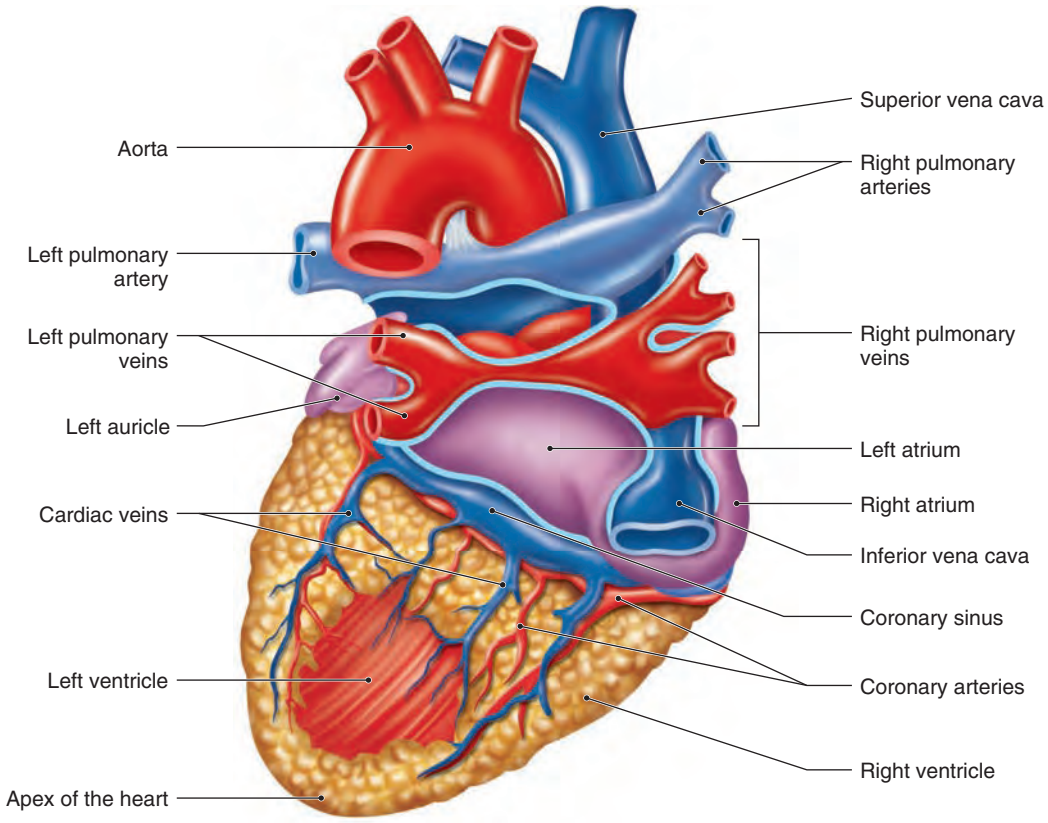


Figure 12.5 A posterior view of the heart and the associated blood vessels.

Semilunar Valves

The **semilunar valves** are located in the bases of the large arteries that carry blood from the ventricles. The **pulmonary valve** is located at the base of the pulmonary trunk, which extends from the right ventricle. The **aortic valve** is located at the base of the aorta, which extends from the left ventricle.

Each semilunar valve is composed of three pocket-like cusps of dense irregular connective tissue. They allow blood to be pumped from the ventricles into the arteries during ventricular contraction, but they prevent a backflow of blood from the arteries into the ventricles during ventricular relaxation.

Table 12.2 Heart Valves

Valve	Location	Function
Atrioventricular Valves		
Tricuspid valve	Opening between the right atrium and right ventricle	Prevents backflow of blood from the right ventricle into the right atrium
Mitral valve	Opening between the left atrium and left ventricle	Prevents the backflow of blood from the left ventricle into the left atrium
Semilunar Valves		
Pulmonary valve	Entrance to the pulmonary trunk	Prevents backflow of blood from the pulmonary trunk into the right ventricle
Aortic valve	Entrance to the aorta	Prevents backflow of blood from the aorta into the left ventricle

Flow of Blood Through the Heart

Figure 12.7 diagrammatically shows the flow of blood through the heart and the major vessels attached to the heart. Blood is oxygenated as it flows through the lungs and becomes deoxygenated as it releases oxygen to body tissues. Trace the flow of blood through the heart and major vessels in figure 12.7 as you read the following description.

The right atrium receives deoxygenated blood from all parts of the body except the lungs via three veins: the superior and inferior venae cavae and the coronary sinus. The **superior vena cava** (vē′-nah kā′-vah) returns blood from the head, neck, shoulders, upper limbs, and thoracic and abdominal walls. The **inferior vena cava** returns blood from the inferior trunk and lower limbs. The **coronary sinus** drains deoxygenated blood from cardiac muscle tissue. Simultaneously, the left atrium receives oxygenated blood returning to the heart from the lungs via the **pulmonary veins.** Blood flows from the left and right atria into the corresponding ventricles. About 70% of the blood flow into the ventricles is passive, and about 30% results from atrial contraction.

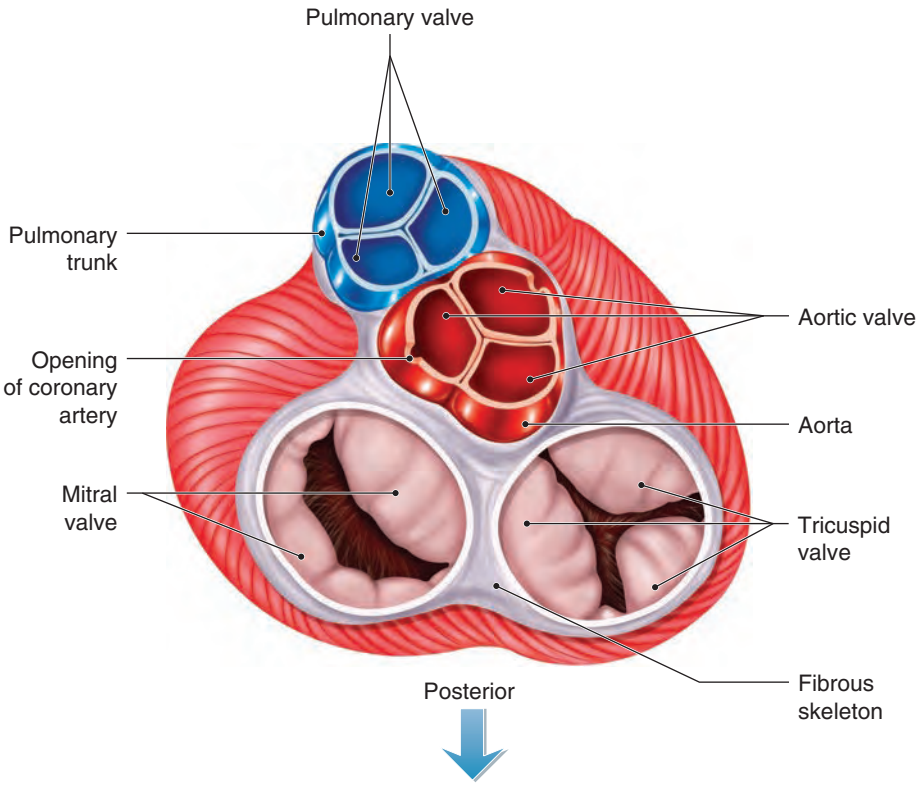


Figure 12.6 A superior view of the heart valves. Note the fibrous skeleton of the heart.

After blood has flowed from the atria into their respective ventricles, the ventricles contract. The right ventricle pumps deoxygenated blood into the **pulmonary trunk.** The pulmonary trunk branches to form the **left** and **right pulmonary arteries,** which carry blood to the lungs. The left ventricle pumps oxygenated blood into the **aorta** (ā-or′-tah). The aorta branches to form smaller arteries that carry blood to all parts of the body except the lungs. Locate these major blood vessels associated with the heart in figures 12.2, 12.4, 12.5, and 12.7.

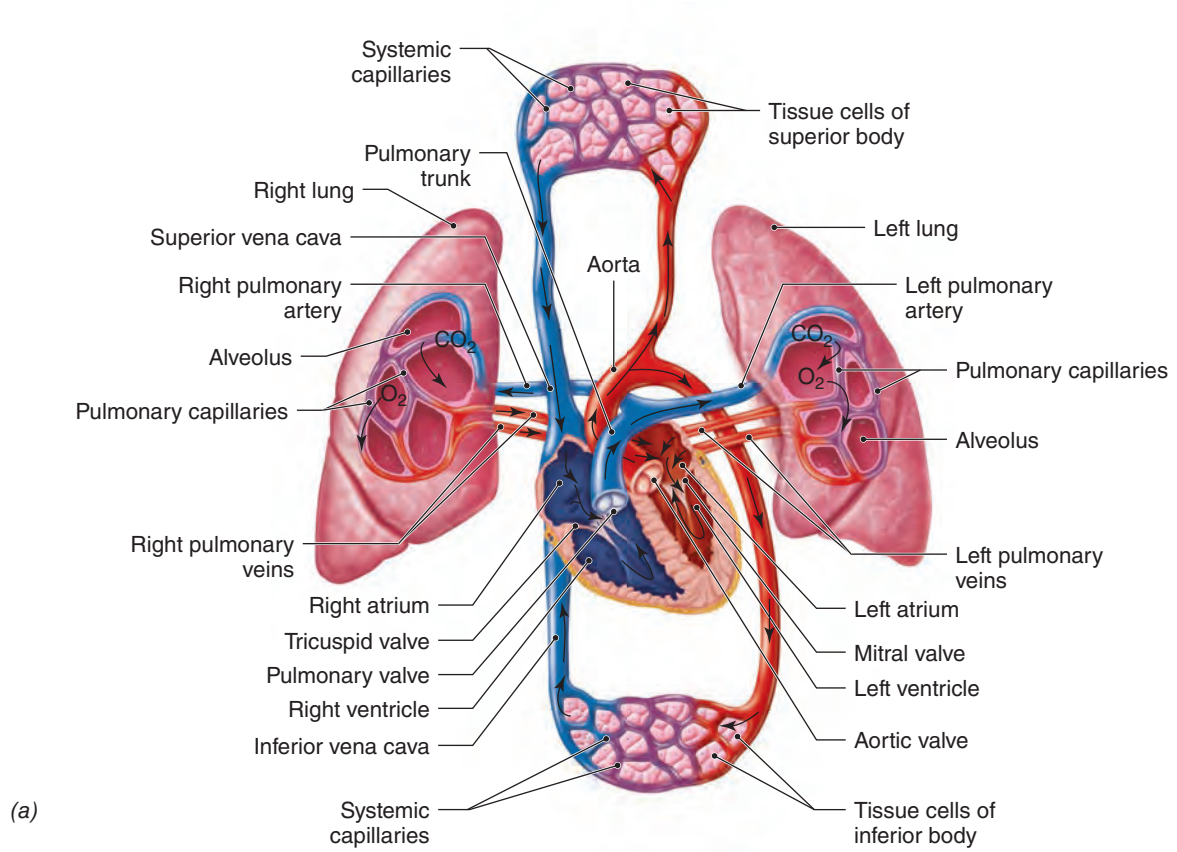
Because the heart is a double pump, there are two basic pathways, or circuits, of blood flow as shown in figure 12.7. The **pulmonary circuit** carries deoxygenated blood from the right ventricle to the lungs and returns oxygenated blood from the lungs to the left atrium. The **systemic circuit** carries oxygenated blood from the left ventricle to all parts of the body except the lungs and returns deoxygenated blood to the right atrium.

Blood Supply to the Heart

The heart requires a constant supply of blood to nourish its own tissues. Blood is supplied by **left** and **right coronary** (kor′-ō-na-rē) **arteries**, which branch from the aorta just distal to the aortic valve (figures 12.6 and 12.18a). Blockage of a coronary artery may result in a heart attack. After passing through capillaries in cardiac muscle tissue, blood is returned via **cardiac** (kar′-dē-ak) **veins**, which lie next to the coronary arteries. These veins empty into the **coronary sinus,** which drains into the right atrium. Locate these blood vessels in figures 12.2 and 12.5 and note the adipose tissue that lies alongside the vessels. Also, study the relationships of the atria, ventricles, and large blood vessels associated with the heart.

Check My Understanding

1. What are the names and functions of the heart chambers?
2. What are the names and functions of the heart valves?
3. Trace a drop of blood as it flows through the heart and the pulmonary and systemic circuits.
4. Describe the flow of blood throughout the myocardium.



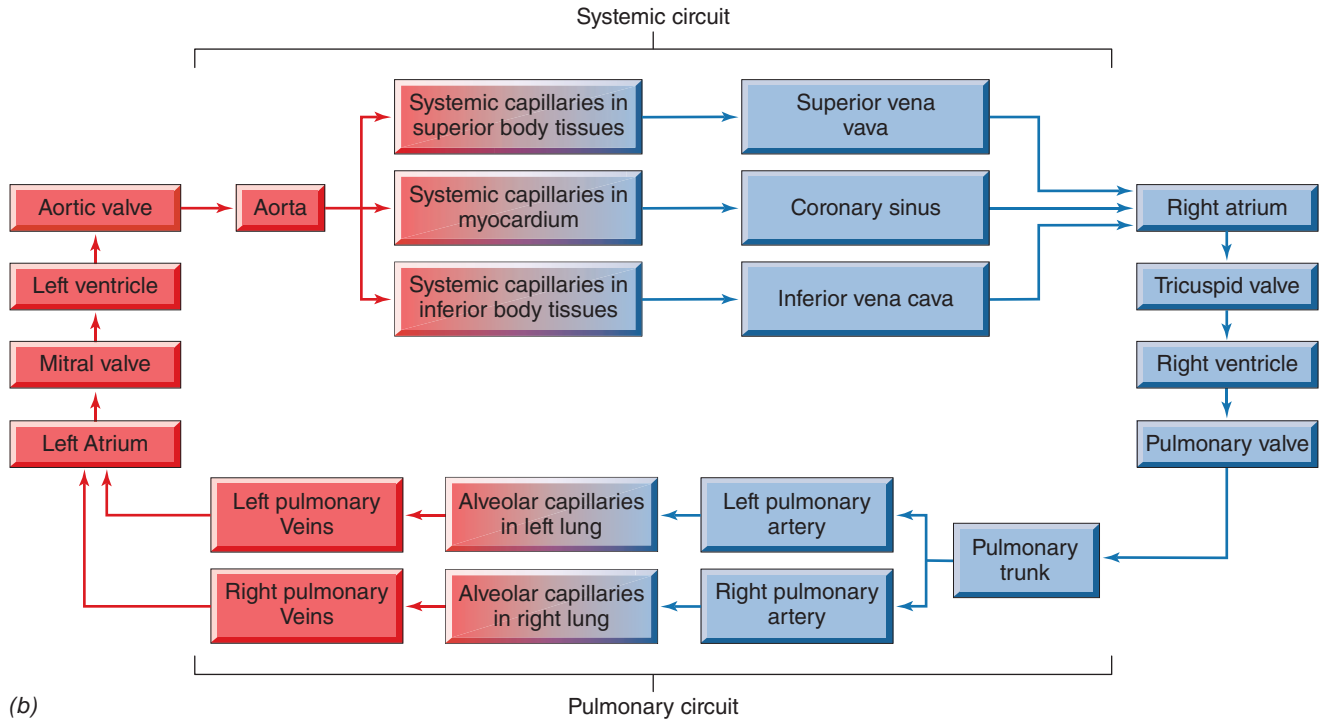


Figure 12.7 Blood flow through the heart and the systemic and pulmonary circuits. Heart chambers and vessels colored red carry oxygenated blood. Those colored blue carry deoxygenated blood.

Clinical Insight

If cusps of an AV valve collapse and open into the atrium, some blood may regurgitate (backflow) into the atrium during ventricular contractions. This is what happens in a disorder known as *mitral valve prolapse (MVP).* In some cases, it causes no serious dysfunction. In others, fatigue and shortness of breath may occur. Persons with MVP are susceptible to *endocarditis,* inflammation of the endocardium, caused by some species of *Streptococcus* bacteria. Endocarditis can result in scarring of the valve cusps, which further decreases valve function. Persons with MVP are often advised to take antibiotics prior to dental work to prevent bacteria from entering the blood and being carried to the heart.

12.2 Cardiac Cycle

Learning Objectives

5. Describe the events of the cardiac cycle.
6. Describe the sounds of the heartbeat.

The **cardiac cycle** refers to the sequence of events that occur during one heartbeat. The contraction phase of a cardiac cycle is known as **systole** (sis′-to-lē); the relaxation phase is called **diastole** (dī′-as-to-lē). These phases are illustrated in figure 12.8. Note that the ventricles are relaxed when the atria contract, and the atria are relaxed when the ventricles contract. Systole increases blood pressure within a chamber, while diastole decreases blood pressure within a chamber.

When both the atria and ventricles are relaxed between beats, blood flows passively into the atria from the large veins leading to the heart and then passively into the ventricles. Then, the atria contract (atrial systole), forcing more blood into the ventricles so that they are filled. Immediately thereafter, the ventricles contract. Ventricular systole produces high blood pressure within the ventricles, which causes both AV valves to close and both semilunar valves to open. Opening of the semilunar valves allows blood to move into the arteries leading from the heart. Ventricular diastole immediately follows and the decrease in ventricle pressure allows the AV valves to open. Simultaneously, the semilunar valves close because of the greater blood pressure within the arteries. The cardiac cycle is then repeated. Study these relationships in figure 12.8.

Heart Sounds

The sounds of the heartbeat are usually described as *lub-dup* (pause) *lub-dup,* and so forth. These sounds are produced by the closing of the heart valves. The first sound results from the closing of the AV valves in the beginning of ventricular systole. The second sound results from the closing of the semilunar valves in the beginning of ventricular diastole. If any of the heart valves are defective and do not close properly, an additional sound, known as a heart murmur, may be heard.

Check My Understanding

5. What are the events of a cardiac cycle?
6. What produces the heart sounds?

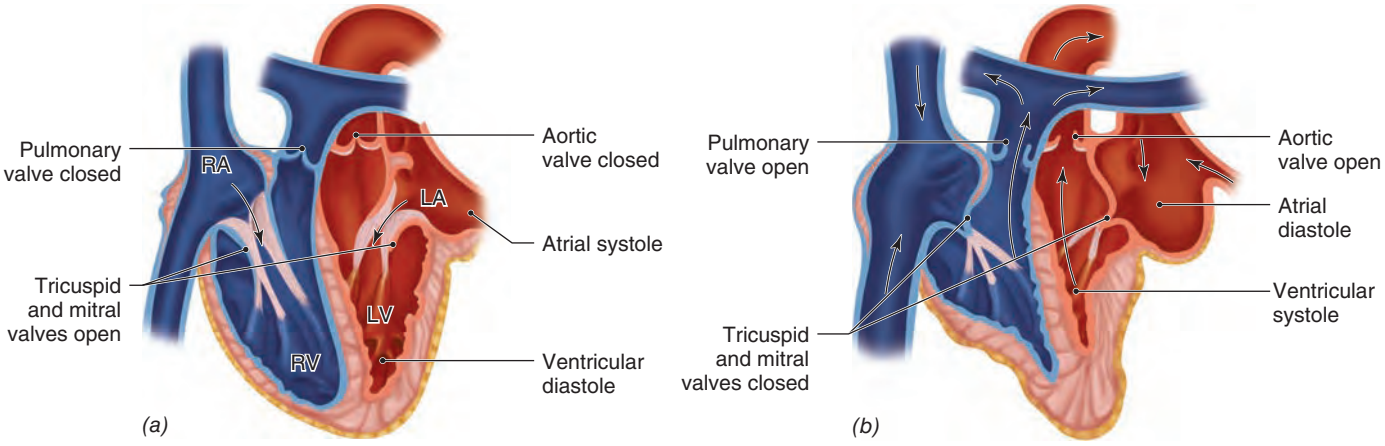


Figure 12.8 The Cardiac Cycle.
(a) Blood flows from the atria into the ventricles during ventricular diastole. *(b)* Blood is pumped from the ventricles during ventricular systole.

12.3 Heart Conduction System

Learning Objective

7. Describe the parts of the heart conduction system and their functions.

The heart is able to contract on its own because it contains specialized cardiac muscle tissue that spontaneously forms impulses and transmits them to the myocardium to initiate contraction. This specialized tissue forms the *conduction system* of the heart, which consists of the sinoatrial node, atrioventricular node, AV bundle, bundle branches, and ventricular fibers. Observe the location of the conduction system and its parts in figure 12.9.

The **sinoatrial** (sī-nō-ā′-trē-al) **node (SA node)** is located in the right atrium at the junction of the superior vena cava. It is known as the pacemaker of the heart because it rhythmically forms electrical impulses to initiate each heartbeat. The impulses are transmitted to the myocardium of the atria, where they produce a simultaneous contraction of the atria. The flow of impulses causes contraction of the atria from superior to inferior, forcing blood into the ventricles. At the same time, the impulses are carried to the **atrioventricular node (AV node),** which is located in the right atrium near the junction with the interventricular septum.

There is a brief time delay as the impulses pass slowly through the AV node, which allows time for the ventricles to fill with blood. From the AV node, the impulses pass along the **AV bundle** *(bundle of His),* a group of large fibers that divide into **left** and **right bundle branches** extending inferiorly to the interventricular septum and superior to the lateral walls of the ventricles. The smaller **ventricular** *(Purkinje)* **fibers** arise from the bundle branches and carry the impulses to the myocardium of the ventricles, where they stimulate ventricular contraction. The distribution of the ventricular fibers causes the ventricles to contract from the apex superiorly so that blood is forced into the pulmonary trunk and aorta.

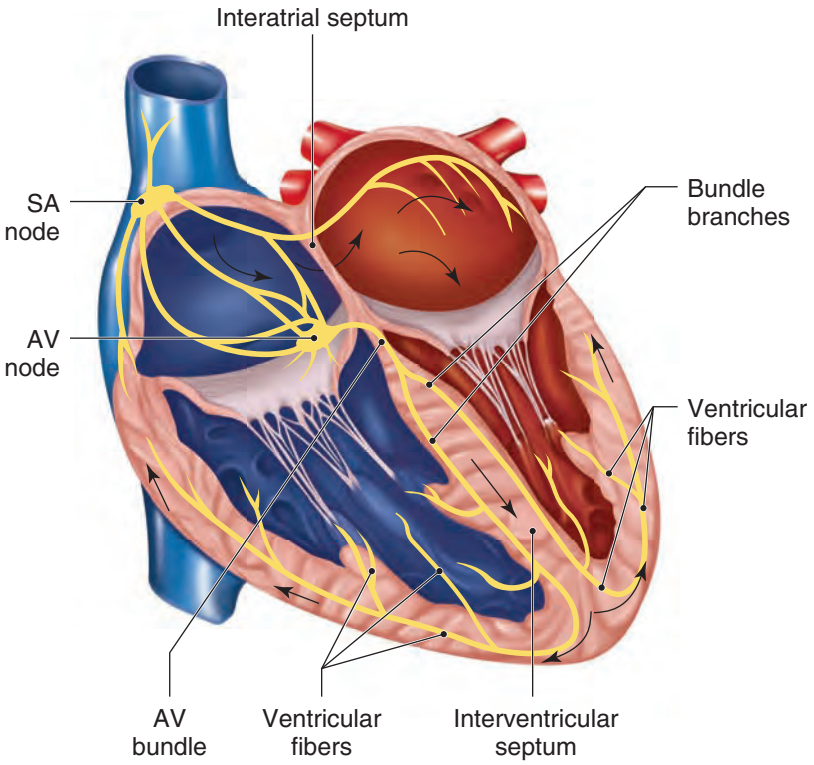


Figure 12.9 The heart conduction system. Arrows indicate the flow of impulses from the SA node.

Clinical Insight

If a coronary artery is partially obstructed by the fatty deposits of *atherosclerosis* (see the disorders section in this chapter for details), portions of the myocardium may be deprived of adequate blood. This produces chest pain known as *angina pectoris*. In severe cases, treatment may involve one of two approaches: coronary angioplasty or coronary bypass surgery.

In *coronary angioplasty,* a catheter that contains a balloon at its tip is inserted into an artery of an upper or lower limb and is threaded into the affected coronary artery. The balloon is positioned at the obstruction and is inflated for a few seconds to compress the fatty deposit and enlarge the lumen of the affected coronary artery. A meshlike metal tube called a stent is then inserted and positioned at the site of the obstruction to hold open the artery. The stent may be coated with a chemical that inhibits the growth of cells to minimize the chances that the artery will become obstructed again.

In *coronary bypass surgery,* a portion of an artery or a vein from elsewhere in the body is removed and is surgically grafted, providing a bypass around the obstruction to supply blood to the distal portion of the affected coronary artery.

Electrocardiogram

The origination and transmission of impulses through the conduction system of the heart generate electrical currents that may be detected by electrodes placed on the body surface. An instrument called an *electrocardiograph* is used to transform the electrical currents picked up by the electrodes into a recording called an **electrocardiogram** (**ECG** or **EKG**).

Figure 12.10 shows a normal ECG of five cardiac cycles and an enlargement of a normal ECG of one cardiac cycle. Note that an ECG consists of several deflections, or waves. These waves correlate with the flow of impulses during particular phases of the cardiac cycle.

An electrocardiogram has three distinct waves: the P wave, QRS complex, and T wave. The *P wave* is a small wave. It is produced by the depolarization of the atria. The *QRS complex* is produced by the depolarization of the ventricles. The greater size of the QRS complex is due to the greater muscle mass of the ventricles. The last wave is the *T wave,* which is produced by the repolarization of the ventricular myocardium. The repolarization of the atria is not detected because it is masked by the stronger QRS complex. An ECG provides important information in the diagnosis of heart disease and abnormalities. In reading an ECG, physicians pay close attention to the height of each wave and to the time required for each wave.

Check My Understanding

7. What composes the cardiac conduction system?
8. What events produce the waves of an electrocardiogram?

12.4 Regulation of Heart Function

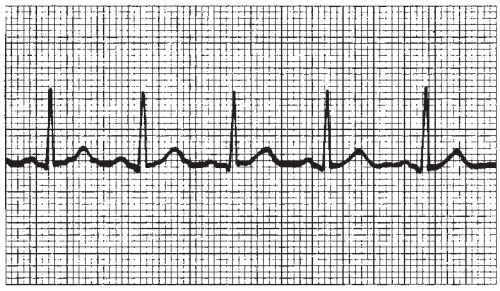
Learning Objective

8. Explain how the heart rate and contraction strength are regulated.

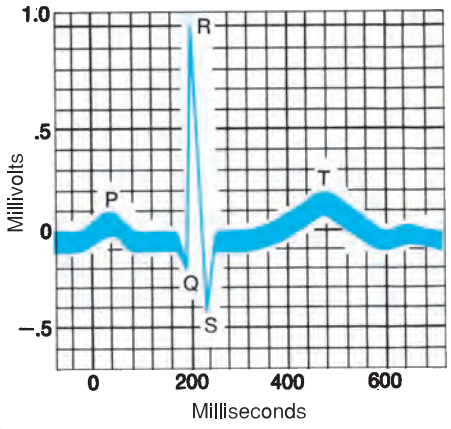
Cardiac output is the volume of blood pumped from each ventricle in one minute, and it is an important measure of heart function. It is determined by two factors: **stroke volume** and **heart rate.** Stroke volume (SV) is the volume of blood pumped from each ventricle per heartbeat. Multiplying this volume by the heart rate (HR), heartbeats per minute, yields the cardiac output (CO).

$$CO = SV \times HR$$

At normal resting values of a stroke volume of 70 ml/beat and a heart rate of 72 beats/min, the cardiac output is 5,040 ml/min. This means that the total volume



(a)



(b)

Figure 12.10 *(a)* A normal ECG showing five cardiac cycles. *(b)* A normal ECG showing one cardiac cycle.

Clinical Insight

Some irregularities in heart rhythms result from improper transmission of impulses by the heart conduction system. In patients in whom the SA node or AV node malfunctions, a normal heartbeat may be obtained by implanting an artificial *pacemaker* in the chest wall. Wires (leads) are threaded through a vein to connect the pacemaker to the heart. This battery-operated device synchronizes heart contractions and controls the heart rate by sending weak electrical pulses to the heart to initiate contraction.

of blood, 4 to 6 liters, passes through each ventricle of the heart each minute. Cardiac output increases with exercise because both stroke volume and heart rate increase.

Heart function is regulated by factors both internal and external to the heart. For example, *venous return,* the amount of blood returning to the heart during diastole, is an internal factor that affects stroke volume. If venous return increases, more blood enters and is pumped from the ventricles, increasing the stroke volume and cardiac output. Heart rate is primarily controlled externally by the autonomic nervous system, although hormones and certain ions also affect it.

Autonomic Regulation

Heart rate regulation is primarily under the control of the **cardiac control center** located within the medulla oblongata of the brain. It receives sensory information about the level of blood pressure from baroreceptors located in the aortic arch and the carotid sinuses of the internal carotid arteries. It also receives sensory information from chemoreceptors in the aortic arch and the carotid bodies of the external carotid arteries (figures 12.11 and 12.19). Baroreceptors are sensitive to changes in vessel wall stretching caused by both high and low blood pressure. Chemoreceptors are stimulated by low blood pH, high blood carbon dioxide levels, and very low blood oxygen levels. The cardiac control center is also affected by emotions, which are generated by the limbic system (see chapter 8).

The cardiac control center consists of both sympathetic and parasympathetic components. Nerve impulses transmitted to the heart via sympathetic axons cause an increase in heart rate and contraction strength, while nerve impulses transmitted by parasympathetic axons cause a decrease in heart rate. The cardiac control center constantly adjusts the frequency of sympathetic and parasympathetic nerve impulses to produce a heart rate and a contraction strength that meets the changing needs of tissue cells (figure 12.11).

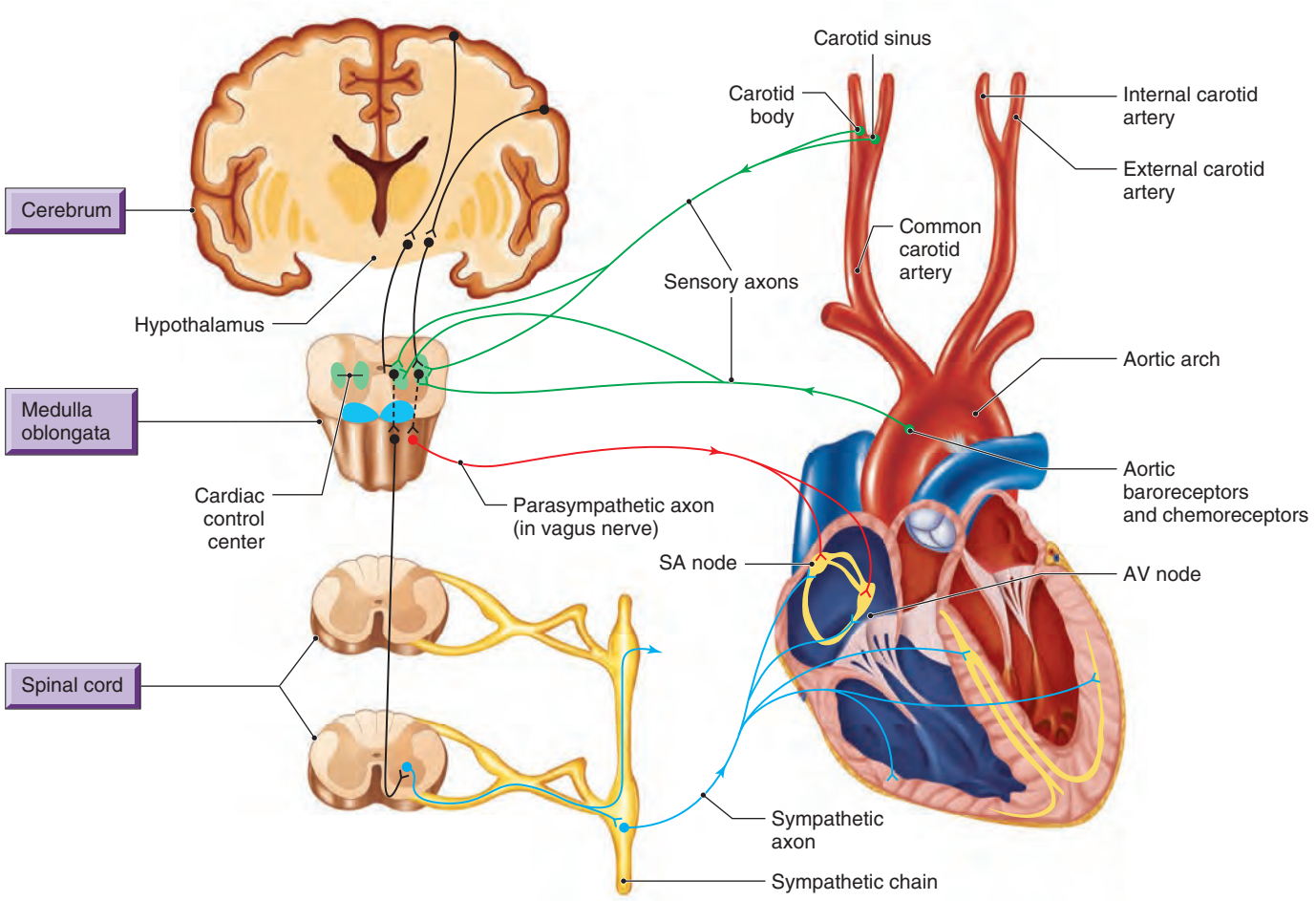


Figure 12.11 The rate and strength of heart contractions are regulated by the antagonistic actions of sympathetic (colored blue) and parasympathetic (colored red) divisions of the autonomic nervous system. Sensory axons are colored green.

Neurons of the sympathetic division extend axons from the cardiac control center down the spinal cord to the thoracic region. There the sympathetic axons exit the spinal cord to innervate the SA node, AV node, and portions of the myocardium. The transmission of nerve impulses causes the sympathetic axons to secrete *norepinephrine* at synapses in the heart. Norepinephrine increases the heart rate and strengthens the force of myocardial contraction. Physical and emotional stresses, such as exercise, excitement, anxiety, and fear, stimulate the sympathetic division to increase heart rate and contraction strength.

Parasympathetic axons arise from the cardiac control center and exit in the vagus nerve (CN X) to innervate the SA and AV nodes. The transmission of nerve impulses causes the parasympathetic axons to secrete *acetylcholine* at the heart synapses, which decreases the heart rate. The greater the frequency of parasympathetic nerve impulses sent to the heart, the slower the heart rate. Excessive blood pressure and emotional factors, such as grief and depression, stimulate the parasympathetic division to decrease the heart rate.

When the heart is at rest, more parasympathetic nerve impulses than sympathetic nerve impulses are sent to the heart. As cellular needs for blood increase, a decrease in the frequency of parasympathetic nerve impulses and an increase in sympathetic nerve impulses cause heart rate to increase.

Other Factors Affecting Heart Function

Age, sex, physical condition, temperature, epinephrine, thyroxine, and the blood levels of calcium and potassium ions also affect the heart rate and contraction strength.

The resting heart rate gradually declines with age, and it is slightly faster in females than in males. Average resting heart rates in females are 72 to 80 beats per minute, as opposed to 64 to 72 beats per minute in males. People who are in good physical condition have a slower resting heart rate than those in poor condition. Athletes may have a resting heart rate of only 40 to 60 beats per minute. An increase in body temperature, which occurs during exercise or when feverish, increases the heart rate.

Epinephrine, which is secreted by the adrenal glands during stress or excitement, affects the heart like norepinephrine–it increases the rate and strength of heart contractions. An excess of thyroxine produces a lesser, but longer-lasting, increase in heart rate.

Reduced levels of blood Ca^{2+} decrease the rate and strength of heart contraction, while increased levels of blood Ca^{2+} increase heart rate and contraction strength, and prolong contraction. In extreme cases, an excessively prolonged contraction may result in death. Excessive levels of blood K^+ decrease both heart rate and contraction strength. A high dose of K^+ is often used in lethal injections, in which the abnormally high levels of blood K^+ cause the heart to stop contracting. Abnormally low levels of blood K^+ may cause potentially life-threatening abnormal heart rhythms.

Check My Understanding

9. How are the heart rate and contraction strength regulated?
10. What other factors affect the heart rate and contraction strength?

12.5 Types of Blood Vessels

Learning Objectives

9. Describe the structure and function of arteries, arterioles, capillaries, venules, and veins.
10. Describe how materials are exchanged between capillary blood and interstitial fluid.

There are three basic types of blood vessels: arteries, capillaries, and veins. They form a closed system of tubes that carry blood from the heart to the tissue cells and back to the heart. Table 12.3 compares these three types.

Structure of Arteries and Veins

The walls of arteries and veins are composed of three distinct layers. The *tunica externa,* the most superficial layer, is formed of dense irregular connective tissue that includes both collagen and elastic fibers. These fibers provide support and elasticity for the vessel. The *tunica media,* the middle layer, usually is the thickest layer. It consists of smooth muscle cells that encircle the blood vessel. The smooth muscle cells not only provide support but also produce changes in the diameter of the blood vessel by contraction or relaxation. The *tunica intima,* the deepest layer, forms the internal lining of blood vessels. It consists of a simple squamous epithelium, called the *endothelium,* supported by thin layers of areolar connective tissue containing elastic and collagen fibers.

The walls of arteries and veins have the same basic structure. However, arterial walls are thicker because their tunica media contains more smooth muscle and elastic connective tissues as an adaptation to the higher blood pressure found in them. The tunica media of veins possesses very little smooth muscle, which leads to a much thinner wall. Veins possess larger lumens than arteries; as a result, they can hold a larger volume of blood. Another difference is that large veins, but not arteries, contain valves formed of endothelium. Venous valves prevent a backflow of blood. Compare the structure of arteries and veins in figure 12.12.

Table 12.3 Comparison of Arteries, Capillaries, and Veins

Type of Vessel	Function	Structure
Arteries	Carry blood from the heart to the capillaries Control blood flow and blood pressure	Composed of tunica intima, tunica media, and tunica externa Contain more smooth muscle and elastic connective tissues than veins
Capillaries	Enable exchange of materials between blood and interstitial fluid	Microscopic vessels composed of endothelium supported by areolar connective tissue
Veins	Return blood from capillaries to the heart Serve as storage areas for blood	Composed of tunica intima, tunica media, and tunica externa Have thinner walls and larger lumens than arteries Large veins have venous valves.

Arteries

Arteries carry blood away from the heart. They branch repeatedly into smaller and smaller arteries and ultimately form microscopic arteries called **arterioles** (ar-te′-rē-ōls). As arterioles branch and form smaller arterioles, the thickness of the tunica media decreases. The walls of the smallest arterioles consist of only the tunica intima and a few encircling smooth muscle cells. Arteries, especially the arterioles, play an important role in the control of blood flow and blood pressure.

Capillaries

Arterioles connect with **capillaries,** the most numerous and the smallest blood vessels. A capillary's diameter is so small that RBCs must pass through it in single file. The walls of capillaries consist of an endothelium supported by a layer of areolar connective tissue. These extremely thin walls facilitate the exchange of materials between blood in capillaries and tissue cells.

The distribution of capillaries in body tissues varies with the metabolic activity of each tissue. Capillaries are especially abundant in active tissues, such as muscle and nervous tissues, where nearly every cell is near a capillary. Capillaries are less abundant in connective tissues and are absent in some tissues, such as cartilage, epidermis, and the lens and cornea of the eye.

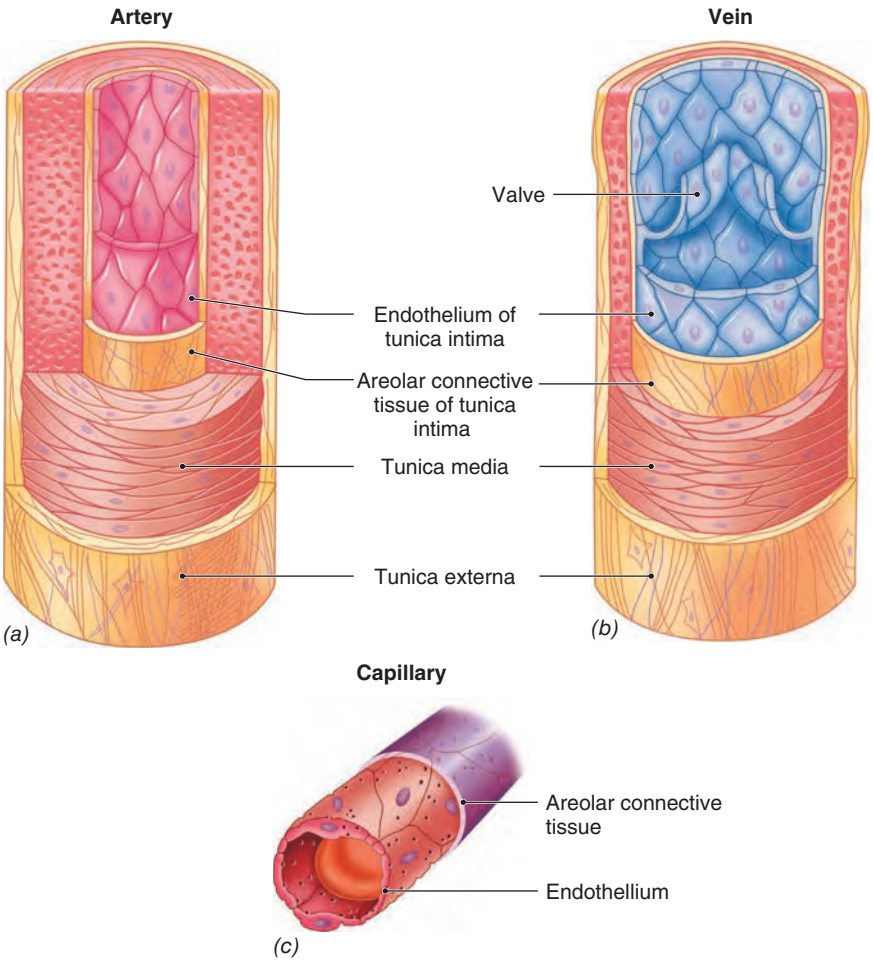


Figure 12.12 *(a)* The wall of an artery. *(b)* The wall of a vein. *(c)* The wall of a capillary.

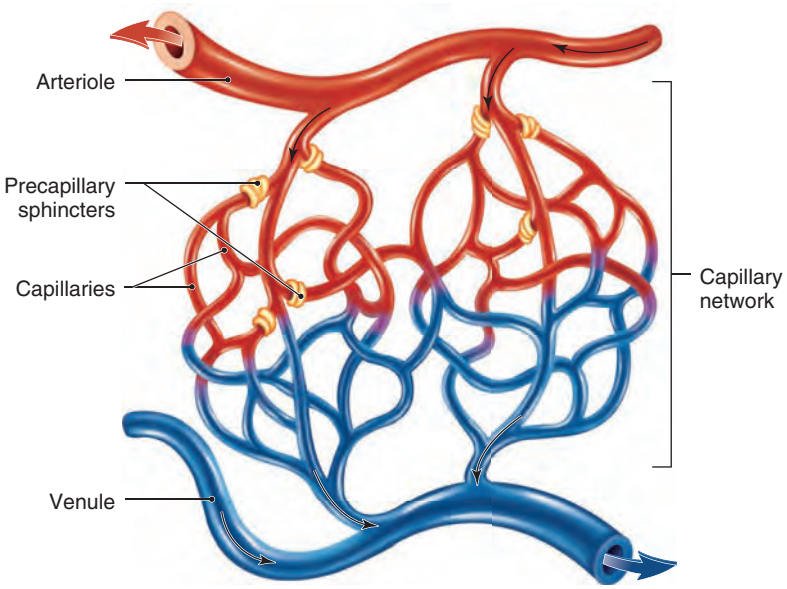


Figure 12.13 A capillary network. Precapillary sphincters regulate the blood flow from an arteriole into a capillary. Oxygenated blood (red) enters a capillary network. Deoxygenated blood (blue) exits the capillaries and enters a venule.

Blood flow in capillaries is controlled by *precapillary sphincters,* smooth muscle cells encircling the bases of capillaries at the arteriole-capillary junctions (figure 12.13). Contraction of a precapillary sphincter inhibits blood flow to its capillary network. Relaxation of the sphincter allows blood to flow into its capillary network to provide oxygen and nutrients for the tissue cells. The flow of blood in capillary networks occurs intermittently. When some capillary networks are filled with blood, others are not. Capillary networks receive blood according to the needs of the cells that they serve. For example, during physical exercise blood is diverted from capillary networks in the digestive tract to fill the capillary networks in skeletal muscles. This pattern of blood distribution is largely reversed after a meal.

Exchange of Materials

The continual exchange of materials between the blood and tissue cells is essential for life. Cells require oxygen and nutrients to perform their metabolic functions, and they produce carbon dioxide and other metabolic wastes that must be removed by the blood.

The cells of tissues are enveloped in a thin film of extracellular fluid called **interstitial fluid,** or *tissue fluid,* that fills tissue spaces and lies between the tissue cells and the capillaries. Therefore, all materials that pass between the blood and tissue cells must pass through the interstitial fluid. Dissolved substances such as oxygen and nutrients diffuse from blood in the capillary into the interstitial fluid and from the interstitial fluid into tissue cells. Carbon dioxide and metabolic wastes diffuse in the opposite direction.

Recall that the capillary walls are so thin that materials can readily diffuse through them, and the junctions between these cells are not tight so fluid is able to move between the cells. Two opposing forces determine the movement of fluid between capillary blood and interstitial fluid: osmotic pressure and blood pressure. Osmotic pressure of the blood results from plasma proteins. Osmotic pressure tends to "pull" fluid from interstitial fluid into the capillaries by osmosis. Blood pressure against the capillary walls results from the force of ventricular contractions. It tends to push fluid out of the capillaries into the interstitial fluid. This type of transport, forcing substances through a membrane due to greater hydrostatic pressure on one side of the membrane, is known as **filtration.**

At the arteriolar end of a capillary, blood pressure exceeds osmotic pressure, so fluid moves out of the capillary into the interstitial fluid. In contrast, at the venular end of the capillary, osmotic pressure exceeds blood pressure, so fluid moves from the interstitial fluid into the capillary by osmosis (figure 12.14). About nine-tenths of the fluid that moves from the arteriolar end of a capillary into the interstitial fluid returns into the venular end of the capillary. The remainder is picked up by the lymphoid system and ultimately is returned to the blood (see chapter 13).

Veins

After blood flows through the capillaries, it enters the **venules,** the smallest **veins.** Several capillaries merge to form a venule. The smallest venules consist only of endothelium and areolar connective tissue, but larger venules also contain smooth muscle tissue. Venules unite to form small veins. Small veins combine to form progressively larger veins as blood is returned to the heart. Larger veins, especially those in the upper and lower limbs, contain valves that prevent a backflow of blood and aid the return of blood to the heart.

Because nearly 60% of the blood volume is in veins at any instant, veins may be considered as storage areas for blood that can be carried to other parts of the body in times of need. Venous sinusoids in the liver and spleen are especially important reservoirs. If blood is lost by hemorrhage, both blood volume and pressure decline. In response, the sympathetic division sends nerve impulses to constrict the muscular walls of the veins, which reduces the venous volume while increasing blood volume and pressure in the heart, arteries and capillaries. This effect compensates for the blood loss. A similar response occurs during strenuous muscular activity in order to increase the blood flow to skeletal muscles.

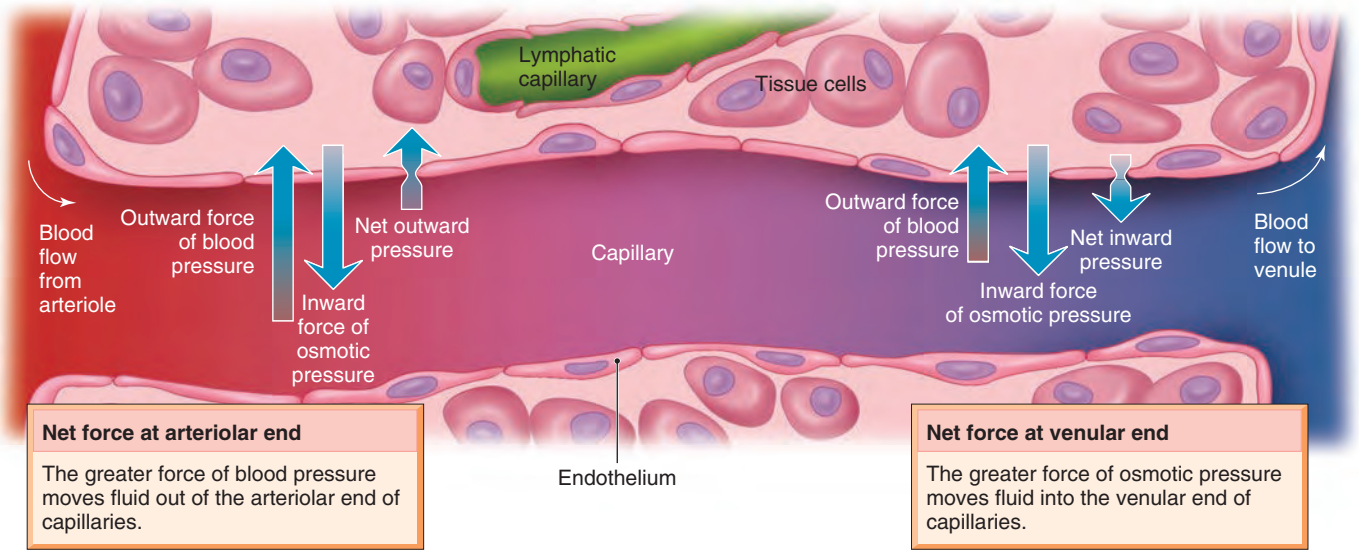


Figure 12.14 Fluid exchange across capillary walls. Fluid moves out of or into capillaries according to the net difference between blood pressure and osmotic pressure. Solutes diffuse out of or into capillaries according to each solute's concentration gradient.

Check My Understanding

11. Compare the structure and function of arteries, capillaries, and veins.
12. How does the exchange of materials occur between blood in capillaries and tissue cells?

12.6 Blood Flow

Learning Objective

11. Describe the mechanism of blood circulation.

Blood circulates because of differences in blood pressure. Blood flows from areas of higher pressure to areas of lower pressure. Blood pressure is greatest in the ventricles and lowest in the atria. Figure 12.15 shows the decline of blood pressure in the systemic circuit with increased distance from the left ventricle.

Contraction of the ventricles creates the blood pressure that propels the blood through the arteries. However, the pressure declines as the arteries branch into an increasing number of smaller and smaller arteries and finally connect with the capillaries. The decline in blood pressure occurs because of the increased distance from the ventricle. By the time blood has left the capillaries and entered the veins, there is very little blood pressure remaining to return the blood to the heart. The return of venous blood is assisted by three additional forces: *skeletal muscle contractions, respiratory movements,* and *gravity.*

Contractions of skeletal muscles compress the veins, forcing blood from one valved segment to another and on toward the heart because the valves prevent a backflow of

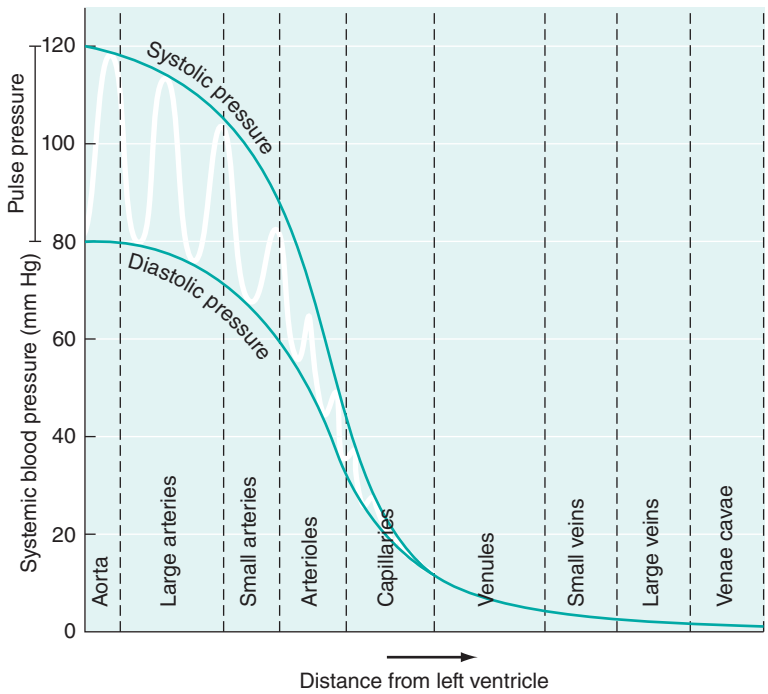


Figure 12.15 Blood pressure decreases as distance from the left ventricle increases.

blood. This method of moving venous blood toward the heart is especially important in the return of blood from the upper and lower limbs, and it is illustrated in figure 12.16.

Respiratory movements aid the movement of blood superiorly toward the heart in the abdominopelvic and thoracic cavities. The inferior movement of the diaphragm as it contracts during inspiration decreases the pressure within the thoracic cavity and increases the pressure within the abdominopelvic cavity. The higher pressure in the abdominopelvic cavity forces blood to move from the abdominopelvic veins superiorly into thoracic veins, where the pressure is reduced. When the diaphragm relaxes and moves superiorly, the thoracic and abdominopelvic pressures reverse. Backflow of blood into the veins of the lower limb is prevented by the presence of venous valves.

Gravity aids the return of blood in veins superior to the heart.

Velocity of Blood Flow

The velocity of blood flow varies inversely with the overall cross-sectional area of the *combined* blood vessels.

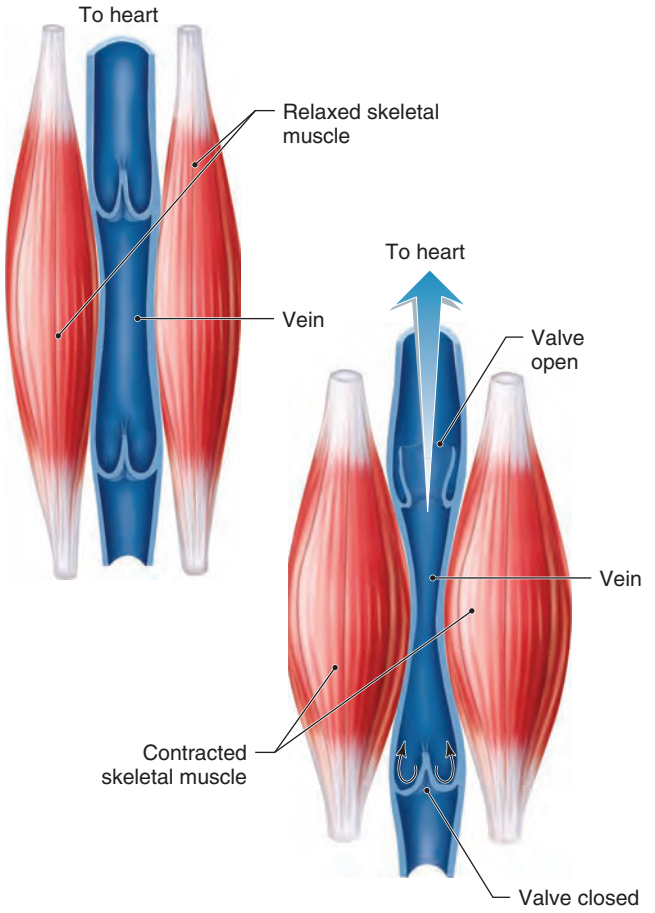


Figure 12.16 Contraction of skeletal muscles compresses veins and aids the movement of blood toward the heart.

Therefore, the velocity progressively decreases as blood flows through an increasing number of smaller and smaller arteries and into the capillaries. Then, the velocity progressively increases as the blood flows into a decreasing number of larger and larger veins on its way back to the heart.

Blood velocity is fastest in the aorta and slowest in the capillaries, an ideal situation providing for the rapid circulation of the blood and yet sufficient time for the exchange of materials between blood in the capillaries and the interstitial fluid surrounding tissue cells.

12.7 Blood Pressure

Learning Objectives

12. Compare systolic and diastolic blood pressure.
13. Describe how blood pressure is regulated.

The term *blood pressure,* the force of blood against the wall of the blood vessels, usually refers to arterial blood pressure in the systemic circuit–in the aorta and its branches. Arterial blood pressure is greatest during ventricular contraction (systole) as blood is pumped into the aorta and its branches. This pressure is called the **systolic blood pressure,** and it optimally averages 110 millimeters of mercury (mm Hg) when measured in the brachial artery. The lowest arterial pressure occurs during ventricular relaxation (diastole). This pressure is called the **diastolic blood pressure,** and it optimally averages 70 mm Hg (figure 12.15).

The difference between the systolic and diastolic blood pressures is known as the *pulse pressure* (figure 12.15). The alternating increase and decrease in arterial blood pressure during ventricular systole and diastole causes a comparable expansion and contraction of the elastic arterial walls. This pulsating expansion of the arterial walls follows each ventricular contraction, and it may be detected as the *pulse* by placing the fingers on a superficial artery. Figure 12.17 identifies the name and location of superficial arteries where the pulse may be detected.

Factors Affecting Blood Pressure

Three major factors affect blood pressure: cardiac output, blood volume, and peripheral resistance. An increase in any of these factors causes an increase in blood pressure, while a decrease in any of these causes a decrease in blood pressure.

Clinical Insight

A blood pressure of 110/70 mm Hg is optimal. Each 20 mm Hg of systolic pressure over 115, and each 10 mm Hg of diastolic pressure over 75 doubles the risk of heart attack, stroke, and kidney disease.

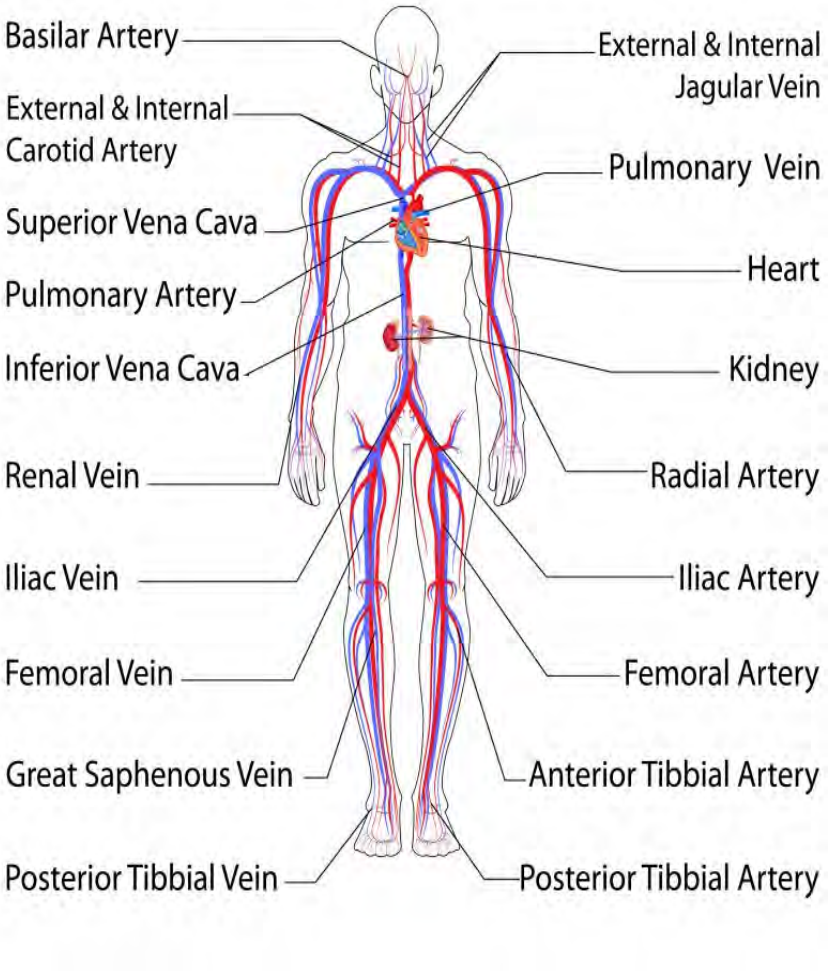


Figure 12.17 Locations and arteries where the pulse may be detected. See figures 12.19 and 12.20 for specific locations of these arteries.

Recall that cardiac output is determined by the heart rate and the stroke volume. An increase or decrease in cardiac output causes a comparable change in blood pressure.

Blood volume may be decreased by severe hemorrhage, vomiting, diarrhea, or reduced water intake. The decrease in blood volume causes a decrease in blood pressure. Many drugs used to treat hypertension (abnormally high blood pressure) act as diuretics, meaning they increase urine volume and as a result decrease blood volume. As soon as the lost fluid is replaced, blood pressure returns to normal. Conversely, if the body retains too much fluid, blood volume and blood pressure increase. A high-salt diet is a risk factor for hypertension because it causes the blood to retain more water as a result of osmosis, leading to an increase in blood volume.

Peripheral resistance is the opposition to blood flow created by friction of blood against the walls of blood vessels. Increasing peripheral resistance will increase blood pressure, while decreasing peripheral resistance decreases blood pressure. Peripheral resistance is determined by *vessel diameters, total vessel length,* and *blood viscosity*. Arterioles play a critical role in controlling blood pressure by changing their diameters. As arterioles constrict, peripheral resistance increases and blood pressure increases accordingly. As arterioles dilate, peripheral resistance and blood pressure decrease. Peripheral resistance is directly proportional to the total length of the blood vessels in the body: the longer the total length of the vessels, the greater their resistance to flow. Obese people tend to have hypertension partly because their bodies contain more blood vessels to serve the extra adipose tissue. *Viscosity* is the resistance of a liquid to flow. For example, water has a low viscosity, while honey has a high viscosity. Blood viscosity is determined by the ratio of plasma to formed elements and plasma proteins. Increasing viscosity, or shifting the ratio in favor of the formed elements and plasma proteins, increases peripheral resistance and blood pressure. Both dehydration (loss of water from plasma) and polycythemia (elevated RBC count) can increase viscosity. Abnormally high levels of blood lipids and sugar are also risk factors for hypertension because they increase blood viscosity, in addition to promoting the formation of plaque on the vessel walls. Decreasing viscosity through over-hydration or certain types of anemia (see chapter 11) will decrease peripheral resistance and blood pressure.

Control of Peripheral Resistance

The sympathetic division of the ANS controls peripheral resistance primarily by regulating the diameter of blood vessels, especially arterioles. The integration center is the **vasomotor center** in the medulla oblongata. An increase in the frequency of sympathetic nerve impulses to the smooth muscle of blood vessels produces **vasoconstriction**, which increases resistance. The increase in resistance increases blood pressure and blood velocity. This response accelerates the rate of oxygen transport to cells and the removal of carbon dioxide from blood by the lungs. A decrease in sympathetic nerve impulse frequency results in **vasodilation**, which decreases resistance. The decrease in resistance decreases blood pressure and blood velocity.

Like the cardiac control center, the activity of the vasomotor center is modified by nerve impulses from higher brain areas, and sensory nerve impulses from baroreceptors and chemoreceptors in the aortic arch and the internal and external carotid arteries. For example, a decrease in pressure, pH, or oxygen concentration of the blood stimulates vasoconstriction. Conversely, an increase in these values promotes vasodilation.

In addition, arterioles and precapillary sphincters are affected by localized changes in blood concentrations of oxygen, carbon dioxide, and pH. These local effects override the control by the vasomotor center, through a process called *autoregulation,* and increase the rate of exchange of materials between tissue cells and the capillaries. For example, if a particular muscle group is active for an extended period, a localized decrease in oxygen concentration and an increase in carbon dioxide concentration result. These chemical changes stimulate the vasodilation of local arterioles and precapillary sphincters, which increases the flow of blood into capillary networks of the affected muscles to provide more oxygen and to remove more carbon dioxide.

Check My Understanding

13. How does blood pressure affect the flow of blood through blood vessels?
14. How are systolic and diastolic blood pressure different?
15. How do cardiac output, blood volume, and peripheral resistance affect blood pressure?

12.8 Circulation Pathways

Learning Objective

14. Compare the systemic and pulmonary circuits.

As noted earlier, the heart is a double pump that serves two distinct circulation pathways: the pulmonary and systemic circuits. These circuits were shown earlier in figure 12.7.

Pulmonary Circuit

The **pulmonary circuit** carries deoxygenated blood to the lungs, where oxygen and carbon dioxide are exchanged between the blood and the air in the lungs. The right ventricle pumps deoxygenated blood into the pulmonary trunk, a short, thick artery that divides to form the left and right pulmonary arteries. Each pulmonary artery enters a lung and divides repeatedly to form arterioles, which continue into the alveolar capillaries that surround the air sacs (alveoli) of the lungs (see chapter 14). Oxygen diffuses from the air in the alveoli into the capillary blood, and carbon dioxide diffuses from the blood into the air in the alveoli. Blood then flows from the capillaries into venules, which merge to form small veins, which, in turn, join to form progressively larger veins. Two pulmonary veins emerge from each lung to carry oxygenated blood back to the left atrium of the heart.

Systemic Circuit

The systemic circuit carries oxygenated blood to the tissue cells of the body and returns deoxygenated blood to the heart. The left ventricle pumps the freshly oxygenated blood, received from the pulmonary circuit, into the aorta for circulation to all parts of the body except the lungs. The aorta branches to form many major arteries, which continually branch to form arterioles leading to capillaries, where the exchange of materials between the blood and interstitial fluid takes place. Oxygen diffuses from the capillary blood into the tissue cells, while carbon dioxide diffuses from the tissue cells into the blood. From the capillaries, blood enters venules, which merge to form small veins, which join to form progressively larger veins. Ultimately, veins from the superior body (head, neck, shoulders, upper limbs, and superior trunk) join to form the superior vena cava, which returns blood from these regions back to the right atrium. Similarly, veins from the inferior body (inferior trunk and lower limbs) enter the inferior vena cava, which also returns blood into the right atrium. The **coronary sinus** drains the blood from the myocardium into the right atrium (see figure 12.5).

12.9 Systemic Arteries

Learning Objective

15. Identify the major systemic arteries and the organs or body regions that they supply.

Major Branches of the Aorta

The aorta ascends from the heart, arches to the left and posterior to the heart, and descends through the thoracic and abdominal cavities just anterior to the vertebral column. Because of its size, the aorta is divided into four regions: the ascending aorta, the aortic arch, the thoracic aorta, and the abdominal aorta. Figure 12.18 shows the major branches of the aorta and their relationships to the internal organs. Tables 12.4 and 12.5 list the major branches of the aorta and the organs and body regions that they supply.

The first arteries to branch from the aorta are the left and right coronary arteries, which supply blood to the heart. They branch from the aorta just distal to the aortic valve in the base of the *ascending aorta.*

Three major arteries branch from the *aortic arch.* In order of branching, they are the **brachiocephalic** (brāk-ē-ō-se-fal′-ik) **trunk,** the **left common carotid** (kah-rot′-id) **artery,** and the **left subclavian** (sub-klā′-vē-an) **artery.**

Pairs of **posterior intercostal** (in-ter-kos′-tal) **arteries** branch from the *thoracic aorta* to supply the intercostal

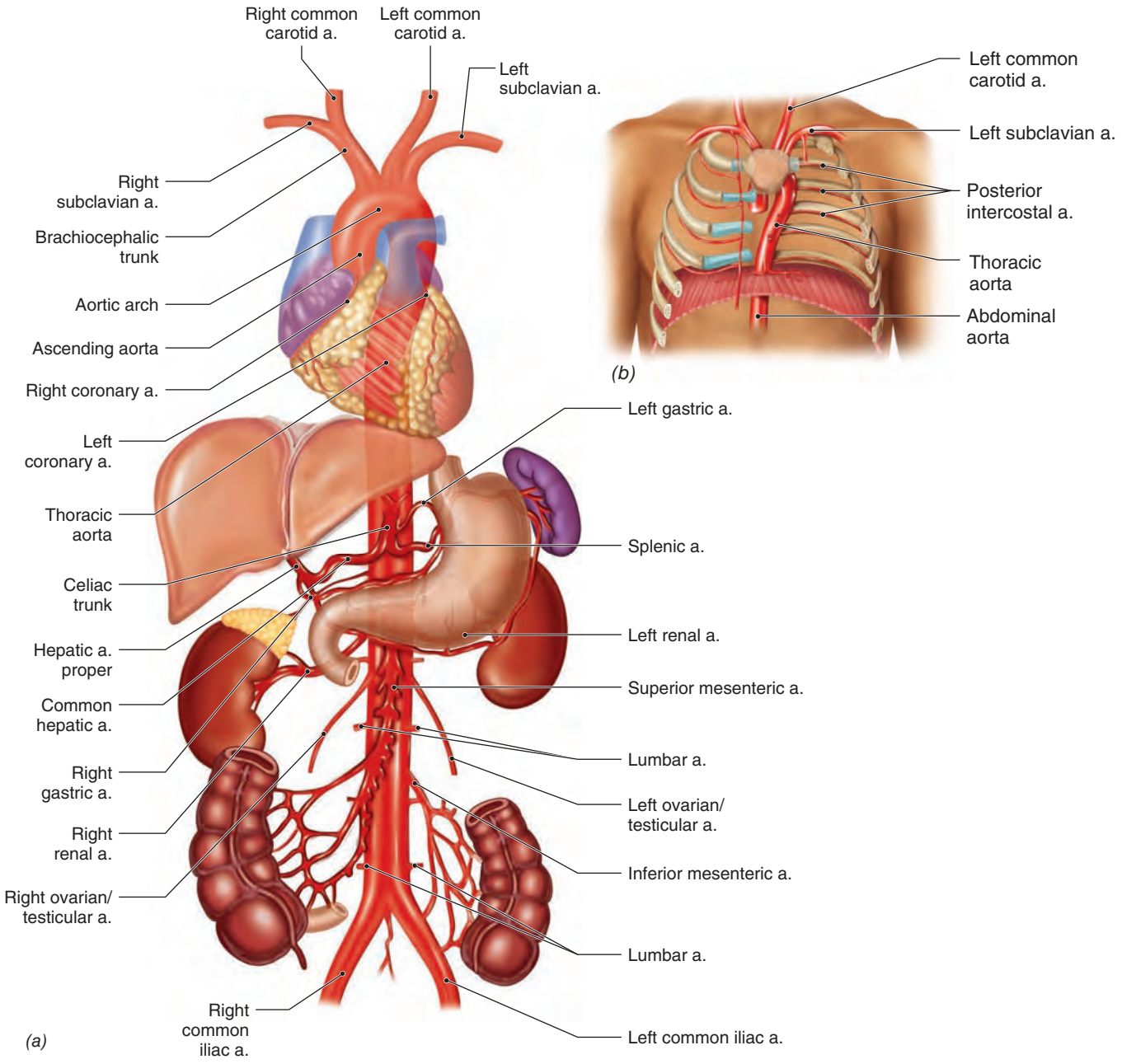


Figure 12.18 *(a)* The major arteries that branch from the aorta. *(b)* Major arteries supplying the thoracic cage. (a. = artery)

muscles between the ribs and other organs of the thoracic wall. A number of other small arteries supply the organs of the thoracic cavity.

Once the aorta descends through the diaphragm, it is called the *abdominal aorta*, and it gives off several branch arteries to the abdominal wall and visceral organs. The **celiac** (sē′-lē-ak) **trunk** is a short artery that divides to form three branch arteries: (1) the **left gastric artery** supplies the stomach and esophagus, (2) the **splenic artery** supplies the spleen, stomach, and pancreas, and (3) the **common hepatic artery** supplies the liver, gallbladder, stomach, duodenum, and pancreas.

The **superior mesenteric** (mes-en-ter′-ik) **artery** supplies the pancreas, most of the small intestine, and the proximal portion of the large intestine. The left and right **renal arteries** supply the kidneys. The left and right **ovarian arteries** supply the ovaries in females. The left and right **testicular arteries** supply the testes in males.

Table 12.4 Major Arteries Branching from the Ascending Aorta, Aortic Arch, and Thoracic Aorta

Artery	Origin	Region Supplied
Coronary	Ascending aorta	Myocardium
Brachiocephalic trunk	Aortic arch	Branches as below
Right common carotid	Brachiocephalic trunk	Right side of head and neck
Right subclavian	Brachiocephalic trunk	Right shoulder and upper limb, thoracic wall
Left common carotid	Aortic arch	Left side of head and neck
External carotid	Common carotid	Scalp, face, and neck
Internal carotid	Common carotid	Brain
Left subclavian	Aortic arch	Left shoulder and upper limb, thoracic wall
Vertebral	Subclavian	Neck and brain
Axillary	Subclavian	Axilla and shoulder
Brachial	Axillary	Arm
Radial	Brachial	Forearm and hand
Ulnar	Brachial	Forearm and hand
Posterior intercostal	Thoracic aorta	Thoracic wall

Table 12.5 Major Arteries Branching from the Abdominal Aorta

Artery	Origin	Region Supplied
Celiac trunk	Abdominal aorta	Liver, stomach, spleen, gallbladder, esophagus, and pancreas
Common hepatic	Celiac trunk	Liver, gallbladder, stomach, duodenum, and pancreas
Left gastric	Celiac trunk	Stomach and esophagus
Splenic	Celiac trunk	Spleen, stomach, and pancreas
Renal	Abdominal aorta	Kidney
Superior mesenteric	Abdominal aorta	Pancreas, small intestine, and proximal part of large intestine
Ovarian, testicular	Abdominal aorta	Ovaries or testes
Lumbar	Abdominal aorta	Lumbar region of back
Inferior mesenteric	Abdominal aorta	Distal part of large intestine
Common iliac	Abdominal aorta	Pelvic region and lower limb
Internal iliac	Common iliac	Pelvic wall, pelvic viscera, external genitalia, and medial thigh
External iliac	Common iliac	Pelvic wall and lower limb
Femoral	External iliac	Thigh
Popliteal	Femoral	Knee
Anterior tibial	Popliteal	Leg (anterior) and foot
Posterior tibial	Popliteal	Leg (posterior) and foot

Several pairs of **lumbar arteries** supply the walls of the abdomen and back. The **inferior mesenteric artery** supplies the distal portion of the large intestine.

At the level of the iliac crests, the aorta divides to form two large arteries, the left and right **common iliac** (il′-ē-ak) **arteries,** which carry blood to the inferior portions of the trunk and to the lower limbs.

Arteries Supplying the Head and Neck

The head and neck receive blood from several arteries that branch from the common carotid and subclavian arteries. Note in figures 12.18 and 12.19 that the brachiocephalic trunk branches to form the **right common carotid**

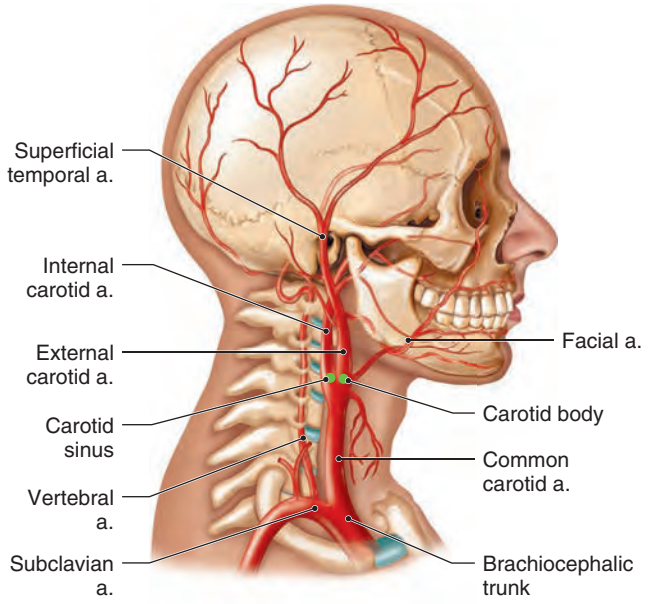


Figure 12.19 Major arteries supplying the head and neck. (a. = artery)

artery and the **right subclavian artery.** The left common carotid and left subclavian arteries branch directly from the aortic arch.

Each common carotid artery divides in the neck to form an **external carotid artery** and the **internal carotid artery.** Near the junction of external and internal carotid arteries are the *carotid body* (the site of chemoreceptors) and *carotid sinus* (the site of baroreceptors), which send sensory nerve impulses to the cardiac control and vasomotor centers in the medulla oblongata. The external carotid arteries give rise to a number of smaller arteries that carry blood to the neck, face, and scalp. The internal carotid arteries enter the cranium and provide the major supply of blood to the brain.

The neck and brain are also supplied by the **vertebral arteries.** They branch from the subclavian arteries and pass superiorly through the transverse foramina of cervical vertebrae to enter the cranium.

Arteries Supplying the Shoulders and Upper Limbs

The subclavian artery provides branches to the shoulder and passes inferior to the clavicle to become the **axillary artery,** which supplies branches to the thoracic wall and axillary region. The axillary artery continues into the arm to become the **brachial artery,** which provides branches to serve the arm. At the elbow, the brachial artery divides to form a **radial artery** and an **ulnar artery,** which supply the forearm and wrist and merge to form a network of arteries supplying the hand (figure 12.20 and table 12.4).

Arteries Supplying the Pelvis and Lower Limbs

As noted earlier, the left and right common iliac arteries branch from the inferior end of the aorta. Each common iliac branches within the pelvis to form internal and external iliac arteries. The **internal iliac artery** is the smaller branch that supplies the pelvic wall, pelvic organs, external genitalia, and medial thigh muscles. The **external iliac artery** is the larger branch, and it supplies the anterior pelvic wall and continues into the thigh, where it becomes the femoral artery (figure 12.20).

The **femoral artery** gives off branches that supply the anterior and medial muscles of the thigh. The largest branch is the **deep femoral artery,** which serves the posterior and lateral thigh muscles. As the femoral artery descends, it passes posterior to the knee and becomes the **popliteal** (pop-li-té′-al) **artery,** which supplies certain muscles of the thigh and leg, as well as the knee. The popliteal artery branches just inferior to the knee to form the anterior and posterior tibial arteries.

The **anterior tibial artery** descends between the tibia and fibula to supply the anterior and lateral portions of the leg, and it continues to become the **dorsalis pedis,** which supplies the ankle and foot. The **posterior tibial artery** lies posterior to the tibia and supplies the posterior portion of the leg, and it continues to supply the ankle and the plantar surface of the foot. Its largest branch is the **fibular artery,** which serves the lateral leg muscles (table 12.5).

Clinical Insight

The pulse may be taken at any superficial artery, but the radial artery at the wrist and the common carotid artery in the neck are the most commonly used sites. Blood pressure is usually taken in the brachial artery of the arm. The radial artery at the wrist and the femoral artery at the groin are the common entry sites for angioplasty, a procedure in which a wire is fed into the arteries for widening narrowed or obstructed coronary or other systemic arteries.

Check My Understanding

16. What is the arterial pathway of blood from the left ventricle to the right side of the brain?
17. What is the arterial pathway of blood from the left ventricle to the small intestine?
18. What is the arterial pathway of blood from the left ventricle to the superior surface of the foot?

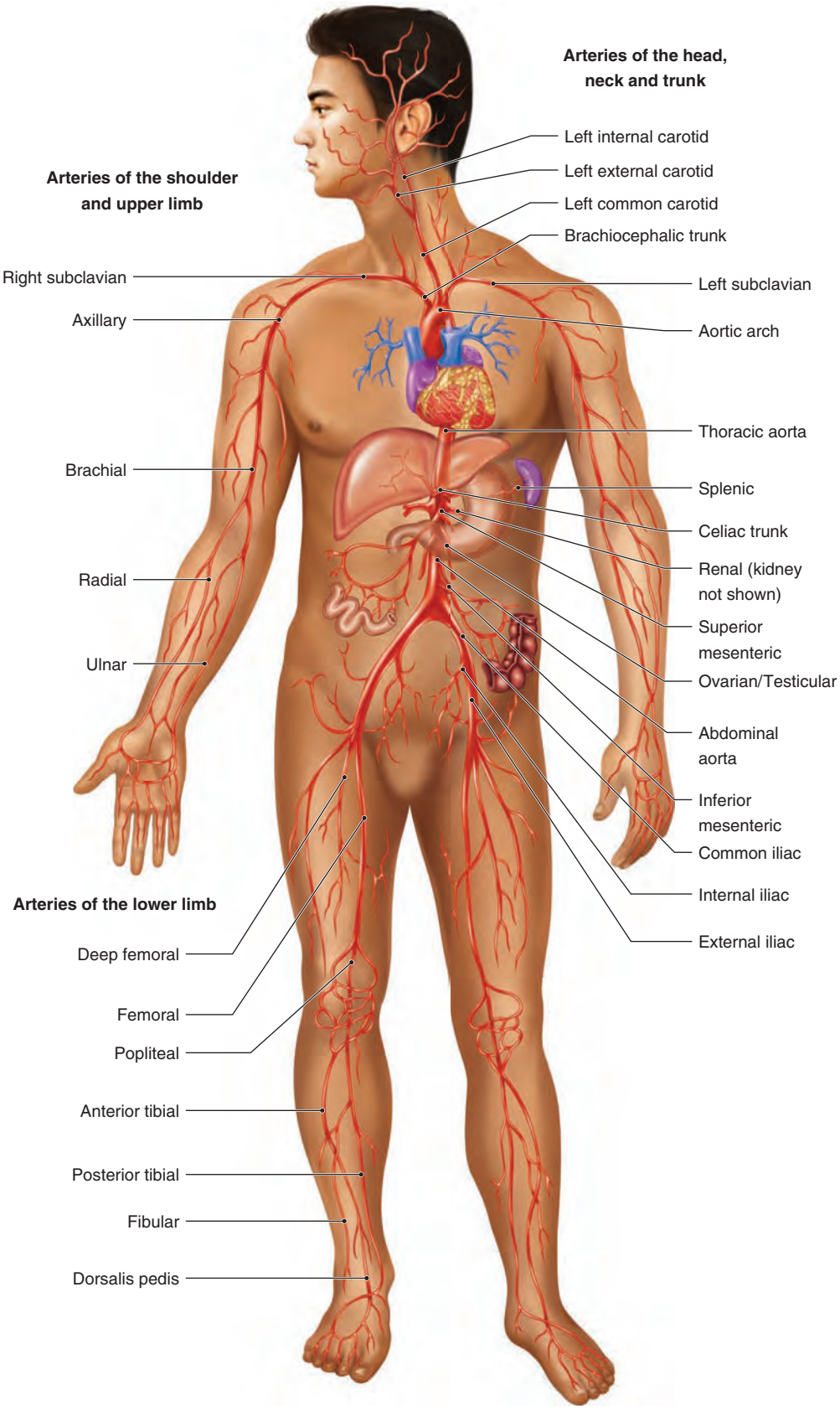


Figure 12.20 Major systemic arteries.

12.10 Systemic Veins

Learning Objectives

16. Identify the major systemic veins and the organs or body regions that they drain.

The systemic veins receive deoxygenated blood from capillaries and return the blood to the heart. Ultimately, all systemic veins merge to form two major veins, the superior and inferior venae cavae, that empty into the right atrium of the heart.

Veins Draining the Head and Neck

As shown in figure 12.21, superficial areas of the head and neck are drained by the left and right **external jugular** (jug′-ū-lar) **veins,** which lead into the left and right **subclavian veins,** respectively. The left and right **vertebral veins** carry blood from the cervical spinal cord and deep neck regions into the subclavian veins as well.

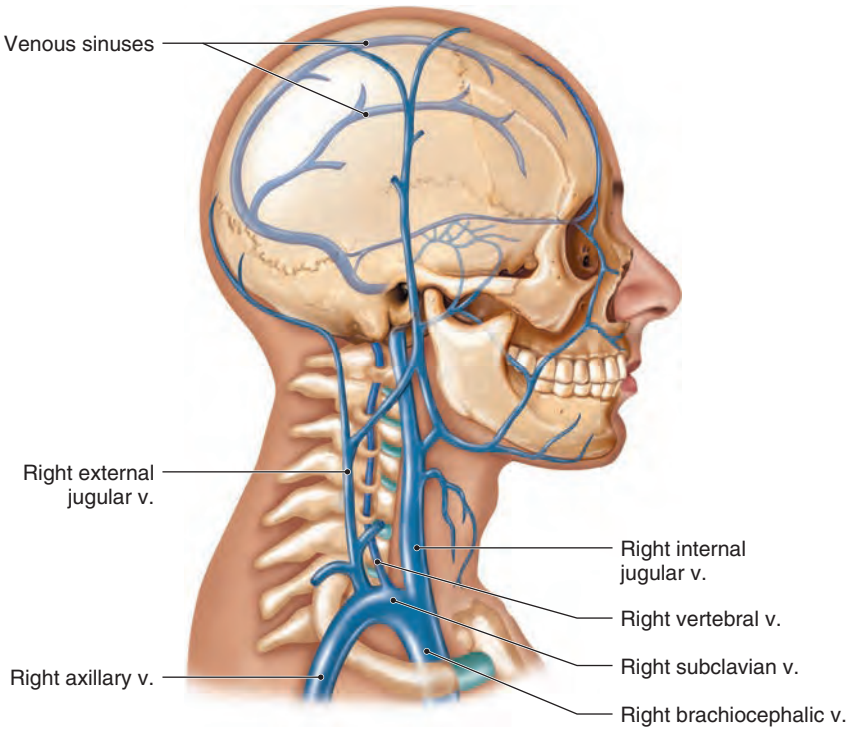


Figure 12.21 Major veins draining the head and neck. (v. = vein)

Most of the blood from the brain, face, and neck is carried by the left and right **internal jugular veins.** Each internal jugular vein merges with a subclavian vein to form a **brachiocephalic vein.** The left and right brachiocephalic veins join to form the **superior vena cava,** which returns blood to the right atrium of the heart (table 12.6).

Table 12.6 Major Veins Draining to the Superior Vena Cava

Vein	Region Drained and Location	Receiving Vein
Head and Neck		
External jugular	Face, scalp, and neck	Subclavian
Vertebral	Cervical spinal cord and deep neck	Subclavian
Internal jugular	Brain, face, and neck	Brachiocephalic
Upper Limb and Shoulder		
Radial	Hand and forearm (deep)	Brachial
Ulnar	Hand and forearm (deep)	Brachial
Basilic	Medial upper limb (superficial)	Axillary
Cephalic	Lateral upper limb (superficial)	Axillary
Brachial	Arm (deep)	Axillary
Axillary	Axilla and shoulder	Subclavian
Subclavian	Shoulder and thoracic wall	Brachiocephalic
Trunk		
Brachiocephalic	Head, neck, shoulder, upper limb, and thoracic wall	Superior vena cava
Azygos	Thoracic and abdominal walls	Superior vena cava
Posterior intercostal	Thoracic wall	Azygos
Ascending lumbar	Abdominal wall	Azygos

Veins Draining the Shoulders and Upper Limbs

Deep regions of the forearm are drained by the **radial** and **ulnar veins.** These two veins join at the elbow to form the **brachial vein,** which drains the deep areas of the arm (figure 12.22).

Superficial regions of the hand, forearm, and arm are drained by the laterally located **cephalic** (se-fal′-ik) **vein** and the medially located **basilic** (bah-sil′-ik) **vein.** Note the **median cubital** (kyū-bi-tal) **vein,** which connects the basilic and cephalic veins.

The basilic and brachial veins merge in the axilla to form the **axillary vein,** which, in turn, joins with the cephalic vein to form the **subclavian vein.** As noted earlier, the subclavian vein joins with the internal jugular vein to form the brachiocephalic vein (table 12.6).

Veins Draining the Pelvis and Lower Limbs

The **anterior** and **posterior tibial veins** drain the foot and deep regions of the leg. They join inferior to the knee to form the **popliteal vein.** The **small saphenous** (sah-fē′-nus) **vein** drains the superficial posterior part of the leg and merges with the popliteal vein. The **fibular vein** drains the lateral portion of the leg and joins with the popliteal vein at the knee to form the **femoral vein,** which drains the deep regions of the thigh and hip.

The **great saphenous vein** originates from the venous arches in the foot, and it drains the medial and superficial portions of the foot, leg, and thigh. It merges with the femoral vein to form the **external iliac vein.** The external iliac vein and the **internal iliac vein** receive branches that drain the superior thigh and pelvic areas, and they merge to form the **common iliac vein.** The left and right common iliac veins merge to form the **inferior vena cava,** which returns blood to the right atrium of the heart (see figure 12.22).

Clinical Insight

The median cubital vein is the vein of choice when drawing a sample of blood for clinical tests. It is easily located just deep to the skin on the anterior surface of the elbow joint. In coronary bypass surgery, a segment of the internal thoracic artery, saphenous vein, or radial artery is grafted to the afflicted coronary artery on each side of the blockage. The subclavian vein is a common site for implanting the central line, a long-term catheter for administering medications and taking blood samples.

Veins Draining the Abdominal and Thoracic Walls

The **azygos** (az′-i-gō-s) **vein** drains most of the thoracic and abdominal walls, and it empties into the superior vena cava near the right atrium. The azygos vein receives blood from a number of smaller veins, including the **posterior intercostal veins** and the **ascending lumbar vein,** which drains the wall of the abdomen (figure 12.23).

Veins Draining the Abdominal Viscera

The **hepatic portal vein** carries blood from the stomach, intestines, spleen, and pancreas to the liver instead of the inferior vena cava. The hepatic portal vein is formed by the union of the **superior mesenteric vein,** which drains the small intestine and proximal large intestine, and the **splenic vein,** which drains the spleen. The splenic vein receives blood from the **inferior mesenteric vein,** which drains the distal large intestine, and the **pancreatic vein,** which drains the pancreas. The **gastric veins,** from the stomach, drain directly into the hepatic portal vein. All of these veins compose the **hepatic portal system.**

After entering the liver, the blood flows through the venous sinusoids, where materials are either removed or added before the blood enters the **hepatic veins,** which empty into the inferior vena cava (figure 12.24a). Note that 75% of the blood supply to the liver comes from the hepatic portal vein; the rest comes from the hepatic artery proper (see figure 12.18*a*). The hepatic portal system allows the liver to monitor and adjust the concentrations of substances in blood coming from the digestive tract before it enters the general circulation.

The left and right **renal veins** carry blood from the kidneys, and the left and right **ovarian** or **testicular veins** return blood from the ovaries in females or the testes in males, respectively. Both renal veins and the right ovarian or testicular vein drain into the inferior vena cava. The left ovarian or testicular vein empties into the left renal vein (figure 12.24*b* and table 12.7).

Check My Understanding

19. What is the venous pathway of blood from the left side of the head to the right atrium?
20. What is the venous pathway of blood from the small intestine to the right atrium?
21. What is the venous pathway of blood from the posterior portion of the ankle to the right atrium?

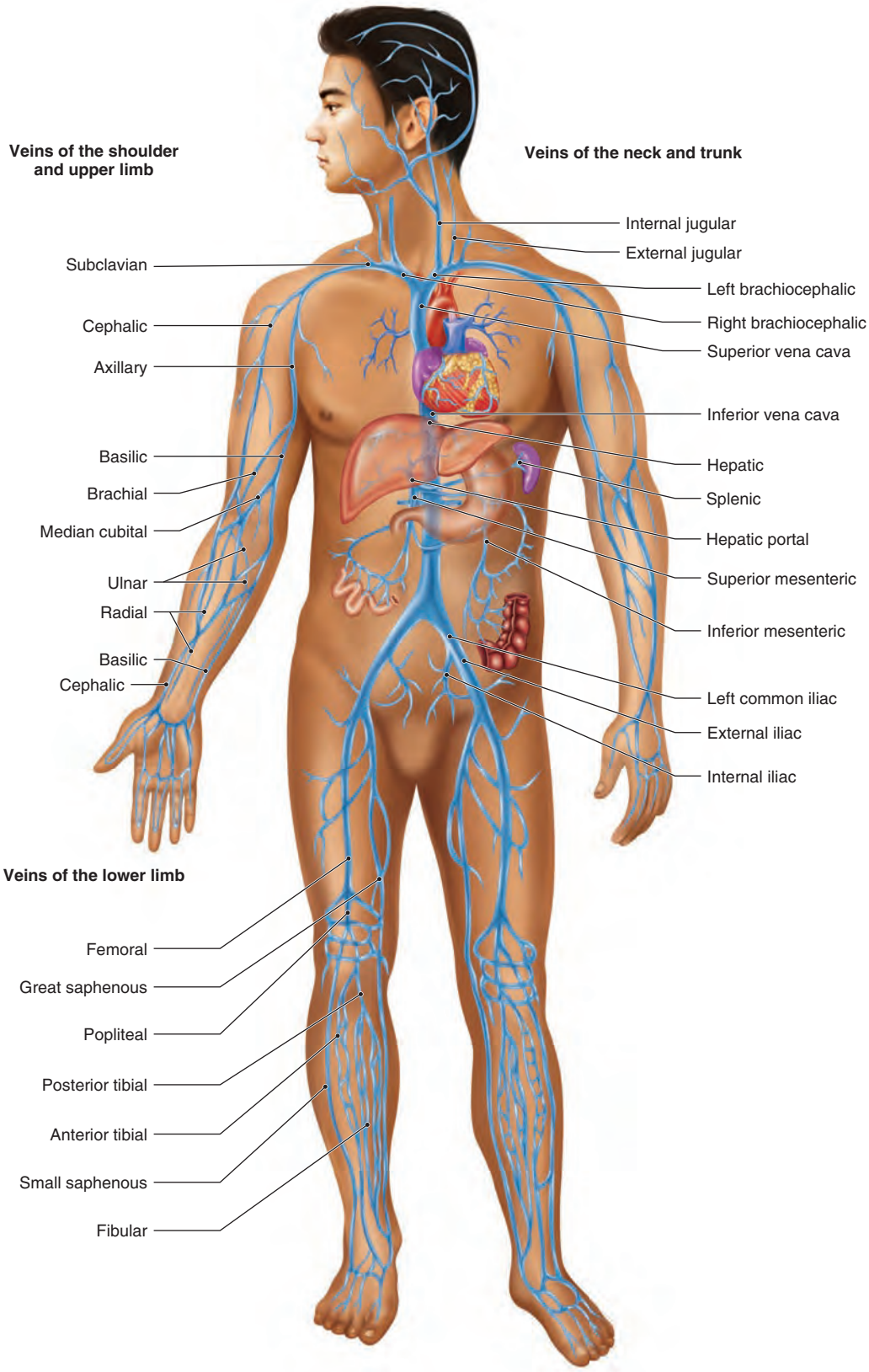


Figure 12.22 Major systemic veins.

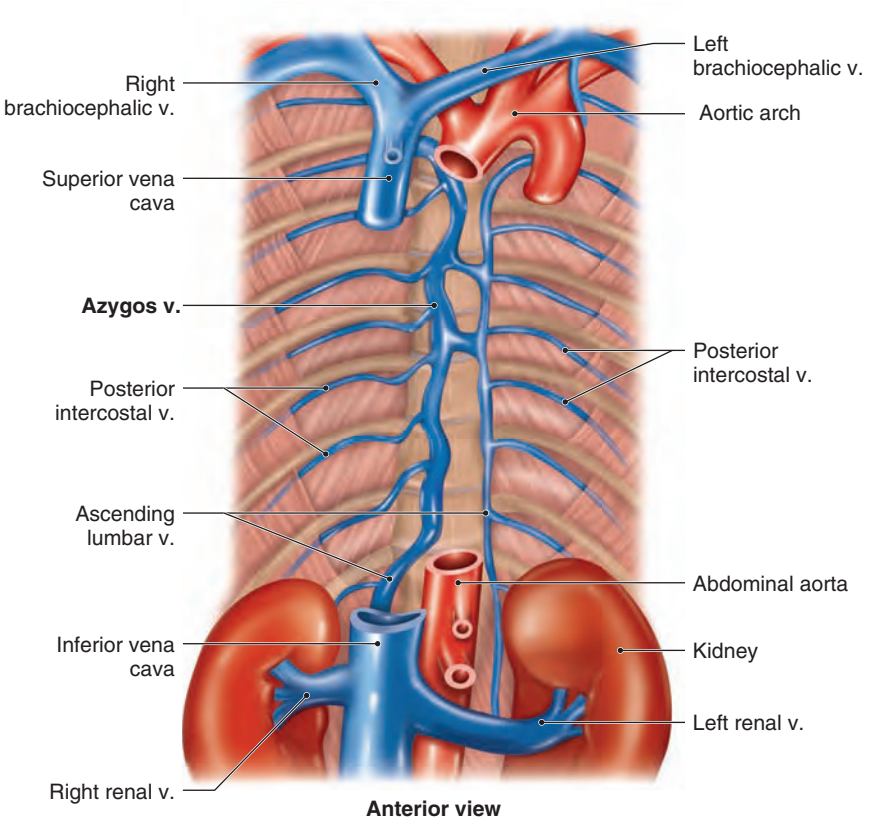


Figure 12.23 Major veins of the thoracic cavity.

Table 12.7 Major Veins Draining to the Inferior Vena Cava

Vein	Region Drained and Location	Receiving Vein
Lower Limb		
Anterior and posterior tibial	Foot and leg	Popliteal
Popliteal	Knee	Femoral
Small saphenous	Posterior leg (superficial)	Popliteal
Great saphenous	Lower limb (superficial)	Femoral
Femoral	Thigh	External iliac
Trunk		
Hepatic portal	Intestines, stomach, spleen, and pancreas	Liver sinusoids
Hepatic	Liver	Inferior vena cava
Renal	Kidneys	Inferior vena cava
Right ovarian or testicular	Right ovary or testis	Inferior vena cava
Left ovarian or testicular	Left ovary or testis	Left renal
External iliac	Pelvic wall and lower limb	Common iliac
Internal iliac	Viscera in pelvis and inferior abdominal cavity, pelvic wall, and superior thigh	Common iliac
Common iliac	Pelvic and inferior abdominal regions and lower limb	Inferior vena cava

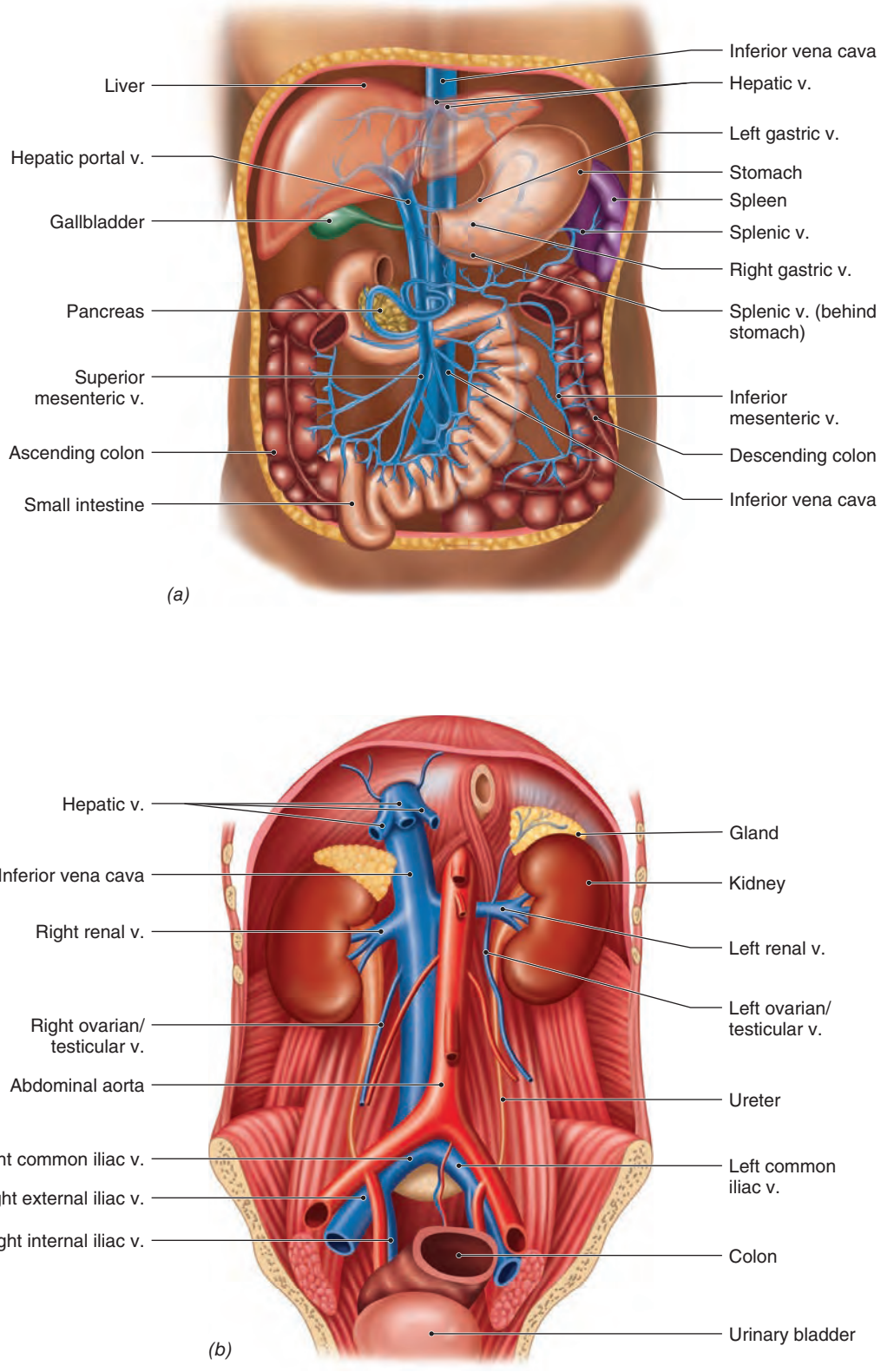


Figure 12.24 *(a)* An anterior view of the veins of the hepatic portal system. *(b)* An anterior view of the major veins draining into the inferior vena cava.

12.11 Disorders of the Heart and Blood Vessels

Learning Objective

17. Describe the common disorders of the heart and blood vessels.

These disorders are grouped according to whether they affect primarily the heart or the blood vessels. In some cases, the underlying cause of a heart ailment is a blood vessel disorder.

Heart Disorders

Arrhythmia (ah-rith′-mē-ah), or dysrhythmia, refers to an abnormal heartbeat. It may be caused by a number of factors, including damage to the heart conduction system, drugs, electrolyte imbalance, or a diminished supply of blood via the coronary arteries. In addition to irregular heartbeats, arrhythmia includes

- Bradycardia–a slow heart rate of less than 60 beats per minute. Note that the bradycardia in well-trained athletes is a healthy condition because it saves energy during resting heart contraction and has a greater potential to increase cardiac output.
- Tachycardia–a fast heart rate of over 100 beats per minute.
- Heart flutter–a very rapid heart rate of 200 to 300 beats per minute.
- Fibrillation–a very rapid heart rate in which the contractions are uncoordinated so that blood is not pumped from the ventricles. Ventricular fibrillation is usually fatal without prompt treatment.

Congestive heart failure (CHF) is the acute or chronic inability of the heart to pump out the blood returned to it by the veins. Symptoms include fatigue; edema (accumulation of fluid) of the lungs, feet, and legs; and excess accumulation of blood in internal organs. CHF may result from atherosclerosis of the coronary arteries, which deprives the myocardium of adequate blood.

Heart murmurs are unusual heart sounds. They are usually associated with defective heart valves, which allow a backflow of blood. Unless there are complications, heart murmurs have little clinical significance.

Myocardial infarction (mī-ō-kar′-dē-al in-fark′-shun) is the death of a portion of the myocardium due to an obstruction in a coronary artery. The obstruction is usually a blood clot that has formed as a result of atherosclerosis. This event is commonly called a "heart attack," and it may be fatal if a large portion of the myocardium is deprived of blood.

Pericarditis is the inflammation of the pericardium and is usually caused by a viral or bacterial infection. It may be quite painful as the inflamed membranes rub together during each heart cycle.

Blood Vessel Disorders

An **aneurysm** (an′-yū-rizm) is a weakened portion of a blood vessel that bulges externally, forming a balloonlike sac filled with blood. Rupture of an aneurysm in a major artery may produce a fatal hemorrhage.

Arteriosclerosis (ar-te″-rēō-skle-rō′-sis) is hardening of the arteries. It results from calcium deposits that accumulate in the tunica media of arterial walls and is usually associated with atherosclerosis.

Atherosclerosis is the formation of fatty deposits (cholesterol and triglycerides) along the tunica intima of arterial walls. The atherosclerotic plaques reduce the lumen of the arteries and increase the probability of blood clots being formed. Such deposits in the coronary, carotid, or cerebral arteries may lead to serious circulatory problems (figure 12.25).

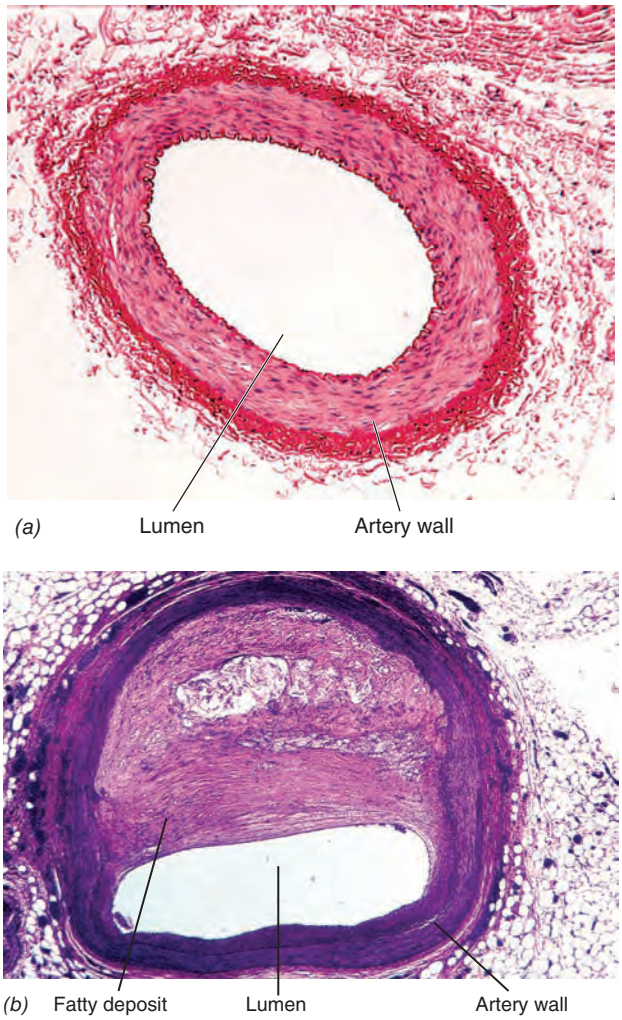


Figure 12.25 Cross sections of *(a)* a normal artery and *(b)* an atherosclerotic artery whose lumen is diminished by fatty deposits. Atherosclerosis promotes the formation of a blood clot within the artery.

Hypertension refers to chronic high blood pressure. It is the most common disease affecting the heart and blood vessels. Blood pressure that exceeds 140/90 mm Hg is indicative of hypertension. A systolic blood pressure of 120 to 139 mm Hg and a diastolic blood pressure of 80 to 89 mm Hg is considered to be *prehypertension*. Hypertension may be caused by a variety of factors, but persistent stress and smoking are commonly involved.

Phlebitis (flē-bī′-tis) is inflammation of a vein, and it most often occurs in a lower limb. If it is complicated by the formation of a blood clot, it is called *thrombophlebitis*.

Varicose veins are veins that have become dilated and swollen because their valves are not functioning properly. Heredity seems to play a role in their occurrence. Pregnancy, standing for prolonged periods, and lack of physical activity reduce venous return and promote varicose veins in the lower limbs. Chronic constipation promotes their occurrence in the anal canal, where they are called **hemorrhoids** (hem′o-royds).

Chapter Summary

12.1 Anatomy of the Heart

- The heart wall consists primarily of the myocardium, a thick layer of cardiac muscle tissue. It is lined internally by the thin endocardium and externally by the thin epicardium.
- The pericardial sac is composed of the parietal layer of the serous pericardium and fibrous pericardium. The pericardial cavity is filled with pericardial fluid.
- The heart contains four chambers. The superior chambers are the left and right atria, which receive blood returning to the heart. The inferior chambers are the left and right ventricles, which pump blood out of the heart. There are no openings between the atria or between the ventricles.
- Atrioventricular valves allow blood to flow between each atrium and its corresponding ventricle but prevent a backflow of blood. The mitral valve lies between the left atrium and left ventricle. The tricuspid valve lies between the right atrium and right ventricle.
- Semilunar valves allow blood to be pumped from the ventricles into their associated arteries but prevent a backflow of blood. The aortic valve is located in the base of the aorta. The pulmonary valve is located in the base of the pulmonary trunk.
- The right atrium receives deoxygenated blood from the superior and inferior venae cavae and the coronary sinus, and the left atrium receives oxygenated blood from the pulmonary veins.
- The right ventricle pumps deoxygenated blood into the pulmonary trunk, which divides into the left and right pulmonary arteries, which lead to the lungs. At the same time, the left ventricle pumps oxygenated blood into the aorta, which leads to all parts of the body except the lungs.
- The myocardium receives blood from the coronary arteries, which branch from the ascending aorta. Blood is returned from the myocardium by the cardiac veins, which open into the coronary sinus, which leads to the right atrium.

12.2 Cardiac Cycle

- The cardiac cycle includes both contraction (systole) and relaxation (diastole) phases.
- During atrial diastole, blood returns to the atria and flows on into the ventricles. Atrial systole forces more blood into the ventricles to fill them.
- During ventricular diastole, blood flows into the ventricles. Ventricular systole pumps blood from the ventricles into their associated arteries.
- The normal lub-dup heart sound is caused by the closure of the heart valves. The first sound results from the closure of the atrioventricular valves. The second sound results from the closure of the semilunar valves.

12.3 Heart Conduction System

- The SA node is the pacemaker, which rhythmically initiates impulses that cause the heart contractions.
- Impulses pass through the atria, causing atrial systole, and simultaneously reach the AV node.
- Impulses pass from the AV node along the AV bundle and bundle branches to the ventricular fibers, which transmit the impulses to the myocardium, causing ventricular systole.
- An electrocardiogram is a recording of the formation and transmission of impulses through the heart conduction system.
- An electrocardiogram consists of a P wave, a QRS complex, and a T wave, and it is used in the diagnosis of heart ailments.

12.4 Regulation of Heart Function

- Cardiac output is a measure of heart function. It is determined by stroke volume and heart rate:

$$CO = SV \times HR$$

- Cardiac output is regulated by factors internal and external to the heart.
- Heart rate and stroke volume are controlled by the autonomic nervous system. The cardiac control center is in the medulla oblongata. It receives sensory nerve impulses from baroreceptors and chemoreceptors, and is also affected by nerve impulses from the cerebrum and hypothalamus.

- Sympathetic axons release norepinephrine at heart synapses, which causes an increase in the heart rate and contraction strength. Parasympathetic axons release acetylcholine at heart synapses, which causes a decrease in heart rate.
- The dynamic balance in the frequency of sympathetic and parasympathetic nerve impulses reaching the heart adjusts the heart rate and stroke volume to meet body needs.
- Heart rate and stroke volume are also affected by age, sex, physical condition, temperature, epinephrine, thyroid hormones, and the blood concentration of Ca^{2+} and K^{+}.

12.5 Types of Blood Vessels

- The three basic types of blood vessels are arteries, capillaries, and veins. Large arteries and veins are formed of a superficial tunica externa of dense irregular connective tissue, a middle tunica media of smooth muscle, and a deep tunica intima of endothelium supported by areolar connective tissues.
- Arteries have thick, muscular walls and carry blood from the heart. Large arteries divide repeatedly to form the smallest arteries, arterioles, which connect with capillaries.
- Capillaries are the smallest and most numerous blood vessels. They are composed of an endothelium supported by a layer of areolar connective tissue. Their thin walls allow an exchange of materials between the blood and the interstitial fluid. Dissolved substances are exchanged by diffusion. Fluid exits the arteriolar end of a capillary because blood pressure is greater than osmotic pressure, and it reenters at the venular end of the capillary because osmotic pressure is greater than blood pressure.
- Veins have thinner walls than arteries and carry blood from capillaries toward the heart. The smallest veins are venules, which lead from capillaries and merge to form small veins. Large veins contain valves that prevent a backflow of blood.

12.6 Blood Flow

- Blood circulates from areas of higher pressure to areas of lower pressure. Blood pressure is highest in the ventricles and lowest in the atria.
- Systemic blood pressure declines as blood is carried from the arteries through the capillaries and through the veins. Skeletal muscle contractions and respiratory movements are important forces that aid the return of venous blood.
- Blood velocity varies inversely with the cross-sectional area of the combined blood vessels. Blood velocity is fastest in the aorta and slowest in the capillaries. The velocity progressively increases as the blood flows from capillaries to the larger veins.

12.7 Blood Pressure

- Optimal systolic blood pressure is 115 mm Hg. Optimal diastolic blood pressure is 75 mm Hg.
- The difference between systolic and diastolic pressures is the pulse pressure. The pulse may be detected by palpating superficial arteries.
- Blood pressure is determined by three factors: cardiac output, blood volume, and peripheral resistance.
- Peripheral resistance is determined by vessel diameters, total vessel length, and blood viscosity.
- The vasomotor center in the medulla oblongata provides the autonomic control of blood vessel diameter. In this way, the autonomic nervous system controls peripheral resistance and blood pressure.
- Local autoregulation of arterioles overrides autonomic control and regulates blood flow in capillaries according to the needs of the local tissues.

12.8 Circulation Pathways

- The pulmonary circuit carries blood from the heart to the lungs and back again.
- The systemic circuit carries blood from the heart to all parts of the body, except the lungs, and back again.

12.9 Systemic Arteries

- The aorta is divided into the ascending aorta, aortic arch, thoracic aorta, and abdominal aorta.
- The major branch arteries of the aorta are the coronary, brachiocephalic trunk, left common carotid, left subclavian, posterior intercostals, celiac trunk, superior mesenteric, renal, ovarian/testicular, lumbar, inferior mesenteric, and common iliac arteries.
- The major arteries supplying the head and neck are paired arteries. Each common carotid artery branches to form the external and internal carotid arteries. The external carotid supplies the neck, face, and scalp. The internal carotid is the major artery supplying the brain. The vertebral arteries supply the neck and brain.
- Each shoulder and upper limb is supplied by a subclavian artery, which becomes the axillary artery, which becomes the brachial artery of the arm. The brachial artery branches to form the radial and ulnar arteries of the forearm.
- Each common iliac artery branches to form internal and external iliac arteries. The external iliac enters the thigh to become the femoral artery, which becomes the popliteal artery near the knee. The popliteal branches inferior to the knee to form the anterior and posterior tibial arteries.

12.10 Systemic Veins

- Veins draining the head and neck are paired veins. On each side, the external jugular and vertebral veins empty into the subclavian vein. The internal jugular vein and subclavian merge to form the brachiocephalic vein. The left and right brachiocephalic veins join to form the superior vena cava.
- The ascending lumbar veins and the posterior intercostal veins enter the azygos vein, which opens into the superior vena cava.

- Radial and ulnar veins of the forearm join to form the brachial vein of the arm. The basilic vein joins the brachial vein to form the axillary vein, which, in turn, receives the cephalic vein to form the subclavian vein.
- Anterior and posterior tibial veins merge inferior to the knee to form the popliteal vein. The popliteal vein receives the small saphenous and fibular veins to form the femoral vein. The great saphenous vein extends from the foot to join with the femoral vein near the hip, which forms the external iliac vein. The external iliac vein joins with the internal iliac vein to form the common iliac vein. The left and right common iliac veins merge to form the inferior vena cava.
- The splenic vein receives the inferior mesenteric vein and the pancreatic vein, and merges with the superior mesenteric vein to form the hepatic portal vein. The gastric vein drains into the hepatic portal vein. The hepatic portal vein empties into the liver sinusoids. The hepatic vein carries blood from the liver to the inferior vena cava.
- The right ovarian or testicular vein and the paired renal veins empty into the inferior vena cava. The left ovarian or testicular vein drains into the left renal vein.

12.11 Disorders of the Heart and Blood Vessels

- Disorders of the heart include arrhythmia, congestive heart failure, heart murmurs, myocardial infarction, and pericarditis.
- Disorders of blood vessels include aneurysm, arteriosclerosis, atherosclerosis, hypertension, phlebitis, and varicose veins.

Self-Review

Answers are located in appendix B.

1. The membranous sac around the heart is the _____.
2. The _____ is the heart chamber receiving oxygenated blood from the lungs.
3. The _____ valve prevents a backflow of blood from the right ventricle into the _____.
4. During _____ diastole blood fills the atria; during ventricular _____ blood is pumped into arteries leading from the heart.
5. The heartbeat originates in the _____ node: the _____ node relays impulses along the AV bundle and ventricular fibers to the ventricular myocardium.
6. Nerve impulses from _____ axons increase the heart rate; nerve impulses from the _____ axons decrease the heart rate.
7. Blood is carried from the heart in _____ and returned to the heart in _____.
8. Vessels with the thickest walls are _____; those with the thinnest walls are _____.
9. The exchange of materials between capillary blood and interstitial fluid occurs by _____ and _____.
10. The heart chambers and vessels in the pulmonary circuit are _____ ventricle, pulmonary _____, pulmonary _____, alveolar capillaries, pulmonary _____, _____ atrium.
11. The arterial pathway of blood from the heart to the right side of the brain is ascending aorta, aortic arch, _____, common carotid, and _____.
12. The arterial pathway of blood from the heart to the liver is ascending aorta, aortic arch, _____ aorta, abdominal aorta, _____, _____, and _____.
13. The venous pathway returning blood from the digestive tract to the heart is _____, liver _____, _____, and _____ vena cava.
14. The venous pathway returning blood from the posterior of the knee is _____, femoral, _____, _____, and _____ vena cava.
15. The venous pathway from the little finger to the heart is basilic, _____, _____, _____, and _____ vena cava.

Critical Thinking

1. How do the heart valves keep blood flowing in one direction?
2. What factors are involved in creating blood pressure?
3. What enables the heart to change its rate and strength of contraction as needed?
4. What is the advantage of the hepatic portal system?
5. Why are there more superficial veins than superficial arteries?

9
CHAPTER

Respiratory System

One fall weekend, Jesse drives home from college to attend the homecoming football game at his old high school. When Jesse arrives at the game, it is as if the entire town has come out to watch their team battle the rival high school. For three hours, Jesse cheers loudly for every great play and yells at the referee for every bad call. In fact, the stadium is so loud that he has to shout to talk to some old friends who have sat down nearby. When the game ends, Jesse heads home feeling triumphant over his alma mater's victory. However, when he wakes up in the morning, his neck is sore and his voice is very raspy and barely audible. His mother, a registered nurse at the local hospital, diagnoses Jesse as having acute laryngitis. Jesse's loud cheering has inflamed his larynx, or "voice box," which is causing the soreness and difficulty speaking. As he rests his voice and drinks some hot tea with honey, Jesse thinks to himself that supporting his school was completely worth a little discomfort.

CHAPTER OUTLINE

SELECTED KEY TERMS

Alveolar gas exchange The exchange of oxygen and carbon dioxide between the air in alveoli and the blood in alveolar capillaries.
Alveolus (alveol = small cavity) A microscopic air sac within a lung.
Breathing The movement of air into and out of the lungs.
Bronchial tree (bronch = windpipe) The branching bronchi.
Expiration (ex = from; spirat = breathe) Movement of air out of the lungs; exhalation.
Glottis The opening between the vocal folds within the larynx.
Inspiration Movement of air into the lungs: inhalation.
Larynx (laryn = gullet) The cartilaginous box located between the pharynx and the trachea that contains vocal folds.
Pharynx (pharyn = throat) The cavity between the mouth and the esophagus or larynx, used in both breathing and swallowing; the throat.
Surfactant A chemical in alveoli that reduces surface tension and prevents alveolar collapse.
Systemic gas exchange The exchange of oxygen and carbon dioxide between the blood in systemic capillaries and the tissue cells.
Trachea (trache = windpipe) The tube carrying air between the larynx and the bronchi.

THE PRIMARY ROLE of the respiratory system is to make oxygen available to cells for cellular respiration and to remove carbon dioxide, the main byproduct of that metabolism. The entire process of respiration encompasses five unique and sequential processes:

1. **Breathing** (pulmonary ventilation)–the movement of air into and out of the lungs.
2. **Alveolar gas exchange**–the exchange of oxygen and carbon dioxide between the air in alveoli and the blood in alveolar capillaries.
3. **Gas transport**–transport of oxygen and carbon dioxide between the lungs and tissues, accomplished by the cardiovascular system.
4. **Systemic gas exchange**–the exchange of oxygen and carbon dioxide between the blood in systemic capillaries and the tissue cells.
5. **Cellular respiration**–the use of oxygen and production of carbon dioxide during ATP production.

The structures of the respiratory system are involved directly in only two of these processes: breathing and alveolar gas exchange, which is collectively referred to as **external respiration.** Systemic gas exchange and cellular respiration together are referred to as **internal respiration.**

The respiratory system does more than just exchange respiratory gases. It also helps to detect odors, produce sounds, regulate blood pH, trap and defend the body from airborne pathogens, and assist in the movement of venous blood and lymph.

14.1 Structures of the Respiratory System

Learning Objective

1. Describe the structures and functions of the respiratory system.

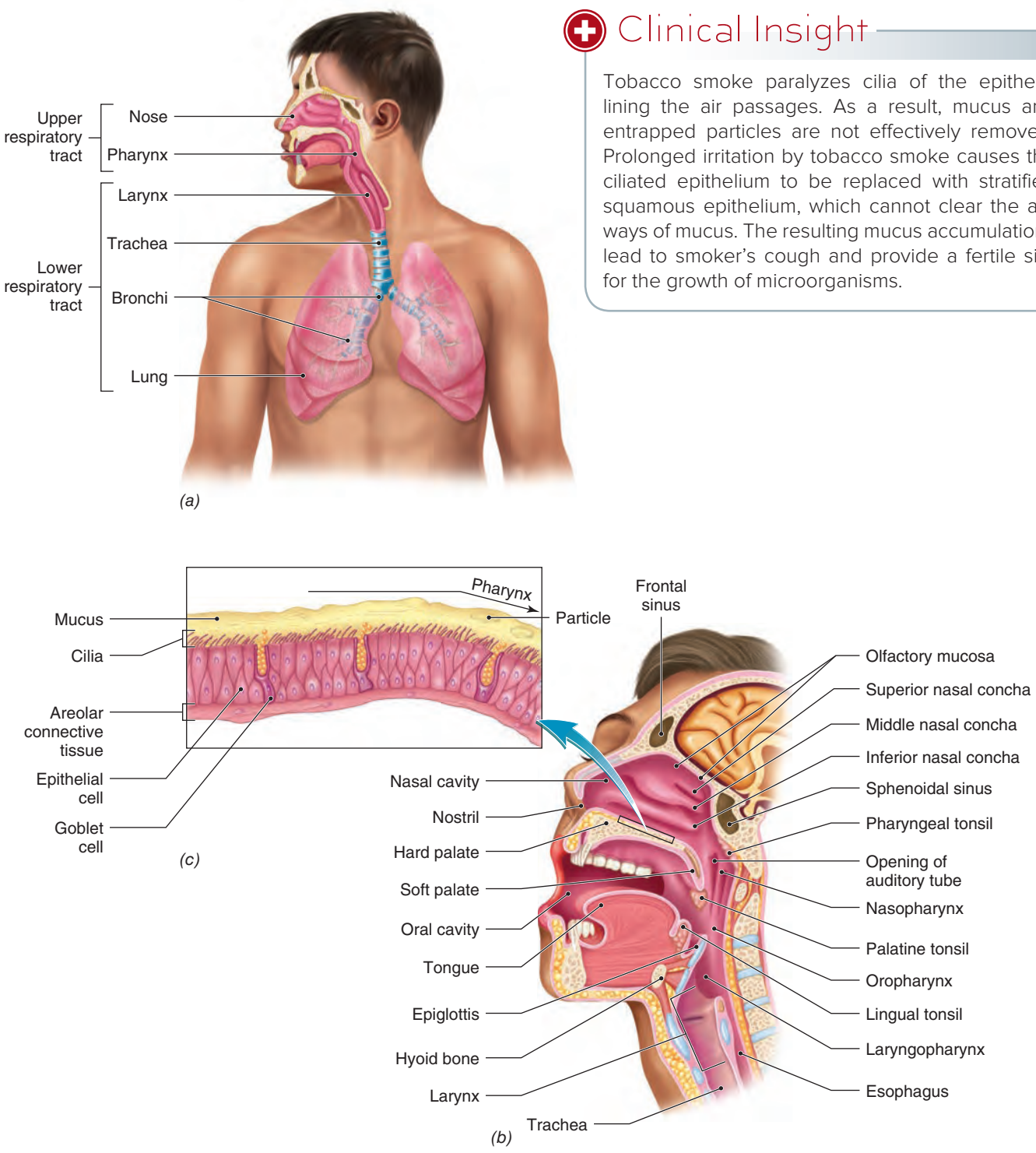
The *respiratory system* is subdivided into upper and lower respiratory tracts. The *upper respiratory tract* includes the nose and pharynx. The *lower respiratory tract* includes the larynx, trachea, bronchi, and lungs (figure 14.1*a*).

Nose

The protruding portion of the *nose* is supported by bone and nasal cartilage (figure 14.1*b*). The nasal bones form a rigid support for the bridge of the nose, and nasal cartilage supports the remaining portions and is responsible for the flexibility of the nose. The *nostrils*, or *nares*, are the two external openings in the nose that allow air to enter and leave the nasal cavity. Stiff hairs around the nostrils tend to keep out large airborne particles and insects.

The **nasal cavity** is the internal chamber of the nose that is surrounded by skull bones. It is separated from the oral cavity by the **palate** (roof of the mouth), which consists of two basic portions. The anterior *hard palate* is formed by the palatine processes of the maxillae and the palatine bones. The posterior soft palate is composed of skeletal muscle tissue. The nasal cavity is divided into left and right portions by the **nasal septum,** a vertical partition of bone and nasal cartilage that is located on the midline. Three *nasal conchae* project from each lateral wall and serve to increase the surface area of and create air turbulence in the nasal cavity.

The superior nasal concha and superior nasal septum are lined with **olfactory mucosa** containing the olfactory epithelium, the tissue containing the olfactory receptors used in detecting chemicals for the sense of smell (see chapter 9). The rest of the nasal cavity, larynx, trachea, and bronchi are covered by **respiratory mucosa** containing pseudostratified ciliated columnar epithelium. Goblet cells within the epithelium produce mucus to coat the epithelial surface. As air flows through the nasal cavity, it is warmed by the blood-rich mucosae and is moistened by the mucus. In addition, airborne particles, including microorganisms,



Clinical Insight

Tobacco smoke paralyzes cilia of the epithelia lining the air passages. As a result, mucus and entrapped particles are not effectively removed. Prolonged irritation by tobacco smoke causes the ciliated epithelium to be replaced with stratified squamous epithelium, which cannot clear the airways of mucus. The resulting mucus accumulations lead to smoker's cough and provide a fertile site for the growth of microorganisms.

Figure 14.1 *(a)* The general organization of the respiratory system. *(b)* Major structures of the upper respiratory tract. *(c)* Mucus and entrapped particles are moved by cilia of the mucosa from the nasal cavity to the pharynx.

are trapped in the mucus of the respiratory mucosa. Within the larynx, trachea, and bronchi, cilia of the epithelium slowly move the layer of mucus with its entrapped particles toward the pharynx (figure 14.1c), where it is swallowed. Upon reaching the stomach, most microorganisms in the mucus are destroyed by the gastric juice.

Several bones surrounding the nasal cavity contain **paranasal sinuses,** air-filled cavities. Sinuses are located

in the frontal bone, ethmoid, maxillae, and sphenoid adjacent to the nasal cavity. The sinuses lighten the skull and serve as sound-resonating chambers during speech. The sinuses open into the nasal cavity, which increases nasal cavity surface area, and are lined with ciliated mucosae that are continuous with the mucosae of the nasal cavity. The secreted mucus drains into the nasal cavity.

Pharynx

The **pharynx** (fayr′-inks), commonly called the throat, is a short passageway that lies posterior to the nasal and oral cavities and extends inferiorly to the larynx and esophagus. It has a muscular wall and it is lined with mucosae containing stratified squamous epithelium. As shown in figure 14.1*b*, the pharynx consists of three parts: the *nasopharynx* posterior to the nose; the *oropharynx* posterior to the mouth; and the *laryngopharynx* posterior to the larynx.

The *auditory* (eustachian) *tubes* (figure 14.1*b*), which extend to the middle ear, open into the nasopharynx. Air moves in or out of the auditory tubes to equalize the air pressure on each side of the tympanic membrane.

The tonsils, clumps of lymphoid tissue, occur at the openings to the pharynx. The *palatine tonsils* are located bilaterally at the junction of the oropharynx and the oral cavity. The *pharyngeal tonsil* (adenoid) is located in the superior nasopharynx, and the *lingual tonsils* are found on the posterior tongue. Tonsils are sites of immune reactions and may become sore and swollen when infected. Enlargement of the palatine tonsils tends to make swallowing painful and difficult. A swollen pharyngeal tonsil tends to block the flow of air between the nasal cavity and the pharynx, which promotes mouth breathing and can create snoring. When breathing through the mouth, air is not adequately warmed, filtered, and moistened.

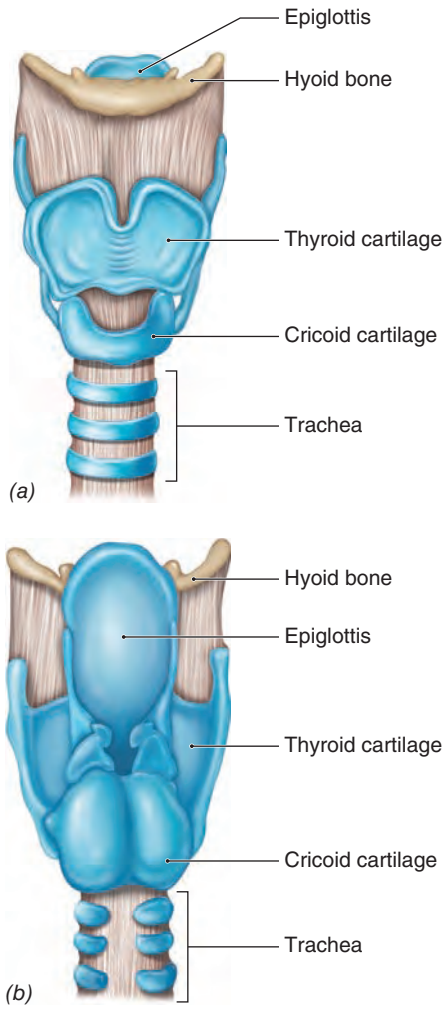


Figure 14.2 The Larynx.
(a) Anterior view. *(b)* Posterior view.

Larynx

The **larynx** (layr′-inks) is a boxlike structure, composed of several cartilages, that provides a passageway for air between the pharynx and the trachea. The three largest cartilages are the *thyroid cartilage*, which projects anteriorly to form the Adam's apple; the *cricoid cartilage*, which forms the attachment to the trachea; and the *epiglottis*, a cartilaginous flap that helps to keep solids (food) and liquid from entering the larynx. The larynx is supported by ligaments that extend from the hyoid bone (figure 14.2).

The **vocal folds** are two bands of elastic connective tissue covered by mucosa located within the larynx (figure 14.3). They are relaxed during normal breathing, but when contracted, they vibrate to produce vocal sounds when exhaled air passes over them. The pitch (high or low tone) of a sound is determined by the vibration frequency of the vocal folds. High frequency vibrations lead to high pitch sound and vice versa. The loudness (volume) of a sound is related to the vibration amplitude of the vocal folds. The larger the amplitude the louder the volume and vice versa. The opening between the vocal folds, the **glottis,** leads to the trachea. The **vestibular folds,** which lie superior to the vocal folds, are composed of a small amount of elastic connective tissue covered by mucosa. They prevent food from entering the glottis and are not involved in sound production.

Because the oropharynx and laryngopharynx are also passageways for food, a mechanism exists to prevent food from entering the larynx and to direct food into the esophagus (ē-sof′-ah-gus), the flexible tube that carries food to the stomach. When swallowing, muscles lift the larynx superiorly, which causes the epiglottis to fold over and cover the opening into the larynx. This action directs food into the esophagus, whose opening is located just posterior to the larynx. Sometimes this mechanism does not work perfectly and a small amount of food or drink enters the larynx, stimulating a coughing reflex that usually expels the substance.

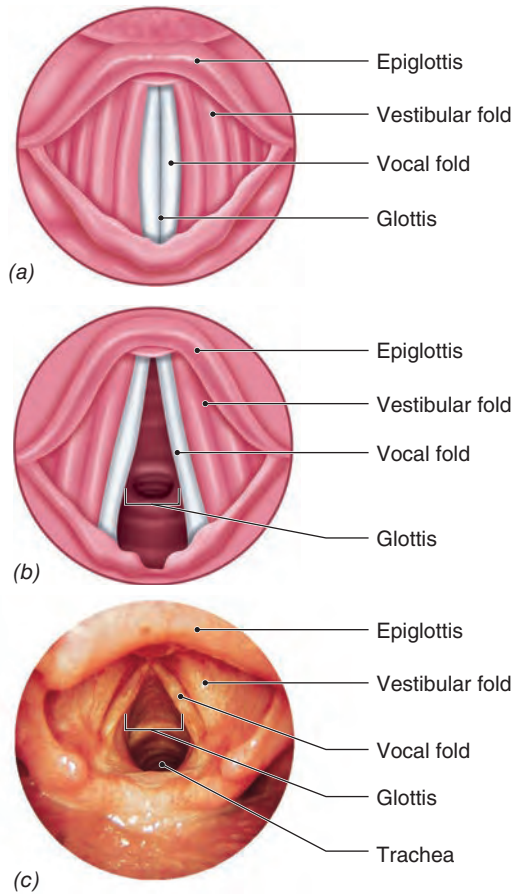


Figure 14.3 Vocal folds viewed superiorly with the glottis *(a)* closed and *(b)* open. *(c)* Photograph of the glottis and vocal folds.

Trachea

The **trachea** (trā′-kē-ah), or windpipe, is a tube that extends from the larynx into the thoracic cavity, where it branches to form the right and left main bronchi. The walls of the trachea are supported by C-shaped *tracheal cartilages* that hold the passageway open in spite of the air pressure changes that occur during breathing (figure 14.4*a*). The open portion of the tracheal cartilages is oriented posteriorly against the esophagus (see figure 14.2*b*). This orientation allows the esophagus to expand slightly as food passes down to the stomach.

The internal wall of the trachea is lined with mucosa containing pseudostratified ciliated columnar epithelium, the same type of epithelium lining most of the upper respiratory tract. Mucus produced by the goblet cells coats the surface of the epithelium and traps airborne particles, including microorganisms. The beating cilia move the mucus and entrapped particles superiorly to the pharynx where they are coughed out or swallowed. Microorganisms are usually killed by gastric juice in the stomach.

Bronchi, Bronchioles, and Alveoli

The trachea branches at about midchest into the left and right *main bronchi* (brong′-kī; singular, bronchus). Each main bronchus enters its respective lung, where it branches to form smaller *lobar bronchi,* one for each lobe of the lung. Lobar bronchi branch to form segmental bronchi that lead to different bronchopulmonary segments of each lung lobe. The bronchi continue to branch into smaller and smaller bronchi. Because the bronchi resemble tree branches, they are collectively called the **bronchial tree** (figure 14.4*a*).

The walls of the bronchi contain cartilaginous rings similar to those of the trachea, but as the branches get progressively smaller, the amount of cartilage gradually decreases and finally is absent in the very small tubes called the **bronchioles** (brong′-kē-ōls). As the amount of cartilage decreases, the amount of smooth muscle increases. The smooth muscle plays an important role in regulating the airflow through the air passageways. Contraction of the smooth muscle causes *bronchoconstriction,* which decreases airflow. Relaxation of the smooth muscle results in *bronchiodilation,* which increases airflow. Air passageways larger than bronchioles are lined with ciliated mucosae that continue to trap and remove airborne particles. Bronchioles are lined with mucosae containing simple cuboidal epithelium, so foreign particles that reach them are not effectively removed. Bronchioles branch to form smaller and smaller bronchioles that lead to microscopic **alveolar ducts,** which terminate in tiny air sacs called **alveoli** (al-vē′-ō-lī; singular, *alveolus*). Alveoli resemble tiny grapes clustered about an alveolar duct and are composed of simple squamous epithelium (figure 14.5*a*).

The primary function of the bronchial tree and bronchioles is to carry air into and out of the alveoli during breathing. The exchange of respiratory gases occurs between the air in the alveoli and the blood in the capillary networks that surround the alveoli (figure 14.5*b*). Oxygen and carbon dioxide diffuse readily through the thin **respiratory membrane,** which is composed of squamous cells of the alveolar wall and the capillary wall (figure 14.5*c*). Alveoli are extremely numerous–about 300 million in each lung. They have a combined surface area of about 75 square meters and can hold about 6,000 ml of air.

Alveoli contain very small spaces, which are coated with a watery fluid. The attraction (surface tension) between water molecules would cause the alveoli to collapse if it were not for surfactant. **Surfactant** (ser-fak′-tant) is a mixture of lipoproteins secreted by special cells in alveoli. It reduces the attraction between water molecules and keeps alveoli open so they may fill with air during inspiration. Without surfactant, alveoli would collapse and become very difficult to reinflate.

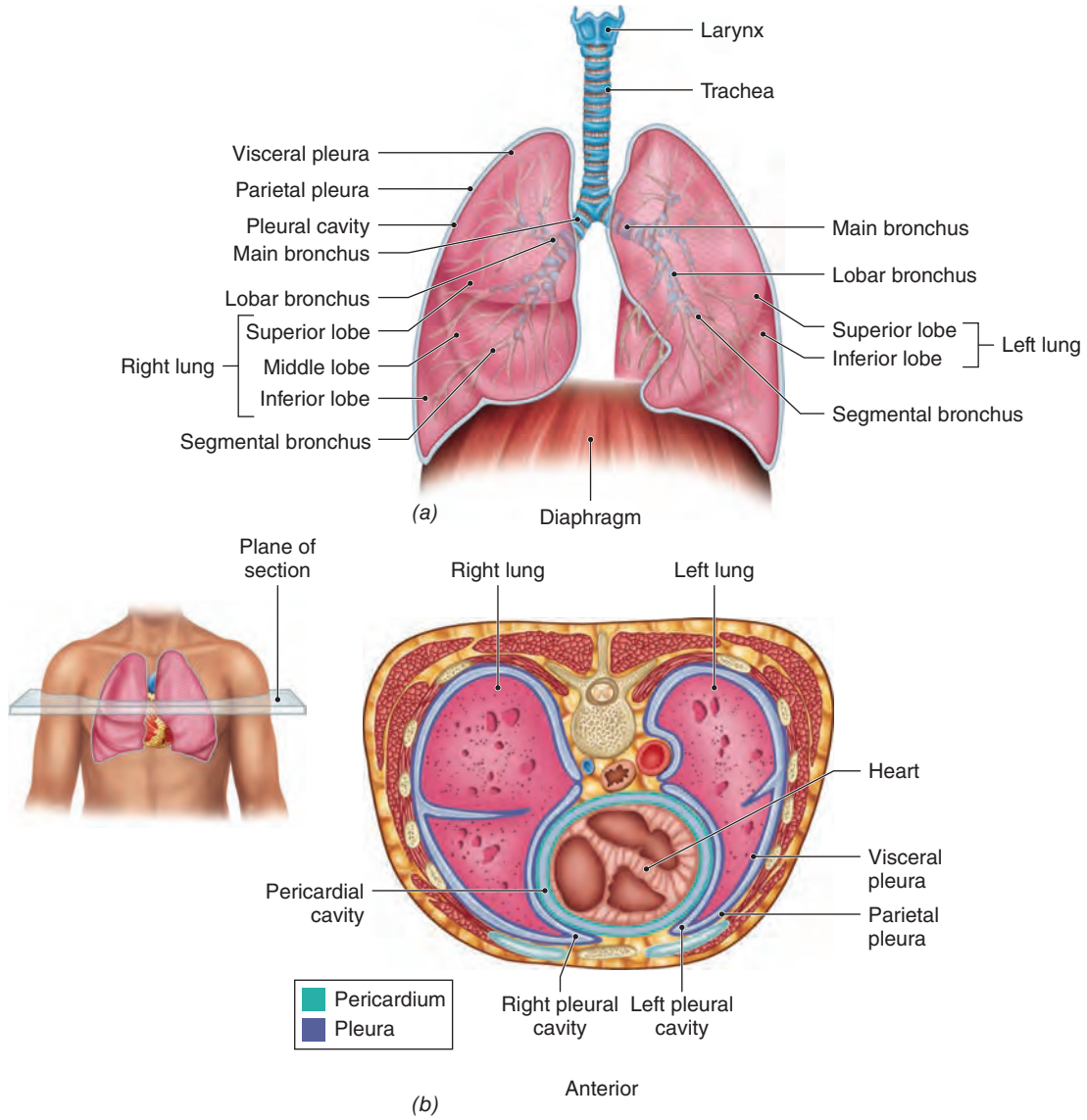


Figure 14.4 *(a)* Anterior view of the lower respiratory tract. *(b)* Transverse section of the thoracic cavity shows the pleurae and the relationship of the lungs to other thoracic organs.

Lungs

The paired **lungs** are large organs that occupy much of the thoracic cavity. They are roughly cone-shaped and are separated from each other by the mediastinum. Each lung is divided into lobes. The left lung has two lobes (superior and inferior) and is somewhat smaller than the right lung, which is composed of three lobes (superior, middle, and inferior) (see figure 14.4*a*). Each lobe is supplied by a lobar bronchus, blood and lymphatic vessels, and nerves. The lungs consist primarily of air passages, alveoli, blood and lymphatic vessels, nerves, and connective tissues, giving the lungs a soft, spongy texture.

Two layers of serosae, called pleural membranes, enclose and protect each lung. The **visceral pleura** is firmly attached to the surface of each lung, and the **parietal pleura** lines the internal wall of the thoracic cage. The potential space between the visceral and parietal pleurae is known as the **pleural cavity.** A thin film of pleural fluid occupies the pleural cavity and reduces friction between the pleurae as the lungs inflate and deflate during breathing. Although lungs are elastic and tend to recoil, the attraction of water molecules in the pleural fluid within the pleural cavity keeps the visceral and parietal pleurae stuck together (figure 14.4*b*).

Table 14.1 summarizes the functions of the respiratory structures.

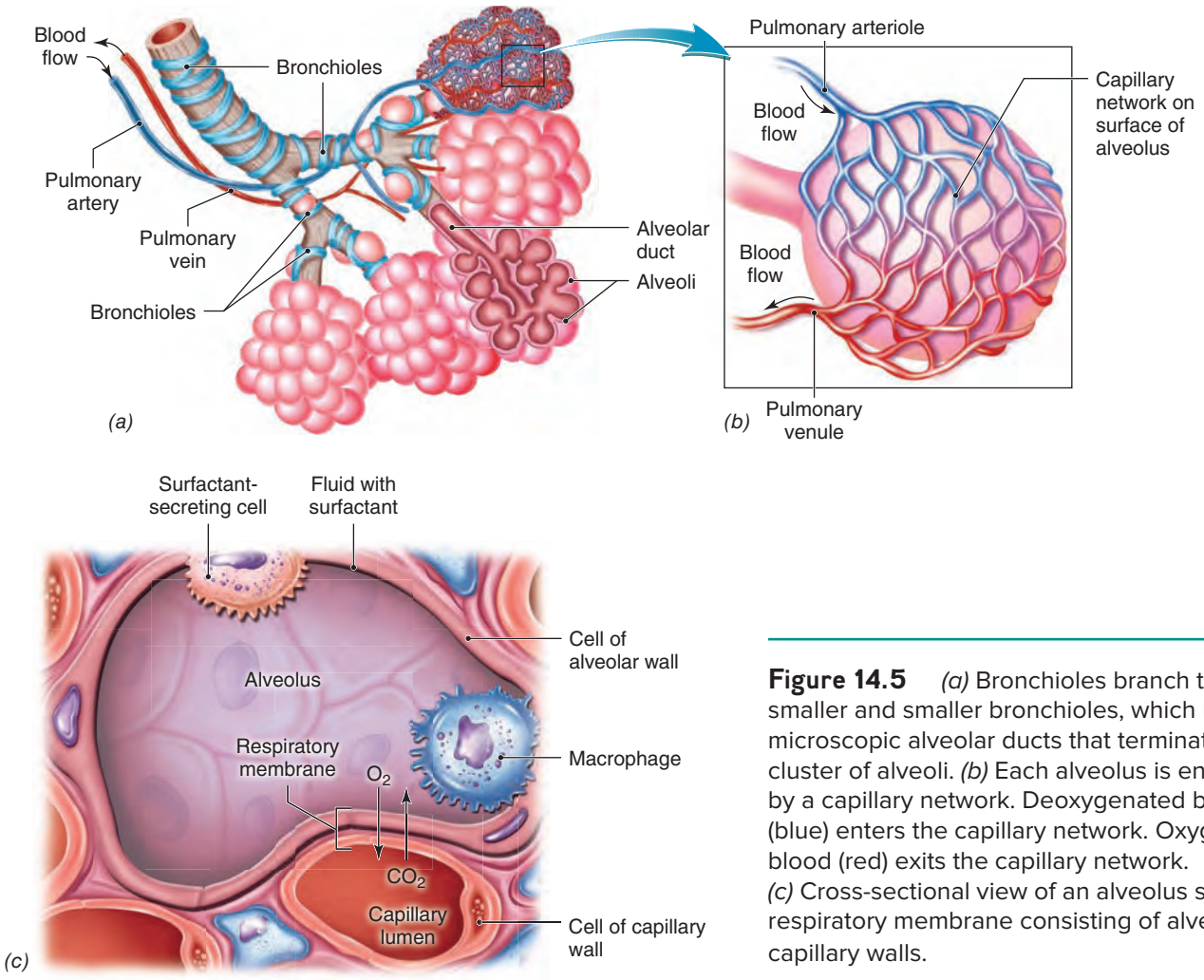


Figure 14.5 *(a)* Bronchioles branch to form smaller and smaller bronchioles, which lead to microscopic alveolar ducts that terminate in a cluster of alveoli. *(b)* Each alveolus is enveloped by a capillary network. Deoxygenated blood (blue) enters the capillary network. Oxygenated blood (red) exits the capillary network. *(c)* Cross-sectional view of an alveolus shows the respiratory membrane consisting of alveolar and capillary walls.

Check My Understanding

1. What are the functions of the nose?
2. What are the three divisions of the pharynx, and where are they located?
3. What are the functions of the glottis and epiglottis?
4. What are the functions of the vocal folds and vestibular folds?
5. What is the function of the cartilage in the walls of the trachea and bronchi?
6. What are the functions of the bronchi and bronchioles?
7. Why is surfactant important?

Table 14.1 Summary of Functions of the Respiratory Structures

Component	Function
Nose	Nostrils allow air to enter and exit the nasal cavity; the nasal cavity filters, warms, and moistens the inhaled air
Pharynx	Carries air between the nasal cavity and the larynx; filters, warms, and moistens the inhaled air; serves as passageway for food from the mouth to the esophagus; equalizes air pressure with middle ear via auditory tube
Larynx	Carries air between the pharynx and trachea; contains vocal folds for producing sounds in vocalization; prevents objects from entering the trachea
Trachea	Carries air between the larynx and the bronchi; filters, warms, and moistens the inhaled air
Bronchi	Carries air between the trachea and the bronchioles; filters, warms, and moistens the inhaled air
Bronchioles	Regulates the rate of airflow through bronchoconstriction and bronchodilation
Alveoli	Allow the gas exchange between the air in the alveoli and the blood in surrounding capillaries

14.2 Breathing

Learning Objective

2. Describe the mechanism of breathing.

Breathing, or pulmonary ventilation, is the process that exchanges air between the atmosphere and the alveoli of the lungs. Air moves into and out of the lungs along an air pressure gradient–from regions of higher pressure to regions of lower pressure. There are three pressures that are important in breathing:

1. *Atmospheric pressure* is the pressure of the air that surrounds the earth. Atmospheric pressure at sea level is 760 mm Hg, but at higher elevations it decreases because there is less air at higher elevations.
2. *Intra-alveolar (intrapulmonary) pressure* is the air pressure within the lungs. As we breathe in and out, this pressure fluctuates between being lower than atmospheric pressure and higher than atmospheric pressure.
3. *Intrapleural pressure* is the pressure within the pleural cavity. It is about 2 to 6 mm Hg below the atmospheric pressure during various phases of breathing. This lower intrapleural pressure is often described as "negative pressure," and it keeps the lungs stuck to the internal walls of the thoracic cage and helps expand the lungs, even as the thoracic cage expands and contracts during breathing. If the intrapleural pressure were to equal atmospheric pressure, the lungs would collapse and be nonfunctional.

Inspiration

The process of moving air into the lungs is called **inspiration,** or inhalation. When the lungs are at rest, the air pressure in the lungs is the same as the atmospheric pressure. In order for air to flow into the lungs, the intra-alveolar pressure must be decreased to below atmospheric pressure. This change allows for air to flow from the higher air pressure in the atmosphere towards the lower air pressure within the lungs. The contraction of the diaphragm and the external intercostals during inspiration causes an increase in lung volume, which results in a decrease in intra-alveolar pressure.

The dome-shaped **diaphragm** is a thin sheet of skeletal muscle separating the thoracic and abdominal cavities. When it contracts, the diaphragm pulls inferiorly and becomes flattened, which increases the volume of the thoracic cavity. At the same time, contraction of the *external intercostals* elevates and protracts the ribs and pushes the sternum anteriorly, which further increases the volume of the thoracic cavity (figures 14.6, 14.7*a*).

Clinical Insight

The presence of air in the pleural cavity is called a *pneumothorax* (nū-mō-thō′-raks). This may occur due to a thoracic injury or surgery that allows air to enter the pleural cavity. It also occurs in emphysema patients when air escapes from ruptured alveoli into the pleural cavity. A pneumothorax causes the affected lung to collapse and become nonfunctional. Because each lung is in a separate pleural cavity, the collapse of one lung does not adversely affect the other lung. Treatment involves removing the intrapleural air to restore the normal pressure so that the lung may inflate.

Because the negative intrapleural pressure and the surface tension of the pleural fluid keep the visceral pleura stuck to the parietal pleura, the lungs are pulled along when the thoracic cage expands. Therefore, the expansion of the thoracic cavity increases the volume of the lungs, which decreases the intra-alveolar pressure. Then, the higher atmospheric pressure forces air through the air passageways into the lungs until intra-alveolar and atmospheric pressures are equal. Quiet inspiration requires the contraction of the diaphragm and the external intercostals only. Forceful inspiration requires the involvement of additional muscles in the neck and chest, such as the sternocleidomastoid, scalenes, serratus anterior, and pectoralis minor (figure 14.6). The contraction of these muscles elevates and protracts the ribs to a greater extent, leading to a greater increase in the volume of the thoracic cavity. Through this further increase in thoracic volume, intra-alveolar pressure decreases to a greater extent, which results in greater airflow into the lungs.

Expiration

Expiration, or exhalation, occurs when the diaphragm and external intercostals relax, allowing the thoracic cage and lungs to return to their original size. This results in a decrease in the volume of the thoracic cavity and lungs. The decrease in lung volume increases intra-alveolar pressure to a level higher than atmospheric pressure. The higher intra-alveolar pressure forces air out of the lungs until intra-alveolar and atmospheric pressures are equal.

Expiration during quiet breathing is a rather passive process because the abundant elastic connective tissue in the lungs and thoracic wall causes them to return to their original size as soon as the muscles of inspiration relax. However, a forceful expiration is possible by contraction of the *internal intercostals* (figure 14.6), which depresses and retracts the ribs, and by the muscles of the abdominal wall, which move the abdominal viscera and diaphragm

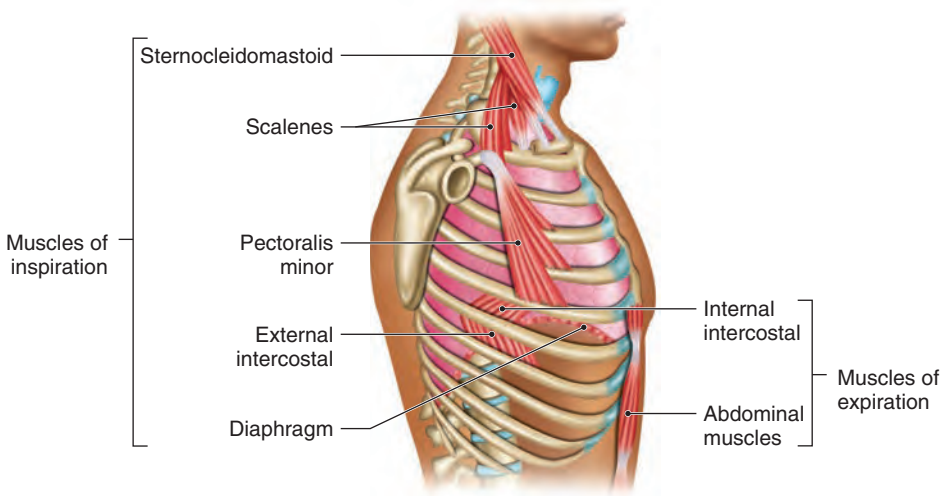


Figure 14.6 Respiratory muscles. Sternocleidomastoid, scalenes, and pectoralis minor are involved in forceful inspiration only. Internal intercostals and abdominal muscles are involved in forceful expiration only.

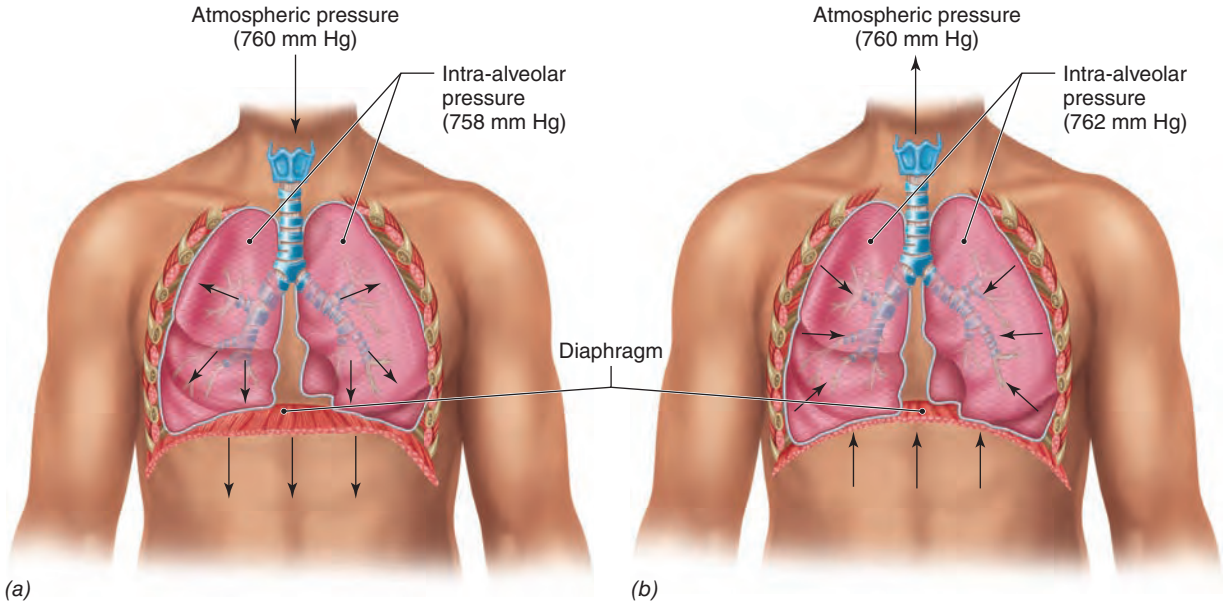


Figure 14.7 The Mechanisms of Breathing.
(a) During quiet inspiration, the increasing volume of the thoracic cavity and lungs reduces the intra-alveolar pressure, leading to air flowing into the lungs. *(b)* During quiet expiration, the decreasing volume of the thoracic cavity and lungs increases the intra-alveolar pressure, leading to air flowing out of the lungs.

superiorly. These contractions further decrease the volume of the thoracic cavity and lungs, which increases the intra-alveolar pressure, causing more air to flow out of the lungs.

Check My Understanding

8. How do intrapleural pressure and pleural fluid in the pleural cavity affect breathing?
9. Describe the mechanisms of inspiration and expiration.

14.3 Respiratory Volumes and Capacities

Learning Objective

3. Describe the various respiratory volumes and capacities and the significance of each.

Healthy adults average 12 to 15 quiet breathing cycles per minute. A *breathing cycle* is one inspiration followed by one expiration. The volume of air inhaled and exhaled

in a quiet or forceful breathing cycle varies with size, sex, age, and physical condition. The average respiratory volumes have been determined by size, age, and sex in order to enable evaluation of pulmonary functions. Respiratory volumes that are 80% or less than the healthy range usually indicate some form of pulmonary disease.

An instrument called a *spirometer* is used to determine respiratory volumes. It produces a *spirogram,* a graphic record of the volume of air exchanged.

The volume of air inhaled or exhaled in a quiet breathing cycle is about 500 ml, and it is known as the *tidal volume (TV).* Forceful inspirations and expirations can exchange a much greater volume of air. The maximum volume of air that can be forcefully inhaled after a tidal inspiration is about 3,000 ml, and it is known as the *inspiratory reserve volume (IRV).*

The maximum volume of air that can be forcefully exhaled after a tidal expiration is about 1,100 ml, and it is known as the *expiratory reserve volume (ERV).* About 1,200 ml of air remains in the lungs after a maximum forced expiration. This residual air is known as the *residual volume (RV).* Once an infant takes its first breath, there is always residual volume in the lungs. The surfactant in alveoli keeps the alveoli from collapsing. The intrapleural pressure and the surface tension of the pleural fluid keep the lungs partially inflated.

Respiratory capacities can be calculated by summation of two or more respiratory volumes. The maximum amount of air that can be forcefully exchanged is known as the *vital capacity (VC),* and it is equal to the sum of the tidal volume, the inspiratory reserve volume, and the expiratory reserve volume–about 4,600 ml. The *total lung capacity (TLC)* is equal to the sum of the vital capacity and the residual volume–about 5,800 ml.

The respiratory volumes are summarized in table 14.2 and are graphically shown in figure 14.8.

Table 14.2 Summary of Respiratory Volumes and Capacities

Name	Definition	Average Volume
Tidal volume (TV)	Volume of air inhaled or exhaled during quiet breathing	500 ml
Inspiratory reserve volume (IRV)	Volume of air that can be forcefully inhaled after a tidal volume inhalation	3,000 ml
Expiratory reserve volume (ERV)	Volume of air that can be forcefully exhaled after a tidal volume expiration	1,100 ml
Vital capacity (VC)	Maximum volume of air that can be forcefully exhaled after a maximum forceful inhalation VC = TV + IRV + ERV	4,600 ml
Residual volume (RV)	Volume of air remaining in the lungs after a maximum forceful exhalation	1,200 ml
Total lung capacity (TLC)	Maximum volume of air that the lungs can contain TLC = VC + RV	5,800 ml

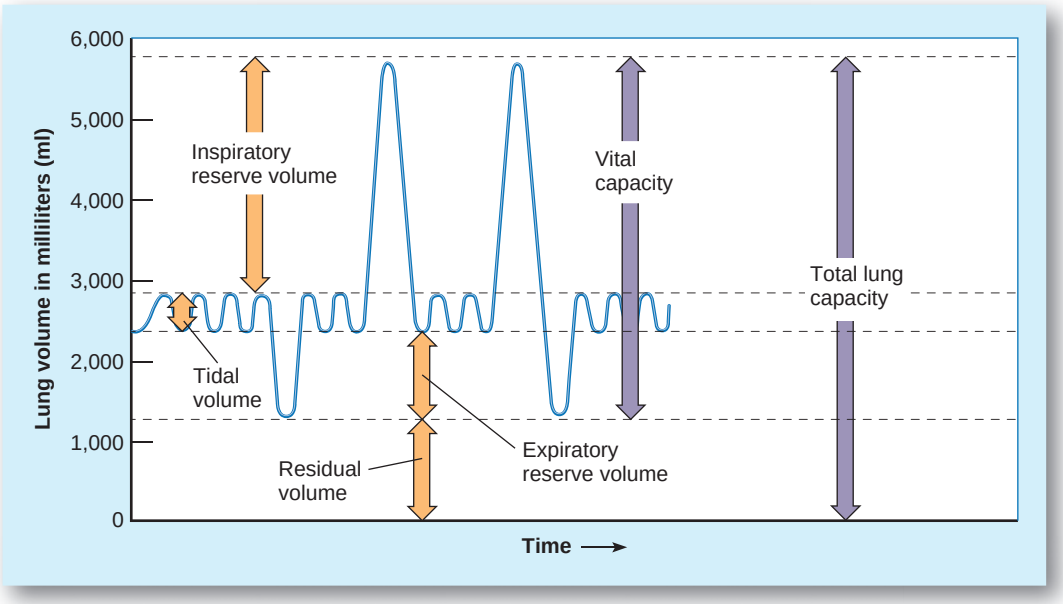


Figure 14.8 Respiratory volumes and capacities. The wavy blue line is a spirometer tracing that indicates the volumes of air exchanged as the respiratory movements are performed.

Check My Understanding

10. What distinguishes inspiratory reserve volume and expiratory reserve volume?
11. What distinguishes tidal volume and vital capacity?

Clinical Insight

The determination of the lung volumes is useful in identifying the two basic categories of pulmonary disease: obstructive and restrictive disorders. Each category has a characteristic pattern of abnormal test results. It is possible for a patient to exhibit both patterns simultaneously.

The *obstructive pattern* occurs where there is airway obstruction from any cause, such as in asthma, bronchitis, and emphysema. In this pattern, RV is increased and the RV/TLC ratio is increased.

The *restrictive pattern* occurs when there is a loss of lung tissue or when expansion of the lungs is limited. This pattern may result from lung tumors, weakness of respiratory muscles, pulmonary edema, or fibrosis of the lungs. In this pattern, the TLC is decreased, the RV/TLC ratio is normal or increased, and the VC is decreased.

14.4 Control of Breathing

Learning Objective

4. Describe the neural control of breathing.

The normal rhythmic cycle of breathing is involuntary—we don't have to think about it. It continues when we are sleeping or even unconscious. However, we can voluntarily override the normal pattern and take deep breaths and breathe faster or slower if we wish. The centers for involuntary control of breathing lie in the brainstem, where two groups of neurons in the medulla oblongata and one group of neurons in the pons regulate breathing. The voluntary override of breathing is controlled by the primary motor area of the cerebral cortex (figure 14.9).

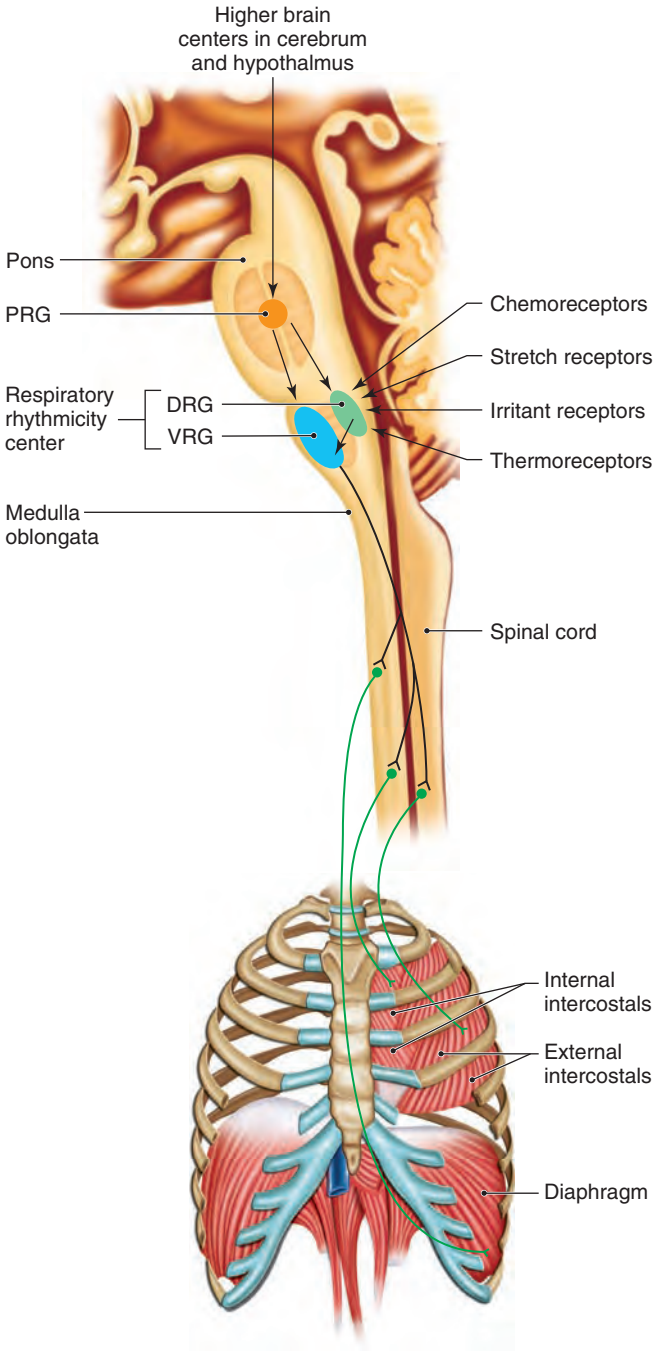


Figure 14.9 The control of breathing. Respiratory control centers are located in the medulla oblongata and the pons.

Respiratory Centers

Two bilateral groups of neurons compose the respiratory rhythmicity center in the medulla oblongata: the ventral respiratory group and the dorsal respiratory group. The *ventral respiratory group (VRG)* is responsible for the normal rhythmic cycle of breathing. It sends nerve impulses to the diaphragm and external intercostals causing them to contract, which results in inspiration. Inspiration continues as long as the VRG sends out the nerve impulses; but when nerve impulses cease, the muscles of inspiration relax and expiration occurs. This pattern of alternating neural activity and inactivity of the VRG

produces the cyclic nature of inspiration and expiration. In quiet breathing, inspiration lasts about two seconds, and expiration lasts about three seconds.

However, breathing can be deeper or shallower and faster or slower as the needs of the body change. The VRG receives input from other sources that result in such changes in the breathing cycle. The *dorsal respiratory group (DRG)* serves as a center for receiving and integrating input from sensory sources. It sends nerve impulses to the VRG to make necessary changes in the breathing pattern in accordance with the sensory input. Sensory input is considered in the next section.

A third respiratory center, the *pontine respiratory group (PRG)*, is located in the pons. It receives input from higher brain centers and sends nerve impulses to the DRG and VRG that modify the breathing pattern. The PRG contains two types of neurons: those that stimulate and those that inhibit the DRG and VRG. Thus, the PRG can either speed up or slow down the transition from inspiration to expiration, which alters the rate and depth of breathing. The PRG plays a key role in adapting breathing to speaking, singing, exercise, sleep, and emotional respiratory responses such as crying or laughing.

Check My Understanding

12. Where are the respiratory centers located?
13. How is breathing controlled by the nervous system?

14.5 Factors Influencing Breathing

Learning Objective

5. Describe the factors that influence breathing and how they produce their effect.

The respiratory areas of the medulla oblongata and pons are influenced by a number of factors that cause modifications in the rate and depth of breathing. Factors involved in involuntary control are detected by sensory receptors, which forward nerve impulses to the DRG. Higher brain centers involved in voluntary control send nerve impulses to the pontine respiratory group, which then transmits nerve impulses to the respiratory rhythmicity center (figure 14.9).

Chemicals

The most important chemical factors affecting respiration are the concentrations of CO_2, H^+, and O_2 in the blood or cerebrospinal fluid. Recall from chapters 9 and 12 that sensory receptors that are sensitive to these factors are called chemoreceptors. The chemoreceptors in the medulla oblongata are sensitive to increases in H^+ and CO_2 in the cerebrospinal fluid. The chemoreceptors in the carotid bodies and aortic bodies are sensitive to changes in CO_2, H^+, and O_2. The carotid bodies are located in the walls of external carotid arteries, while aortic bodies are located in the aortic arch. You can see that they are strategically located, especially to monitor blood going to the brain.

You may wonder why the concentration of H^+ is involved in respiratory control. The mechanism for transporting CO_2 in the blood releases H^+ as a by-product. Therefore, an increase in CO_2 concentration produces an increase in the H^+ concentration.

If the concentrations of CO_2 and H^+ in the blood or CSF increase, the DRG relays the information so that the VRG is stimulated to increase the rate and depth of breathing, which increases the rate of CO_2 and H^+ removal and returns their concentrations to normal resting levels. Once homeostasis is restored, the rate and depth of breathing also return to normal quiet levels.

If the CO_2 and H^+ concentrations in the blood or cerebrospinal fluid are abnormally low, breathing is slow and shallow until their concentrations increase to normal levels.

As mentioned previously, only the chemoreceptors in the carotid and aortic bodies are sensitive to changes in blood O_2 levels, specifically to a decline in blood O_2 concentration. Usually, a drop in O_2 concentration is not a strong stimulus for increasing the rate and depth of breathing, and its main effect seems to be to increase the sensitivity of chemoreceptors to changes in the CO_2 concentration.

Inflation Reflex

Baroreceptors (stretch receptors) in the bronchi, bronchioles, and visceral pleurae are sensitive to inflation of the lungs. During inspiration, nerve impulses from the stretch receptors are sent to the DRG via the vagus nerves (CN X), where they inhibit the formation of nerve impulses causing inspiration. This promotes expiration and prevents excessively deep inspirations that may damage the lungs.

Irritant Reflexes

The respiratory tract contains irritant receptors that are sensitive to various chemical and physical irritants, such as smoke, dust, and excess amounts of mucus. When stimulated by irritants, these receptors send sensory nerve impulses to the DRG via the vagus nerves. The DRG then alters the function of the VRG, which triggers a reflex contraction of the respiratory muscles that leads to a sneeze or a cough in order to expel the irritants from the respiratory tract.

Higher Brain Centers

Nerve impulses from higher brain centers also alter the rhythmic cycle of breathing. These nerve impulses may be voluntarily generated in the cerebrum, as when a person chooses to alter the normal pattern of quiet breathing. However, these voluntary controls are limited. For example, if a little child tries to "punish" his mother by holding his breath, the nerve impulses from higher brain centers are ignored and involuntary breathing resumes once CO_2 level in his blood increases to a critical point.

Involuntary nerve impulses may be formed by higher brain centers in the cerebral cortex and the hypothalamus during emotional experiences, such as anxiety, fear, and excitement, which activate the autonomic nervous system. At such times, the breathing rate is increased. Similarly, a sudden emotional experience, or a sharp pain tends to momentarily stop breathing, a condition called *apnea* (ap′-nē-ah).

Body Temperature

An increase in body temperature, such as occurs during strenuous exercise or a fever, increases the breathing rate. Conversely, a decrease in body temperature decreases the breathing rate.

Check My Understanding

14. Which respiratory center receives input from higher brain centers?
15. What factors influence the control of breathing?

14.6 Gas Exchange

Learning Objective

6. Describe the mechanisms of gas exchange in the lungs and the body tissues.

Alveolar Gas Exchange

During alveolar gas exchange, respiratory gases are exchanged between the air in the alveoli and the blood in the capillaries that surround them. Oxygen and carbon dioxide must diffuse through the **respiratory membrane,** which is composed of the squamous cells forming an alveolar wall and the squamous cells forming a capillary wall (see figure 14.5*c*).

Alveolar air has a higher concentration of oxygen and a lower concentration of carbon dioxide than does the capillary blood. Because molecules tend to move from an area of higher concentration to an area of lower concentration, oxygen diffuses from the alveolar air into the blood and carbon dioxide diffuses from the blood into the alveolar air.

Blood entering a capillary network of an alveolus is oxygen poor and carbon dioxide rich. Following the gas exchange, blood leaving the capillary is oxygen rich and carbon dioxide poor (figure 14.10).

Systemic Gas Exchange

After blood has been oxygenated, it returns to the heart and is pumped throughout the body to supply the tissue cells through systemic gas exchange. Blood in the systemic capillaries supplying body tissues contains a

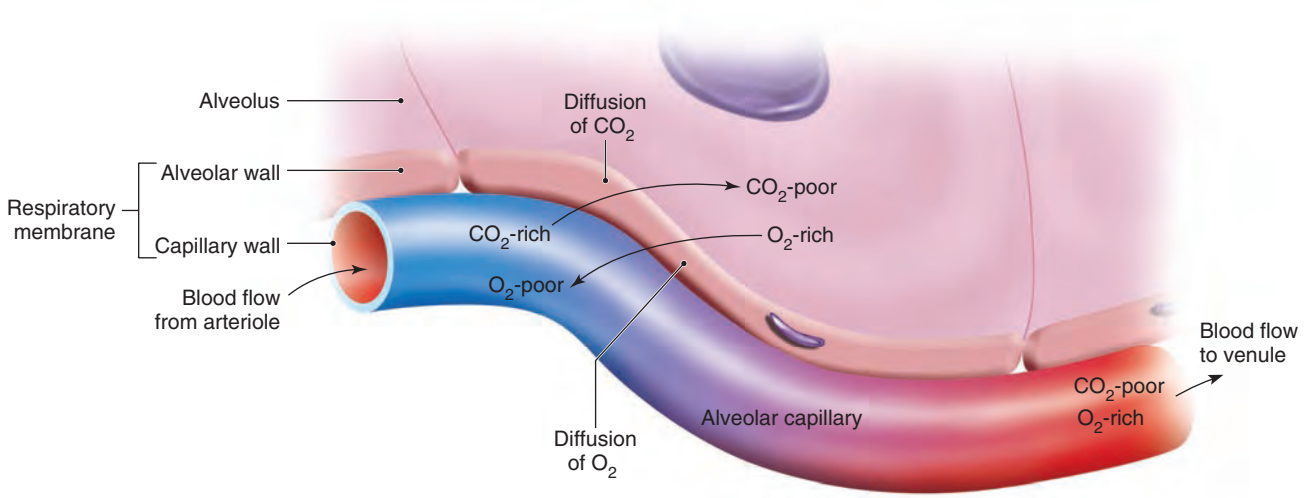


Figure 14.10 Exchange of oxygen and carbon dioxide between air in an alveolus and blood in an alveolar capillary occurs by diffusion.

higher concentration of oxygen and a lower concentration of carbon dioxide than the tissue cells. Therefore, oxygen diffuses from the blood into the interstitial fluid before entering the tissue cells and carbon dioxide diffuses from the tissue cells into the interstitial fluid before entering the blood. In this way, cells are supplied with oxygen for their metabolic activities, and carbon dioxide, which is produced by cellular metabolism, is removed.

Blood entering a systemic capillary network at the tissue level is oxygen rich and carbon dioxide poor. Following gas exchange, blood leaving the systemic capillary is oxygen poor and carbon dioxide rich.

Check My Understanding

16. What structure must oxygen and carbon dioxide diffuse through during alveolar gas exchange?
17. What is the difference between the alveolar capillary blood and the systemic capillary blood?

14.7 Transport of Respiratory Gases

Learning Objective

7. Describe how oxygen and carbon dioxide are transported by the blood.

The RBCs play a major role in the transport of both oxygen and carbon dioxide.

Oxygen Transport

In the lungs, oxygen diffuses from the air in alveoli into the blood of surrounding capillaries. Most of the oxygen enters RBCs and combines with the heme portions of hemoglobin (Hb) to form **oxyhemoglobin (HbO_2).** About 98.5% of the oxygen is transported as oxyhemoglobin. The remaining 1.5% is dissolved in the plasma (figure 14.11).

In body tissues, oxyhemoglobin releases oxygen and it diffuses from capillary blood into the interstitial fluid before entering the tissue cells. Actually, only about 25% of the oxygen is released in healthy individuals at rest, so oxyhemoglobin is present even in deoxygenated blood.

The reason that hemoglobin is such an effective carrier of oxygen is that the chemical bond between oxygen and hemoglobin is relatively unstable. When the surrounding oxygen concentration is high, as in the lungs, hemoglobin combines readily with oxygen; but when the surrounding oxygen concentration is low, as in body tissues, hemoglobin releases oxygen.

Carbon Dioxide Transport

The transport of carbon dioxide is more complex. Carbon dioxide diffuses from body cells into the interstitial fluid before entering the capillary blood. After carbon dioxide enters the blood, it is transported in one of the three ways (figure 14.11):

1. About 7% is dissolved in the plasma.
2. About 23% enters RBCs and combines with hemoglobin to form **carbaminohemoglobin ($HbCO_2$).** Carbon dioxide combines with the globin (protein) portion of hemoglobin, so carbon dioxide and oxygen have different binding sites on hemoglobin. Therefore, hemoglobin can transport oxygen and carbon dioxide at the same time.
3. The remaining 70% of the carbon dioxide also enters RBCs, but it quickly combines with water to form **carbonic acid (H_2CO_3).** This reaction is catalyzed by the enzyme **carbonic anhydrase.** Carbonic acid rapidly breaks down (dissociates) into hydrogen ions (H^+) and **bicarbonate ions (HCO_3^-).** Carbon dioxide is now part of the bicarbonate ions, which then diffuse out of the RBCs and are transported to the lungs in plasma.

When the blood returns to the lungs, all of these reactions run in reverse, releasing carbon dioxide, which diffuses into the alveoli.

Clinical Insight

Carbon monoxide (CO) is an odorless, colorless gas that is produced by burning carbon fuels. It competes with oxygen for the same binding sites on hemoglobin molecules, and it combines with hemoglobin about 200 times more readily than oxygen. Further, CO binds so tightly with hemoglobin that it is hard to remove. Therefore, even low concentrations of CO can displace oxygen from hemoglobin molecules and deprive tissues of needed oxygen. CO poisoning is the leading cause of death from fires. It is especially treacherous because it kills quietly without attracting attention. Treatment includes the administration of 100% oxygen to flush out the CO.

Check My Understanding

18. How does gas exchange occur in the lungs and in systemic tissues?
19. How are oxygen and carbon dioxide transported by the blood?

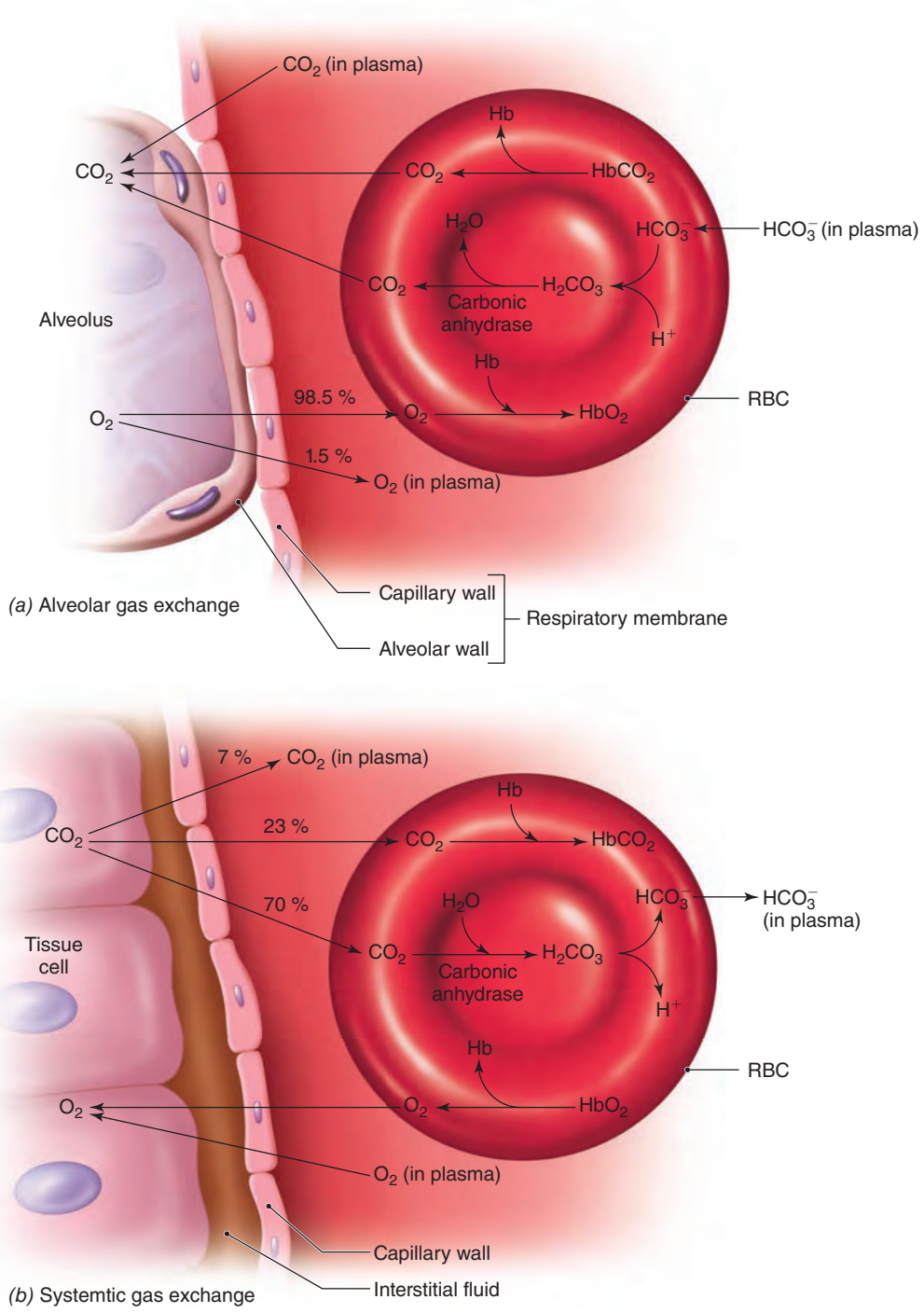


Figure 14.11 Exchange and transport of oxygen and carbon dioxide.

14.8 Disorders of the Respiratory System

Learning Objective

8. Describe the major disorders of respiratory system.

Inflammatory Disorders

Chronic obstructive pulmonary disease (COPD) is a group of disorders in which there is a long-term obstruction that reduces airflow to and from the lungs. The two most important COPDs are chronic bronchitis and emphysema.

Bronchitis is inflammation of the bronchi, and it is characterized by excessive mucus production that partially obstructs air flow. Acute bronchitis is usually caused by viral or bacterial infections. Chronic bronchitis occurs in chronic asthmatics, and it is common in smokers due to persistent exposure to irritants in tobacco smoke.

Emphysema (em-fi-sē′-mah) results from long-term exposure to airborne irritants, especially tobacco smoke. It is characterized by a rupture of the alveoli, forming larger spaces in the lungs, and excess mucus production, which plugs terminal bronchioles, trapping air in the alveoli. These changes reduce the respiratory surface area and impairs gas exchange.

Exhaling requires voluntary effort by the patient. The disease is uncommon except among long-term smokers, and people with long-term exposure to second hand smoke. It usually can be prevented and progressive deterioration can be stopped by removing the airborne irritant—usually tobacco smoke. Otherwise, there is no cure.

Asthma (az′-mah) is another COPD but differs in that reduction in airflow is usually intermittent rather than constant. It is characterized by wheezing upon exhilation and **dyspnea** (labored breathing) that result from bronchoconstriction. It is often caused by an allergic reaction to airborne substances but also may result from hypersensitivity to bacteria or viruses infecting the bronchial tree.

The **common cold** is an infection of the upper respiratory tract. It may be caused by a number of viruses, and often involves rhinitis, laryngitis, and sinusitis. Excessive mucus production, sneezing, and congestion are common symptoms.

Rhinitis (rī-nī′-tis), **laryngitis,** and **sinusitis** are the inflammation of the mucosae lining the nasal cavity, the larynx, and the sinuses, respectively. They are characterized by an increased mucus secretion. Causes may be viral or bacterial infections or airborne allergens.

Influenza, or flu, is an infectious disease that may involve both the upper and the lower respiratory tracts. It is caused by one of several viruses. Symptoms are fever, chills, headache, and muscular aches, followed by cold-like symptoms. In comparison to the common cold, the effects of influenza are much more severe and may lead to the development of pneumonia.

Pneumonia (nū-mōn′-yah) is an acute inflammation of the alveoli that may be caused by viral or bacterial infections. The alveoli become filled with fluid, pathogens, and white blood cells, which reduce space for air exchange. Blood oxygen levels may be greatly reduced. Pneumonia is one of the common causes of death among older people.

Pleurisy (pler′-i-sē) is inflammation of the pleurae. It often results in a decrease in secretion of pleural fluid, which causes sharp pains with each breath. Pleurisy can also cause the opposite effect: an increase in pleural fluid secretion. This type exerts pressure on the lungs and impairs expansion of the lungs.

Tuberculosis (tū-ber″-kū-lō′-sis) is an inflammation caused by the bacterium *Mycobacterium tuberculosis,* which is transmitted by inhalation. When it infects the lungs, the destroyed lung tissue is replaced by dense irregular connective tissue that retards gas exchange and reduces lung elasticity. Fortunately, modern drugs are effective in treating this disease.

Noninflammatory Disorders

Lung cancer is the second most common cancer and the leading cause of death from cancer in American males and females. It usually develops from long-term exposure to irritants, and the most common irritant producing this malignancy is tobacco smoke. The link between lung cancer and cigarette smoking has been firmly established. Lung cancer metastasizes rapidly and is not usually detected until it has spread to other parts of the body. Treatment includes surgical removal of the diseased lung, if detected prior to metastasis, and chemotherapy. More than 90% of lung cancers occur in smokers, so the most effective prevention is the elimination of cigarette smoking.

Pulmonary edema is the accumulation of fluid in the lungs. It results from excessive fluid passing from alveolar capillaries into the alveoli, which may be due to congestive heart failure. Symptoms include labored breathing and a feeling of suffocation. Treatment includes administration of oxygen, diuretics, drugs that dilate the bronchioles, suctioning air passageways, and mechanical ventilation.

Pulmonary embolism refers to a blood clot or gas bubble that blocks a small artery in the lung and prevents blood from reaching a portion of a lung. Gas exchange cannot occur in the affected parts of the lung. A massive embolism affecting a large portion of a lung may cause cardiac arrest.

Infant respiratory distress syndrome (IRDS), or hyaline membrane disease, is a disease of newborn infants, especially premature infants. It results from an insufficient production of surfactant in the alveoli, leading to alveolar collapse.

At birth, the respiratory system of an infant goes through a transition from a nonfunctional, fluid-filled system to a functional, air-filled system. Normally, an infant's first breath is the most difficult because it must open the collapsed alveoli. Succeeding breaths are easier because surfactant keeps the alveoli open after expiration. Without adequate surfactant, alveoli tend to collapse at each expiration and the infant must expend a great amount of energy to force them open at each inspiration.

Chapter Summary

14.1 Structures of the Respiratory System

- The major structures of the respiratory system are the nose, pharynx, larynx, trachea, bronchi, and lungs.
- The external portion of the nose is supported by bone and nasal cartilage, whereas the nasal cavity is surrounded by skull bones. The nasal conchae increase the surface area of the ciliated mucosa that lines the nasal cavity.
- Air enters and leaves the nasal cavity via the nostrils. Inhaled air is filtered, warmed, and moistened by the mucosa of the nasal cavity.
- The pharynx is a short passageway for both air moving between the nasal cavity and the larynx and food passing from the mouth to the esophagus. The pharyngeal, lingual, and palatine tonsils are clumps of lymphoid tissue associated with the pharynx.
- The larynx is a cartilaginous box that conducts air between the pharynx and the trachea, and it houses the vocal folds. During swallowing, the epiglottis prevents food from entering the larynx and directs it into the esophagus.
- The trachea extends from the larynx into the thoracic cavity, where it branches to form the main bronchi, which enter the lungs.
- The bronchial tree consists of main, lobar, segmental, and smaller bronchi. They are supported by cartilaginous rings and are lined with ciliated mucosae. Bronchioles are composed of smooth muscle lined with non-ciliated mucosae. Bronchi and bronchioles carry air into and out of the alveoli. They filter, warm, and moisten the inhaled air.
- Lungs fill most of the thoracic cavity. They consist of air passageways of the bronchial tree and bronchioles, alveoli, blood and lymphatic vessels, nerves, and connective tissues. Gas exchange occurs between air in the alveoli and the blood in the alveolar capillaries.
- Surfactant in the alveoli prevents the collapse of the alveoli.
- The visceral pleurae cover the external surfaces of the lungs, and the parietal pleurae line the internal wall of the thoracic cage. The pleural cavity is the potential space between pleurae and is filled with pleural fluid.

14.2 Breathing

- Breathing involves inspiration and expiration. Air moves into and out of the lungs along a pressure gradient.
- Quiet inspiration results from contraction of the diaphragm and external intercostals, which increases the volume and decreases the pressure within the thoracic cavity and lungs. The higher atmospheric pressure causes air to flow into the lungs until the atmospheric and intra-alveolar pressures are equalized. A forceful inspiration also involves the contraction of neck and chest muscles.
- Quiet expiration results from relaxation of these muscles, which decreases the volume and increases the pressure within the thoracic cavity and lungs. The higher intra-alveolar pressure causes air to flow out of the lungs until the intra-alveolar and atmospheric pressures are equalized. A forceful expiration involves the contraction of internal intercostals and abdominal muscles.

14.3 Respiratory Volumes and Capacities

- Respiratory air volumes vary with size, sex, age, and physical condition. Variations from the norm usually indicate a pulmonary disorder.
- The average values for respiratory volumes and capacities are tidal volume–500 ml; inspiratory reserve volume–3,000 ml; expiratory reserve volume–1,100 ml; vital capacity–4,600 ml; residual volume–1,200 ml; and total lung capacity–5,800 ml.

14.4 Control of Breathing

- Breathing is controlled by the respiratory centers located in the pons and medulla oblongata.
- The two groups of neurons in the medulla oblongata are the ventral respiratory group (VRG) and the dorsal respiratory group (DRG).
- The VRG controls the normal rhythmic breathing cycle. The DRG integrates sensory input and stimulates the VRG to modify breathing to be faster or slower and deeper or shallower.
- The pontine respiratory group (PRG) in the pons relays nerve impulses, especially from higher brain centers, to the DRG and VRG to modify the breathing cycle.

14.5 Factors Influencing Breathing

- Chemoreceptors in the medulla oblongata are sensitive to changes in concentrations of carbon dioxide and hydrogen ions in the cerebrospinal fluid. An increase in their concentrations is the primary stimulus for inspiration. The breathing rate and depth vary directly with changes in blood carbon dioxide and hydrogen ion concentrations.
- Chemoreceptors in the carotid and aortic bodies are sensitive to the concentration of oxygen, carbon dioxide, and hydrogen ions in the blood. Blood oxygen concentration must be very low to produce a direct effect on breathing.
- The stretching of the bronchi, bronchioles, and visceral pleurae during inspiration triggers the inflation reflex, which inhibits excessive inspiration and promotes expiration.
- Higher brain centers can influence the respiratory centers either voluntarily or involuntarily. Sudden pain produces momentary apnea. Anxiety, fear, and excitement increase the breathing rate.
- Stimulation of irritant receptors by irritants triggers irritant reflexes.
- The breathing rate varies directly with changes in body temperature.

14.6 Gas Exchange

- Gas exchange between air in the alveoli and the blood in alveolar capillaries occurs by diffusion, and it is called alveolar gas exchange.

- Oxygen diffuses from air in the alveoli into the blood; carbon dioxide diffuses from the blood into air in the alveoli.
- Gas exchange between tissue cells and blood in systemic capillaries occurs by diffusion, and it is called systemic gas exchange.
- Oxygen diffuses from the blood into the interstitial fluid before entering the tissue cells; carbon dioxide diffuses from the tissue cells into the interstitial fluid before entering the blood.

14.7 Transport of Respiratory Gases

- In the lungs, oxygen combines with hemoglobin to form oxyhemoglobin. In body tissues, oxyhemoglobin releases oxygen to tissue cells. About 98.5% of the oxygen is carried as oxyhemoglobin; only about 1.5% is carried dissolved in plasma.
- Carbon dioxide is mostly carried in bicarbonate ions in plasma. When carbon dioxide diffuses from tissue cells into the blood, 70% of it enters the RBCs. Carbonic anhydrase in RBCs catalyzes the combination of carbon dioxide and water to form carbonic acid, which ionizes to form hydrogen and bicarbonate ions. In the lungs, the reaction reverses to release carbon dioxide into the alveoli.
- 23% of the carbon dioxide is carried as carbaminohemoglobin, and 7% of the carbon dioxide is carried dissolved in the plasma.

14.8 Disorders of the Respiratory System

- Common inflammatory disorders include bronchitis, emphysema, asthma, common cold, rhinitis, laryngitis, sinusitis, influenza, pneumonia, tuberculosis, and pleurisy. Chronic bronchitis, emphysema, and asthma are COPDs.
- Common noninflammatory disorders include lung cancer, pulmonary edema, pulmonary embolism, and infant respiratory distress syndrome.

Self-Review

Answers are located in appendix B.

1. Inhaled air is moistened, _____, and warmed by the _____ lining the nasal cavity and the bronchi.
2. Vocal folds are located within the _____, and the space between relaxed vocal folds is the _____.
3. The walls of the trachea and bronchi are supported by _____, which are absent in _____ and alveolar ducts.
4. The lungs consist largely of blood vessels, air passageways, and tiny air sacs called _____ where gas exchange occurs.
5. The potential space between the visceral and parietal pleurae is the _____.
6. Alveoli do not collapse because _____ reduces the surface tension of water molecules within alveoli.
7. During inspiration, air moves into the lungs because _____ pressure is greater than _____ pressure.
8. The _____ volume, about _____ ml, is the amount of air inhaled or exhaled in quiet breathing.
9. The rhythmic cycle of breathing is controlled by the VRG in the _____, and it is influenced by the _____ in the medulla oblongata and the _____ in the pons.
10. The rate and depth of breathing increase when the blood levels of _____ and _____ increase.
11. In the lungs, _____ moves from alveoli into capillary blood and _____ moves from capillary blood into alveoli.
12. In the blood, oxygen is primarily carried as _____ and carbon dioxide is primarily carried as _____.

Critical Thinking

1. Discuss the drawbacks of breathing through the mouth rather than through the nostrils.
2. Discuss the detrimental effects of smoking on the structure and function of the respiratory system.
3. If an athlete had a transfusion of RBCs a few hours before an athletic event, would it provide a physiological advantage? Explain.
4. Explain how strenuous exercise increases the rate of breathing.
5. Explain the importance of carbonic anhydrase in the transport of carbon dioxide.

10
CHAPTER

Renal Physiology

Because of his family history of hypertension (or high blood pressure), Peter lives an "anti-hypertensive" lifestyle to reduce his chances of developing the disorder. He engages in regular cardiovascular exercise to maintain a healthy body weight, in addition to avoiding canned and processed foods to reduce his dietary sodium intake. He even meditates regularly to help manage the stress effects of everyday life. However, Peter is surprised at his annual physical when he is diagnosed with hypertension at the age of 39. After discussing all of the available treatment options, Peter opts to try the diuretic Lasix in conjunction with his regular exercise regimen and diet. However, he does not understand why changing his kidney function will help to manage his blood pressure. The doctor explains that Lasix causes the kidneys to increase urine output, which will result in a decrease in Peter's overall blood volume. By decreasing his blood volume, his blood pressure will also decrease. If decreasing his blood pressure will decrease his risk of stroke or heart attack, Peter decides he is more than willing to use the restroom more often during the day.

CHAPTER OUTLINE

SELECTED KEY TERMS

Acidosis Condition of arterial blood below pH 7.35.
Alkalosis Condition of arterial blood above pH 7.45.
Glomerular filtrate The fluid that enters the glomerular capsule during glomerular filtration.
Glomerular filtration The forcing of water and small solutes from the blood plasma in a glomerulus into a glomerular capsule.
Glomerulus (glomus = ball) The cluster of capillaries enveloped by the glomerular capsule.
Juxtaglomerular complex (juxta = next to) Specialized cells of the afferent glomerular arteriole and ascending limb of the nephron loop that are involved in controlling glomerular blood pressure.
Micturition (micture = to urinate) Urination.
Nephron (nephros = kidney) The structural and functional unit of the kidneys.
Peritubular capillaries (peri = around) Capillaries surrounding the cortical portion of a renal tubule.
Renal corpuscle (ren = kidney) The portion of a nephron composed of a glomerulus and its enveloping glomerular capsule.
Renal tubule The portion of a nephron composed of a proximal convoluted tubule, a nephron loop, and a distal convoluted tubule.
Tubular fluid The fluid within the renal tubule.
Tubular reabsorption The movement of substances from the tubular fluid into the blood plasma.
Tubular secretion The movement of substances from the blood plasma into the tubular fluid.
Vasa recta (rectus = straight) Straight vessels surrounding medullary portion of the nephron loops.
Water conservation Process of water reabsorption in the collecting duct, which prevents dehydration.

THE *URINARY SYSTEM* CONSISTS of the kidneys, ureters, urinary bladder, and urethra. The paired *kidneys* maintain the composition and volume of body fluids by removing wastes and excess substances in the formation of **urine,** the fluid waste produced by the kidneys. *Ureters* are slender tubes that carry urine from the kidneys to the *urinary bladder* for temporary storage. Urine is carried from the urinary bladder and is expelled from the body through the *urethra* (figure 16.1).

16.1 Functions of the Urinary System

Learning Objectives

1. Describe the general functions of the urinary system.
2. Explain how nitrogenous wastes are kept within normal limits in body fluids.

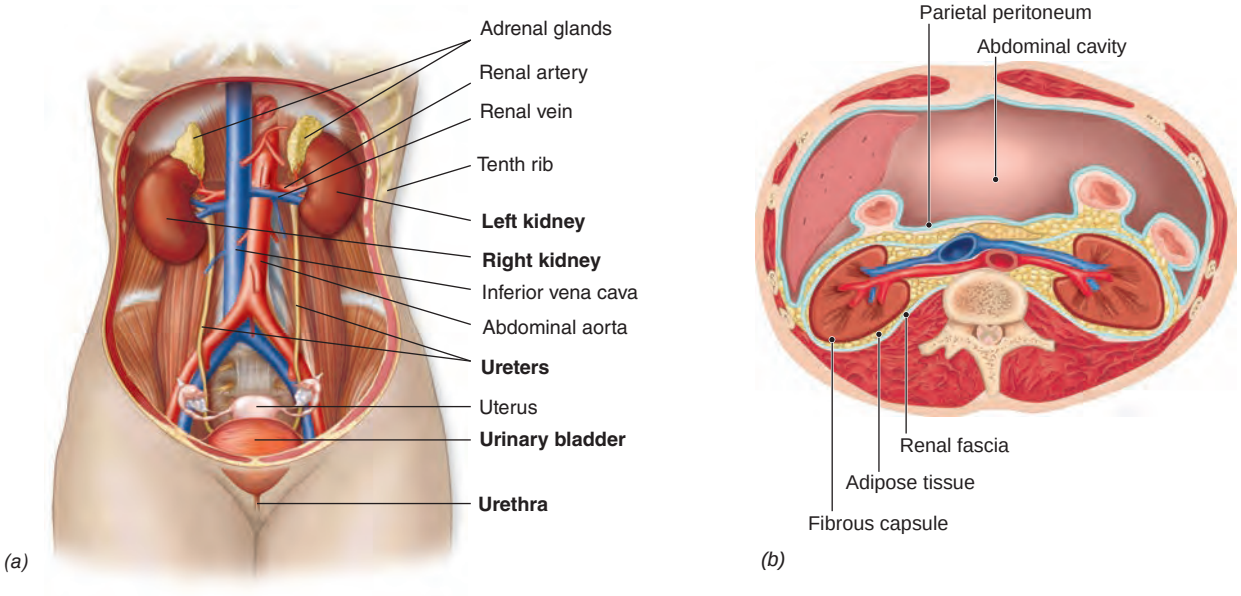


Figure 16.1 *(a)* The urinary system consists of two kidneys, two ureters, a urinary bladder, and a urethra. *(b)* Transverse section showing the retroperitoneal position of the kidneys and their surrounding support structures.

The normal metabolic activities of body cells produce a number of waste materials that tend to change the balance of water and dissolved substances in body fluids. The basic function of the urinary system is to maintain the volume and composition of body fluids within normal limits.

1. **Maintenance of body fluid composition.** One major function of the kidneys is to keep the volume and composition of blood plasma at homeostasis. This is accomplished by balancing of the concentration of water and electrolytes, in addition to blood pH, through the formation of urine.
2. **Maintenance of blood pressure.** Whenever the kidney senses a decrease in blood pressure, they secrete **renin.** Renin is an enzyme that triggers the **renin-angiotensin mechanism,** which increases blood pressure.
3. **Secretion of erythropoietin.** When the blood oxygen level falls below normal, the kidneys release more erythropoietin, which stimulates RBC formation by red bone marrow. The increase in RBC number helps increase the blood oxygen level.
4. **Conversion of vitamin D.** In response to parathyroid hormone (PTH), the kidney converts inactive vitamin D to its active form. Active vitamin D is important in maintaining blood Ca^{2+} levels.
5. **Excretion of nitrogenous wastes.** The kidneys do not remove all nitrogenous wastes but keep their concentrations in the blood within tolerable limits. The primary nitrogenous wastes produced by cellular metabolism are urea, uric acid, and creatinine (see table 16.1).
   - **Urea** is a waste product of amino acid metabolism. In order for amino acids to be used as an energy source in cellular respiration or converted into glucose or fat, the liver removes the amine ($-NH_2$) groups from them. The amine groups react to form ammonia, which is converted to the less toxic urea by the liver.
   - **Uric acid** is a waste product of nucleic acid metabolism. An abnormally elevated concentration of uric acid in the blood and the deposition of uric acid crystals in joints are characteristic of a hereditary disorder called *gout*. Joints of the hands and feet are often the sites of uric acid deposition, which produces inflammation and severe pain.
   - **Creatinine** is a waste product of muscle metabolism and, specifically, the breakdown of creatine phosphate.

Check My Understanding

1. What organs compose the urinary system, and what are their functions?
2. What are the general functions of the urinary system?

16.2 Anatomy of the Kidneys

Learning Objectives

3. Describe the structure and blood supply of the kidney.
4. Describe the structure and functions of a nephron.

The *kidneys* are reddish brown, bean-shaped organs located bilateral to the vertebral column in the retroperitoneal space posterior to the abdominal cavity (figure 16.1*b*). They lie posterior to the parietal peritoneum, which covers their anterior surfaces. The kidneys are located between the levels of the twelfth thoracic vertebra and the third lumbar vertebra and are partially protected by the floating ribs. Each kidney is protected by three layers of connective tissue. A thin *fibrous capsule* tightly envelops each kidney, supporting the soft internal tissues. A thick layer of adipose tissue serves as a cushioning shock absorber, and a fibrous *renal fascia* attaches each kidney to the abdominal wall.

Table 16.1 Concentrations of Selected Chemicals in Blood, Glomerular Filtrate, and Urine*

Chemicals	Blood (g/l)	Glomerular Filtrate (g/l)	Urine (g/l)
Protein	44.4	0.0	0.0
Chloride (Cl^-)	3.5	3.5	6.3
Sodium (Na^+)	3.0	3.0	3.8
Bicarbonate (HCO_3^-)	1.7	1.7	0.4
Glucose	1.0	1.0	0.0
Urea	0.2	0.2	25.0
Potassium (K^+)	0.2	0.2	5.0
Uric acid	0.05	0.05	0.8
Creatinine	0.01	0.01	1.5

*Based on 180 liters of glomerular filtrate and 1.25 liters of urine produced in a 24-hour period.

Gross Anatomy

Each kidney is convex laterally and concave medially with a medial indentation called the *hilum*. Blood vessels, lymphatic vessels, nerves, and the ureter enter or exit at the hilum. An adult kidney is about 12 cm long, 7 cm wide, and 2.5 cm thick.

The internal macroscopic anatomy of a kidney is best observed in frontal section, as shown in figure 16.2*a*. Two functional regions of the kidney are evident: the renal cortex and the renal medulla. The **renal cortex** is the relatively thin, superficial layer. Deep to the renal cortex is the **renal medulla,** which contains the cone-shaped *renal pyramids*. The apex, or *renal papilla*, of each pyramid extends toward the renal pelvis, the most central structure of the kidney. Narrow portions of the renal cortex, the *renal columns*, extend into the renal medulla between the renal pyramids.

The work of the kidneys is performed by microscopic structures called **nephrons** (nef′-rons). Nephrons originate in the renal cortex, dip into the renal medulla, return to the renal cortex, and ultimately join a **collecting duct,** as shown in figure 16.2*b*. Nephrons produce urine, which flows into the collecting ducts of renal pyramids.

The renal papilla of each renal pyramid fits into a funnel-shaped **minor calyx** (kā′-lix), which receives urine from the collecting ducts. Two or three minor calyces (kā′-li-sēz) converge to form a **major calyx,** and two or three major calyces merge to form the funnel-like **renal pelvis.** The renal pelvis is contiguous with the ureter. Thus, the pathway of urine from nephrons to ureter is as follows: nephrons → collecting ducts → minor calyces → major calyces → renal pelvis → ureter. Urine is carried by the ureter to the urinary bladder by peristalsis.

Microscopic Anatomy

Each kidney contains about 1 million nephrons, the functional units of the kidneys. A nephron consists of two major parts: a renal corpuscle and a renal tubule. Figure 16.3 shows the structure of a nephron and its associated blood vessels.

Renal corpuscles are located in the renal cortex of the kidneys. Each renal corpuscle is composed of a **glomerulus** (glō-mer′-ū-lus, plural, *glomeruli*), a tuft of capillaries, which is enclosed in a double-walled **glomerular *(Bowman)* capsule.** The glomerular capsule is an expanded extension of a renal tubule.

A **renal tubule** leads away from the glomerular capsule and consists of three sequential segments. The first part of the renal tubule is the *proximal convoluted tubule* (PCT). It leads from the glomerular capsule to the *nephron loop*, the U-shaped second part of the tubule. The descending limb of the nephron loop descends into the renal medulla, and

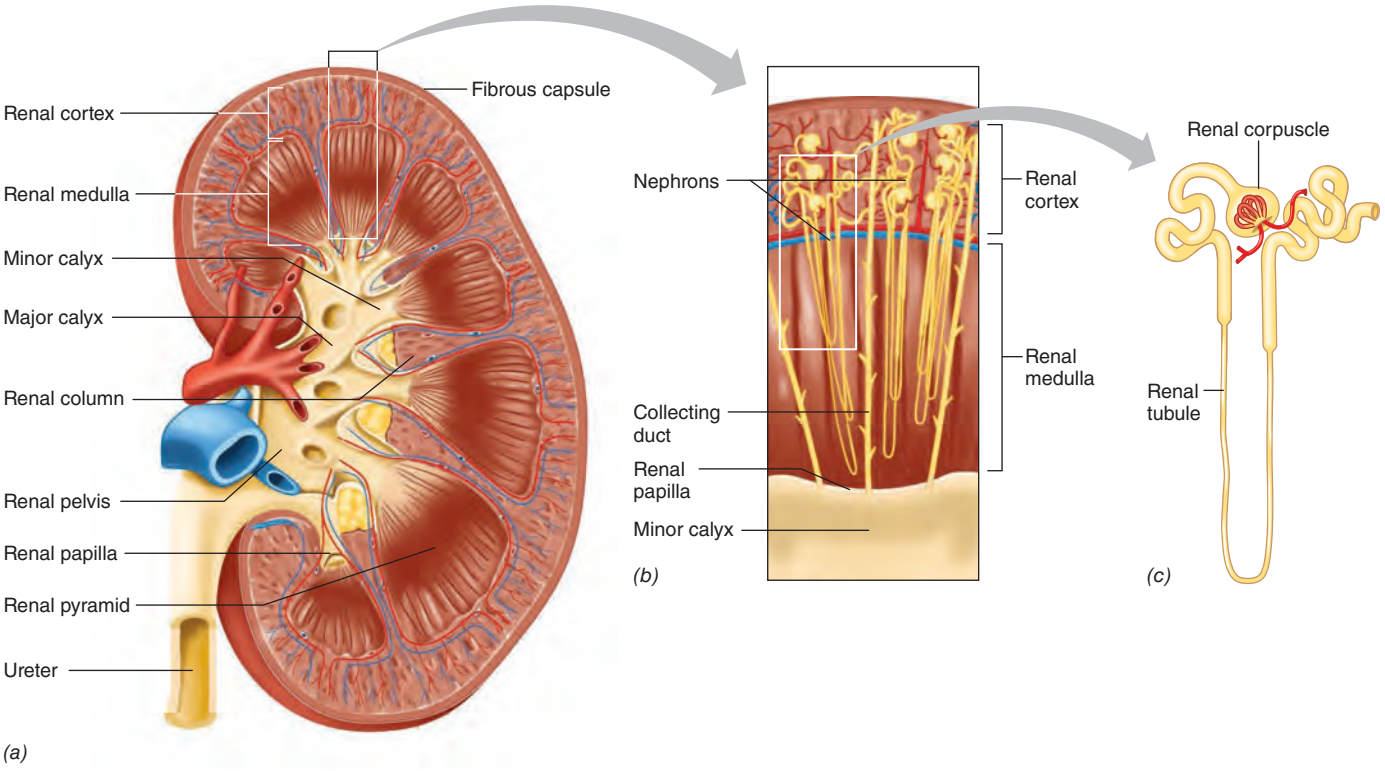


Figure 16.2 Internal Structure of the Kidney.
(a) Frontal section of a kidney. *(b)* A renal pyramid showing the orientation of nephrons and collecting ducts. *(c)* A single nephron.

the ascending limb of the nephron loop ascends back into the renal cortex. The ascending limb of the nephron loop is continuous with the *distal convoluted tubule* (DCT), the third segment of the renal tubule, which unites with a collecting duct. Several nephrons unite with a single collecting duct. Collecting ducts begin in the renal cortex and extend the length of a renal pyramid to its papilla, where the collecting ducts merge before emptying into a minor calyx.

Types of Nephrons

There are two types of nephrons in the kidney: about 80% are cortical nephrons, and about 20% are juxtamedullary nephrons. The glomerular capsules of *cortical nephrons* are located superficially in the renal cortex. The nephron loops of these nephrons are located almost entirely in the renal cortex of the kidney. Cortical nephrons are important in adjusting the composition of the urine. In contrast, the glomerular capsules of *juxtamedullary nephrons* are located deep in the renal cortex near the renal medulla. The nephron loops of these nephrons penetrate deep into the medulla. Juxtamedullary nephrons play an important role in regulating water content of the blood plasma.

Renal Blood Supply

The kidneys receive a large volume of blood–1,200 ml per minute, which is about one-fourth of the total cardiac output. Each kidney receives blood via a *renal artery,* which branches from the abdominal aorta. Within each kidney, the renal artery branches to form three or four *segmental arteries,* which branch further to form several *interlobar arteries* that run along the renal columns between the renal pyramids to the renal cortex. These arteries branch to form smaller and smaller arteries and finally form arterioles.

In the renal cortex, **afferent glomerular arterioles** branch from the smallest arteries, and each afferent glomerular arteriole carries blood to a glomerulus. Blood leaves a glomerulus in an **efferent glomerular arteriole.** Note that a glomerulus is a capillary ball between two arterioles. The efferent glomerular arteriole usually leads to **peritubular capillaries,** which surround the cortical portion of the renal tubule. Sometimes the efferent glomerular arteriole leads to the **vasa recta,** which are vessels surrounding the nephron loops and collecting ducts within the renal medulla. Blood from the peritubular capillaries and vasa recta enters a venule, progressively larger veins that merge to form *interlobar veins,* which finally join to form the renal vein. A *renal vein* carries blood from each kidney to the inferior vena cava (figures 16.3 and 16.4; see figure 16.1).

Juxtaglomerular Complex

The **juxtaglomerular** (juks-tah-glo-mer′-u-lar) **complex** of each nephron is located where the ascending limb of the

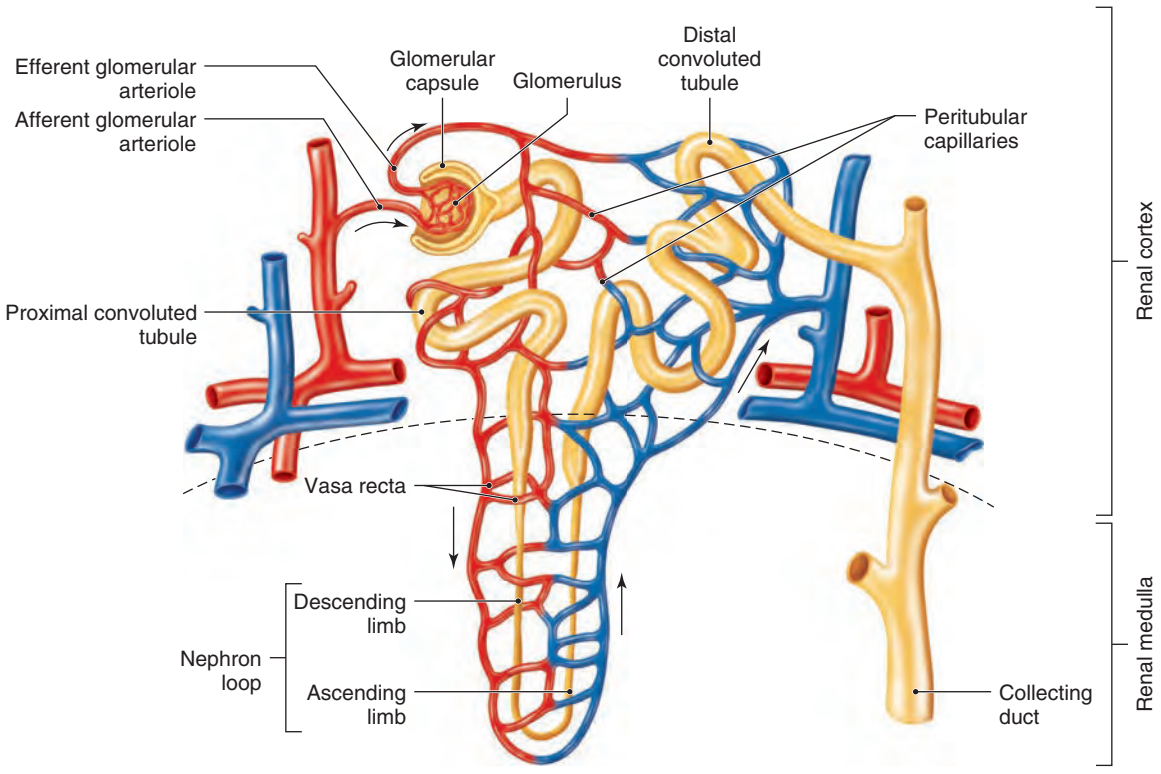


Figure 16.3 A nephron and its associated blood vessels. The nephron has been stretched out to show its parts more clearly. Arrows show the direction of blood flow.

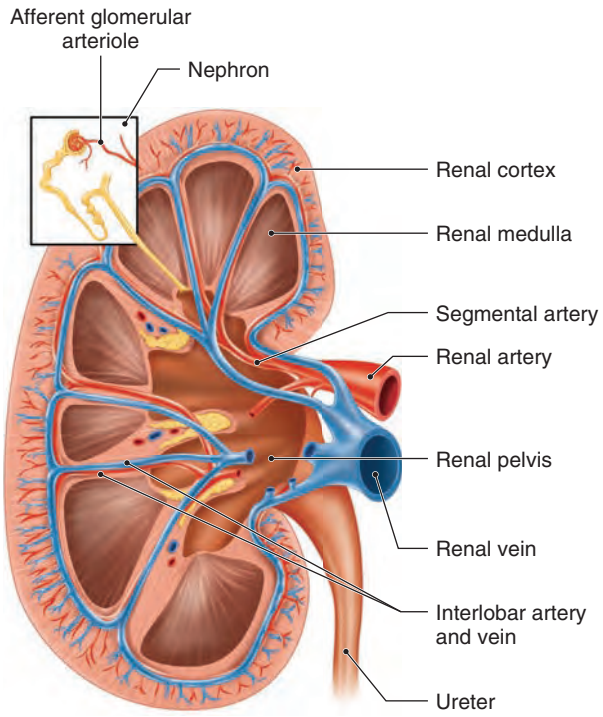


Figure 16.4 Main branches of the renal artery and renal vein.

nephron loop contacts the afferent and efferent glomerular arterioles near the glomerulus (figure 16.5). It consists of two groups of specialized cells: granular cells and the macula densa. *Granular cells,* or juxtaglomerular epithelioid cells, are large smooth muscle cells in the walls of the afferent and efferent glomerular arterioles near their attachment to the glomerulus. The *macula densa* consists of rather narrow, tightly packed cells composing the ascending limb where it contacts the afferent and efferent glomerular arterioles. The juxtaglomerular complex helps to regulate blood pressure, as you will see shortly.

Check My Understanding

3. What are the structural and functional differences between cortical and juxtamedullary nephrons?
4. How does blood flow to, through, and away from the nephron?

16.3 Urine Formation

Learning Objectives

5. Compare glomerular filtration, tubular reabsorption, and tubular secretion.
6. Explain how urine is formed.
7. Indicate the normal components of urine.

The formation of urine is a homeostatic mechanism that maintains the composition and volume of blood plasma within normal limits. In the production of urine, nephrons perform three basic functions: (1) They regulate the concentration of solutes, such as nutrients and ions, in blood plasma, and this also regulates blood pH. (2) They regulate the concentration of water in blood plasma, which in turn helps regulate blood pressure. (3) They remove metabolic wastes and excess substances from the blood plasma.

Four processes are crucial to the formation of urine: (1) **Glomerular filtration** moves water and solutes, except plasma proteins, from blood plasma into the glomerular capsule. The fluid that enters the glomerular capsule is called **glomerular filtrate.** Formed elements normally are not part of the glomerular filtrate. Once the glomerular filtrate passes from the glomerular capsule into the renal tubule it is renamed **tubular fluid.** (2) **Tubular reabsorption** removes useful substances from the tubular fluid and returns them into the blood plasma, and (3) **tubular secretion** moves additional wastes and excess substances from the blood plasma into the tubular fluid. (4) **Water conservation** removes water from the urine, returning it into the blood plasma (figure 16.6).

Glomerular Filtration

Urine formation starts with glomerular filtration, a process that forces some of the water and dissolved substances in blood plasma from the glomeruli into the glomerular capsules. Two major factors are responsible for glomerular filtration: (1) the increased permeability of glomerular capillary walls and (2) the elevated blood pressure within the glomeruli.

Glomerular capillaries are much more permeable to substances in the blood plasma than are other capillaries because their walls contain numerous pores, as shown in figure 16.5*c*. These pores allow water and most dissolved substances to easily pass through the capillary walls into the glomerular capsules. Unlike other capillaries, glomerular capillaries are enveloped by specialized cells called *podocytes,* which have numerous fingerlike cellular extensions that wrap around the capillaries. Podocytes help prevent plasma proteins, and formed elements from entering glomerular capsules.

The elevated glomerular blood pressure results because the diameter of the efferent glomerular arteriole is smaller than that of the afferent glomerular arteriole. Because blood can enter a glomerulus at a faster rate than it can leave it, the greater blood volume within the glomerulus creates an increase in blood pressure. The glomerular blood pressure provides the force for glomerular filtration.

The result of glomerular filtration is the production of glomerular filtrate that consists of the same substances that compose blood plasma, except for plasma proteins that are

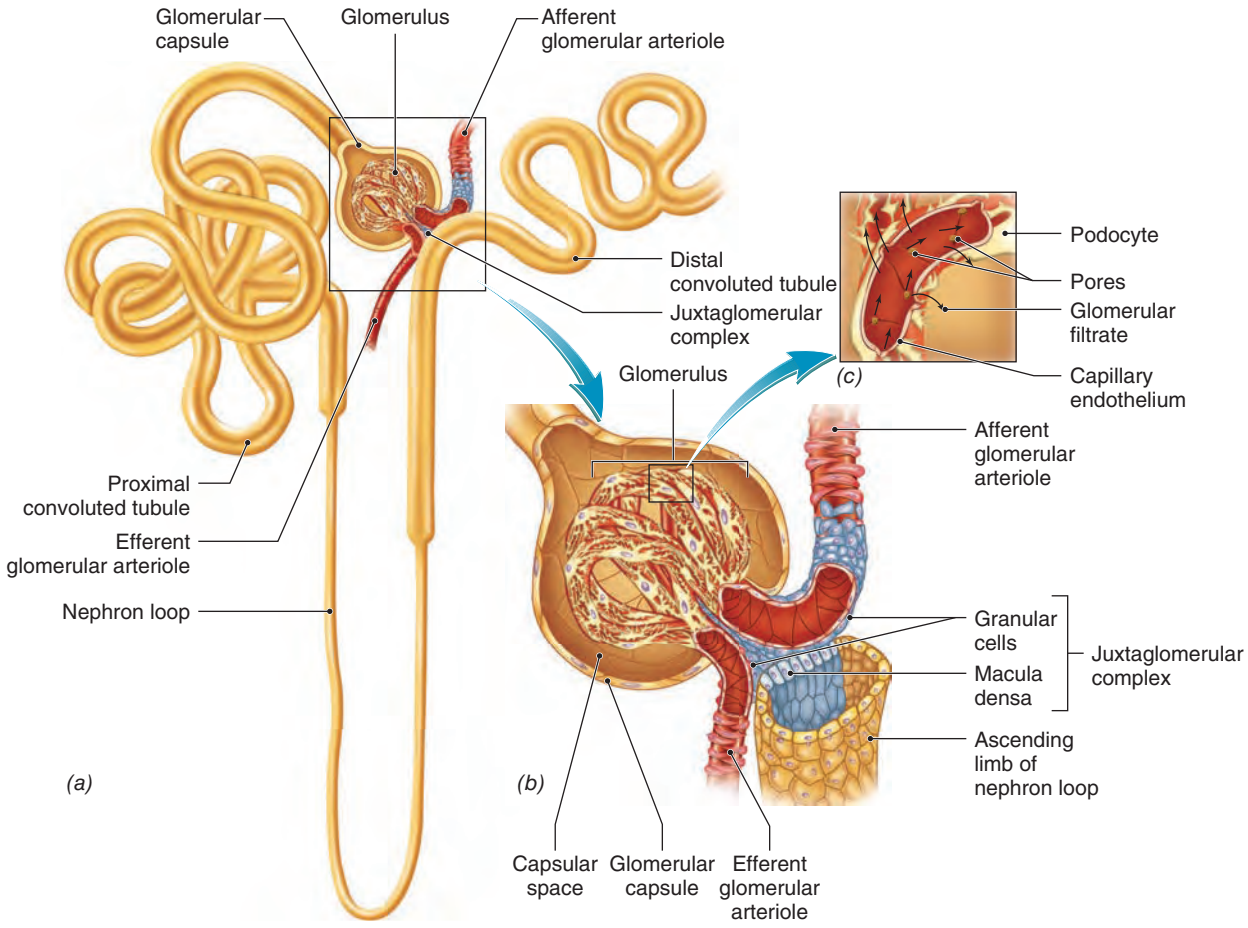


Figure 16.5 Juxtaglomerular Complex.
(*a*) The juxtaglomerular complex is located where the ascending limb of the nephron loop contacts the afferent and efferent glomerular arterioles near a glomerulus. (*b*) Enlargement showing the granular cells and macula densa, which compose the juxtaglomerular complex. (*c*) Magnification of the pores through which glomerular filtration occurs.

too large to pass through the pores of the glomerular capillaries. Because glomerular filtration is a nonselective process, the concentrations of these substances are the same in both blood plasma and glomerular filtrate (table 16.1).

Glomerular Filtration Rate

Glomerular filtration rate (GFR) is about 125 ml per minute, or 7.5 liters per hour. This means that the entire volume of blood is filtered every 40 minutes! In 24 hours, about 180 liters (nearly 45 gallons) of glomerular filtrate is produced. However, most of the glomerular filtrate is reabsorbed, as you will see shortly.

Maintenance of a relatively stable GFR is necessary for normal kidney function. The GFR varies directly with glomerular blood pressure, which, in turn, is primarily determined by systemic blood pressure. The GFR is regulated by three homeostatic processes: renal autoregulation, sympathetic control, and the renin–angiotensin mechanism. These processes operate primarily by controlling the diameter of afferent glomerular arterioles to keep the GFR within normal limits.

Renal autoregulation is the mechanism that keeps the GFR within normal limits, without extrinsic neural or hormonal control, in response to moderate variations in systemic blood pressure. One way this occurs is by the response of smooth muscle in the afferent glomerular arteriole wall to blood pressure changes. If the afferent glomerular arteriole is stretched by increased blood pressure, it contracts; the smaller diameter of the afferent glomerular arteriole means less blood volume enters the glomerulus, thus decreasing blood pressure within the glomerulus. A decline in blood pressure causes the arteriole to dilate, which keeps the GFR stable.

Another autoregulatory mechanism involves the juxtaglomerular complex. The juxtaglomerular complex monitors the GFR by using the macula densa to sense changes in the flow rate and chemical composition in the tubular fluid of the ascending limb. If the GFR increases, the

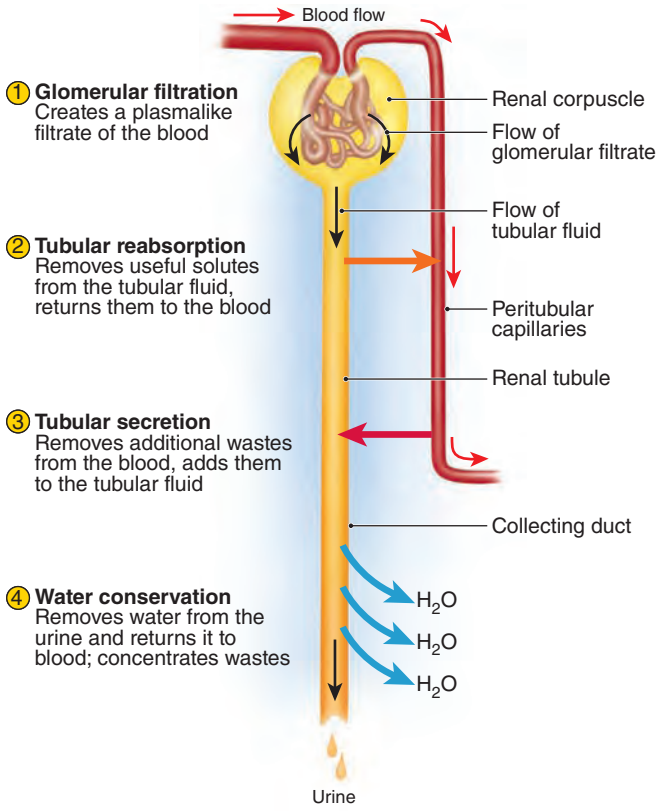


Figure 16.6 The major steps of urine formation.

granular cells constrict the afferent glomerular arteriole, keeping the GFR normal. If the GFR declines, the afferent glomerular arteriole relaxes to maintain a normal GFR.

Sympathetic control is a function of the sympathetic division of the autonomic nervous system, which overrides renal autoregulation in times of large systemic blood pressure shifts or during the "fight or flight" response. If a drop in systemic blood pressure is detected, afferent glomerular arterioles are constricted, which decreases glomerular pressure and GFR. This decreases urine formation, which conserves water to maintain normal blood pressure and volume. If an increase in blood pressure is detected, the afferent glomerular arteriole dilates as a result of the sympathetic control being removed, which increases glomerular pressure and the GFR. This results in an increase in urine production and water excretion to maintain normal blood pressure and volume.

The *renin–angiotensin mechanism* is triggered when the juxtaglomerular complex detects a reduced GFR and releases the enzyme *renin.* Renin is secreted in response to (1) sympathetic stimulation; (2) a drop in blood pressure in the afferent glomerular arteriole; and (3) detection of a reduction of Na^+, K^+, and Cl^- levels in the tubular fluid in the ascending limb of the nephron loop by the macula densa (see figure 16.5). Renin converts a plasma protein (angiotensinogen), which is formed by the liver, into angiotensin I. Angiotension I is rapidly converted into angiotensin II by the *angiotensin-converting enzyme (ACE)* released from endothelial cells of capillaries in the lungs and other organs. Angiotensin II constricts the efferent glomerular arterioles to maintain blood pressure in glomeruli, which maintains an adequate GFR in spite of a decline in blood pressure. It also acts to restore blood volume and blood pressure by (1) constricting systemic arterioles; (2) stimulating aldosterone secretion by the adrenal cortex, which promotes the reabsorption of Na^+, which in turn promotes the reabsorption of water by osmosis; (3) stimulating secretion of antidiuretic hormone (ADH) by the posterior lobe of the pituitary gland, which promotes water reabsorption; and (4) stimulating thirst, which promotes water intake (figure 16.7).

Atrial natriuretic peptide (ANP) is secreted by atria of the heart when they are stretched by an excessive blood volume. ANP promotes water excretion by increasing GFR, and inhibiting Na^+ reabsorption in the DCT, which results in a decrease in blood volume and, in turn, a decrease in blood pressure.

Clinical Insight

ACE inhibitors are a group of drugs commonly used to treat hypertension. These drugs help to reduce the blood pressure by decreasing the activity of ACE, resulting in decreased production of angiotensin II. Decreased production of angiotensin II leads to decreased blood pressure.

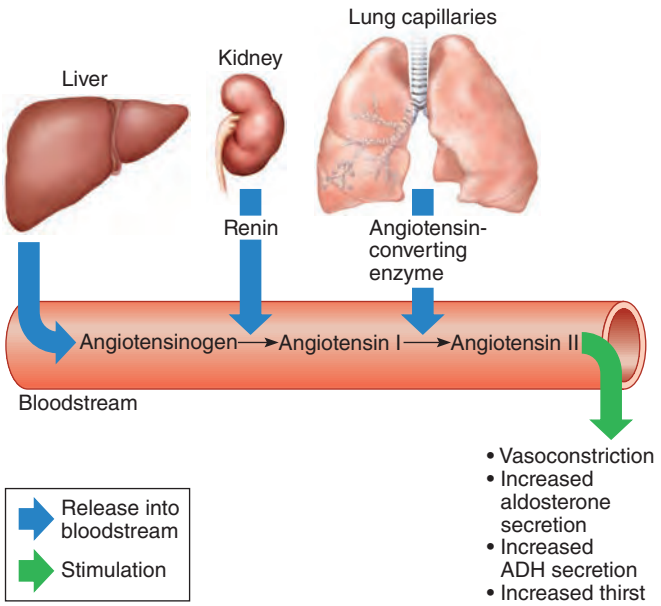


Figure 16.7 The renin–angiotensin mechanism. The multiple actions of angiotensin II help to maintain the GFR and systemic blood pressure.

Tubular Reabsorption and Tubular Secretion

Tubular reabsorption and tubular secretion involve both active and passive transport mechanisms. The effectiveness of passive transport of any substance depends upon (1) the permeability of the renal tubule, peritubular capillaries, and vasa recta to the substance, and (2) the concentration gradient of the substance.

Events in the Proximal Convoluted Tubule

About 65% of the tubular fluid is reabsorbed in the PCT. All nutrients, such as glucose and amino acids, are actively reabsorbed here. Positively charged ions, such as those of Na^+, K^+, and Ca^{2+}, are also actively reabsorbed. The active reabsorption of positively charged ions causes negatively charged ions, such as Cl^- and HCO_3^-, to be passively reabsorbed by electrochemical attraction. The reabsorption of these substances increases the osmotic pressure of the blood plasma in the peritubular capillaries and decreases the osmotic pressure of the tubular fluid. This causes water to be passively reabsorbed from the tubular fluid by osmosis (figure 16.8).

Tubular secretion is the process that extracts substances from blood plasma in the peritubular capillaries and secretes them into the tubular fluid in the renal tubule. Metabolic wastes, such as urea and uric acid, and drugs, are removed from the blood in this way. It not only removes unwanted wastes but also helps regulate the pH of body fluids by selectively removing H^+ and HCO_3^-.

Events in the Nephron Loop

Water is passively reabsorbed by osmosis from the descending limb of the nephron loop into the capillaries supplied by the vasa recta. The ascending limb is impermeable to water, but solutes are reabsorbed passively by diffusion from the proximal ascending limb (figure 16.9).

The ascending limb actively pumps Na^+ out of the tubular fluid, and K^+ and Cl^- follow passively into the interstitial fluid. Some K^+ reenter the tubule, but Na^+ and Cl^- remain in the interstitial fluid. The accumulation of ions in the interstitial fluid of the renal medulla establishes a strong osmotic gradient for the reabsorption of water from the descending limb and the collecting duct. Establishing this osmotic gradient is a major function of the nephron loop.

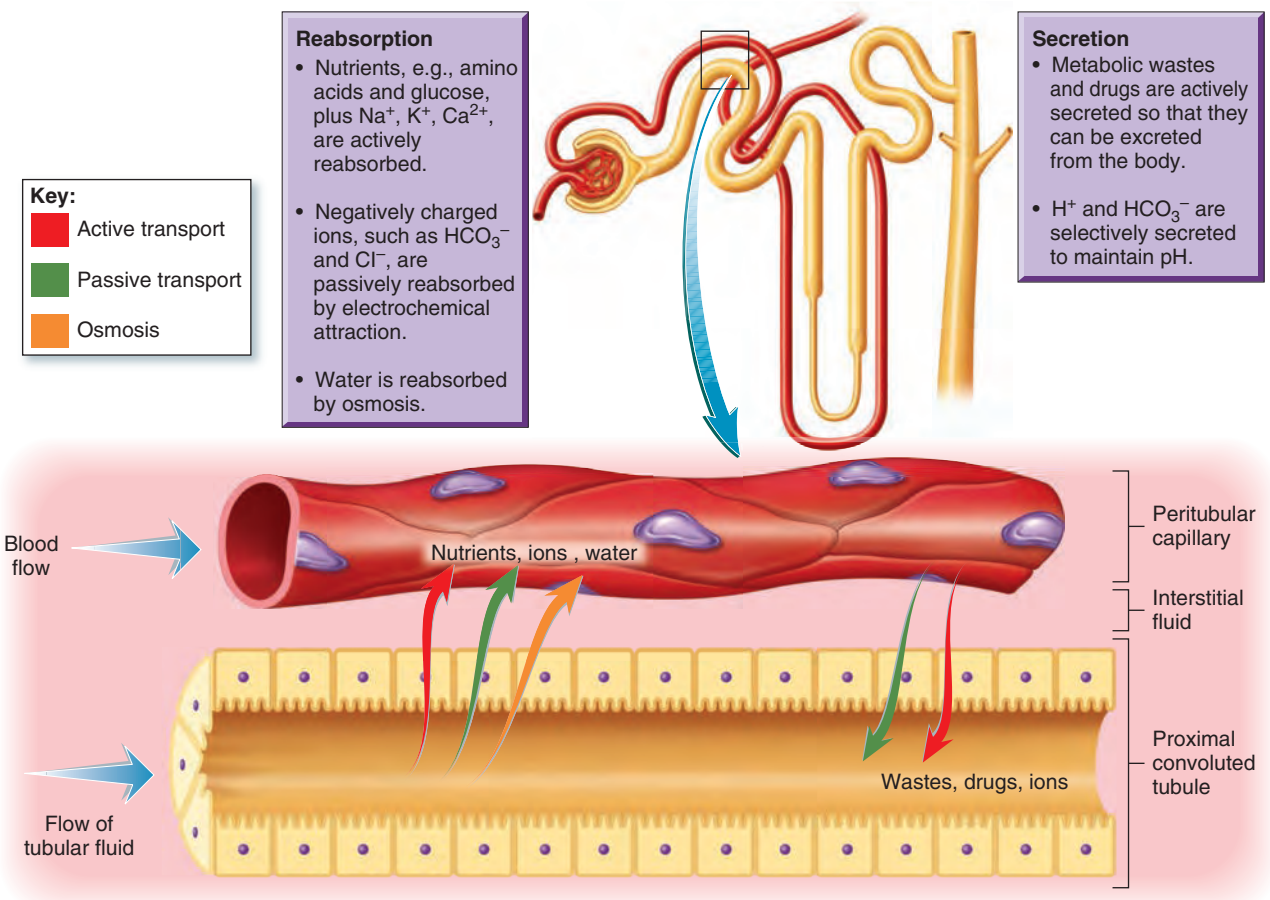


Figure 16.8 Reabsorption and secretion in the proximal convoluted tubule.

Tubular secretion does not occur in the nephron loop. At the end of the nephron loop, the tubular fluid is quite dilute due to the removal of many solutes. It still contains about 20% of the water and 10% of the salts that were present in the glomerular filtrate.

Events in the Distal Convoluted Tubule

Reabsorption in the DCT is under hormonal control. The active reabsorption of Na^+ from the tubular fluid into peritubular capillaries is promoted by the hormone aldosterone. Passive reabsorption of negative ions, such as Cl^- and HCO_3^-, then occurs by electrochemical attraction. The reabsorption of ions decreases the osmotic pressure of the tubular fluid, which causes water to be reabsorbed into the blood plasma by osmosis. However, the amount of water reabsorbed from the tubular fluid in the DCT is controlled by ADH (figure 16.9). Activating the renin-angiotensin system causes these two hormones to increase sodium and water reabsorption, which increases blood volume and blood pressure.

Parathyroid hormone (PTH) and active vitamin D also affect the DCT. They control the amount of Ca^{2+} reabsorption that takes place in the DCT and are very important in maintaining blood Ca^{2+} homeostasis, as will be discussed further in the "Electrolyte Balance" section of this chapter.

Aldosterone release can also be triggered by increased blood K^+ levels (hyperkalemia). Aldosterone causes the DCT to actively secrete K^+ from blood plasma in the peritubular capillaries into the distal convoluted tubule. Hydrogen ions are also actively secreted, as necessary, to maintain the normal blood pH. When necessary, the DCT is the site of active and passive drug secretion and elimination.

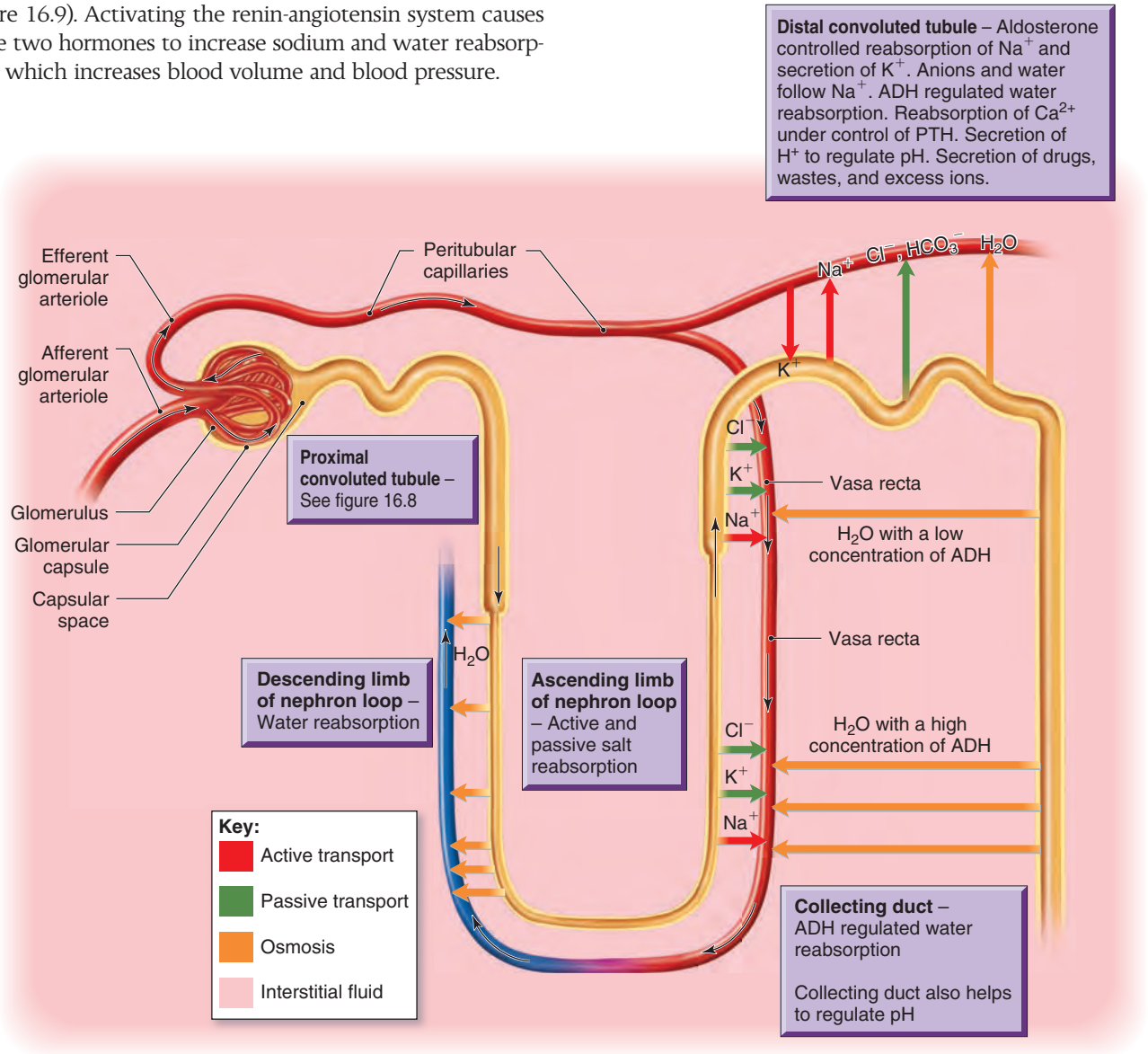


Figure 16.9 Reabsorption and secretion in the nephron loop, distal convoluted tubule, and collecting duct.

Water Conservation

The tubular fluid entering the collecting duct is approximately isotonic with the blood plasma, so it still contains a lot of water. Once tubular fluid enters the collecting duct it is renamed *urine*. Because the collecting duct extends from the renal cortex through the renal medulla to the renal papilla the concentration of ions in the surrounding interstitial fluid increases along the length of the collecting duct. Recall that Na^+, K^+, and Cl^- have been moved into the interstitial fluid by the ascending limb of the nephron loop. This creates a strong osmotic gradient that causes the passive reabsorption of water from the urine in the collecting duct by osmosis. The reabsorption of water causes the urine to become concentrated and hypertonic to blood plasma by the time it exits the collecting duct. The reabsorption of water from the collecting duct is regulated by ADH, which increases the collecting duct's permeability to water (figure 16.9). Only 1% of the original glomerular filtrate volume remains as urine.

Table 16.2 summarizes the functions of each segment of a nephron in the formation of urine.

Characteristics of Urine

The volume of urine produced in a 24-hour period usually is 1.5 to 2.0 liters. In healthy persons, fresh urine is usually clear with a pale yellow to light amber color and a characteristic odor. The color is due to the presence of *urochrome*, a substance produced by the breakdown of bile pigments in the intestine. The more concentrated the urine, the darker is its color.

Urine is usually slightly acidic (about pH 6), although the normal pH range extends from 4.8 to 7.5. Variations in pH usually result from the diet. High-protein diets increase the acidity. Conversely, vegetarian diets tend to make the urine more alkaline.

Urine is heavier than water because of the many solutes it contains. The term *specific gravity* is used to compare how much heavier urine is than water. Pure water has a specific gravity of 1.000, and the specific gravity of normal urine ranges from 1.002 (dilute urine) to 1.030 (concentrated urine). Specific gravity is a measure of the concentration of a urine sample.

The usual solutes of urine have been discussed earlier in this section (table 16.1). Substances not normally

Table 16.2 Summary of the Functions of Nephrons and Collecting Ducts

Structure	Function
Renal Corpuscle	
Glomerulus	Glomerular filtration
	Glomerular blood pressure forces some of the water and dissolved substances (except proteins) from the blood plasma through the pores in the glomerular capillary walls
Glomerular capsule	Receives glomerular filtrate from glomerulus
Renal Tubule	
Proximal convoluted tubule	Active reabsorption of all nutrients, including glucose and amino acids
	Active reabsorption of positively charged ions like sodium, potassium, calcium, and magnesium
	Passive reabsorption by electrochemical attraction of negatively charged ions such as bicarbonate
	Passive reabsorption of water by osmosis
	Active secretion of hydrogen and bicarbonate ions
Nephron loop	
Descending limb	Passive reabsorption of water by osmosis
Ascending limb	Active reabsorption of sodium ions into the interstitial fluid of the renal medulla
	Passive reabsorption of chloride and potassium ions
Distal convoluted tubule	Active reabsorption of calcium ions under the influence of PTH and active vitamin D
	Active reabsorption of sodium ions under influence of aldosterone
	Passive reabsorption by electrochemical attraction of negatively charged ions such as chloride and bicarbonate
	Passive reabsorption of water by osmosis under the influence of ADH
	Active secretion of hydrogen ions
	Active secretion of potassium ions under the influence of aldosterone
Collecting duct	Passive reabsorption of water by osmosis under the influence of ADH

found in urine are glucose, proteins, formed elements, hemoglobin, and bile pigments. The presence of any of these substances suggests possible pathological conditions. Normal values of urine components and some indications of abnormal values are listed on the inside back cover.

Check My Understanding

5. What are the mechanisms of glomerular filtration, tubular reabsorption, tubular secretion, and water conservation?
6. For each section of a nephron and the collecting duct, what substances are reabsorbed and secreted during the formation of the urine entering the minor calyx?

16.4 Excretion of Urine

Learning Objectives

8. Describe the structure and function of the ureters, urinary bladder, and urethra.
9. Describe the control of micturition.

The term *urinary tract* refers collectively to the renal pelvis, the ureters, the urinary bladder, and the urethra. These structures function to carry urine from the kidneys to the external environment. Urine passes from the renal pelvis into the ureter and is carried by peristalsis to the urinary bladder. Urine is voided from the urinary bladder through the urethra.

Ureters

Each **ureter** is a slender tube about 25 cm (10 in) long that extends from a kidney to the urinary bladder. It begins at the kidney with the funnel-shaped renal pelvis and enters the inferior lateral margin of the urinary bladder (figure 16.10; see figure 16.1).

The wall of a ureter is formed of three layers. The external fibrous layer is composed of dense irregular connective tissue. The middle layer consists of smooth muscle cells that produce peristaltic waves for urine transport. The internal layer is a mucosa that is continuous with that of the renal pelvis and the urinary bladder. A flaplike fold of mucosa in the urinary bladder covers the opening of the ureter, and it functions as a valve that prevents backflow of urine into the ureter.

Clinical Insight

A routine urinalysis is a common clinical test that provides information about kidney function and also about general health of the body. Kidney function is also assessed by two blood tests. The *blood urea nitrogen (BUN)* test evaluates how effectively the kidney removes urea from the blood. The normal BUN value is 6 to 20 mg per 100 ml of blood. In acute kidney failure and in later stages of chronic kidney failure, BUN may range from 50 to 200 mg per 100 ml of blood. *Blood (serum) creatinine* is another test that assesses kidney effectiveness. Creatinine levels in the blood are normally stable (0.6–1.5 mg/100 ml), so an increase indicates a decrease in kidney function.

Urinary Bladder

The **urinary bladder** is a hollow, muscular organ located posterior to the pubic symphysis within the pelvic cavity. It lies inferior to the parietal peritoneum. The urinary bladder provides temporary storage of urine, and its size and shape vary with the volume of urine that it contains. When filled with urine, it is almost spherical as its superior surface expands. When empty, its superior surface collapses, giving a deflated appearance.

The internal floor of the urinary bladder contains the *trigone* (trī′-gōn), a smooth, triangular area that contains an opening at each of its angles. The openings of the ureters are located at the two laterally located posterior angles, and the opening of the urethra is located at the anterior angle (figure 16.10).

Four layers compose the wall of the urinary bladder. The most internal layer is the *mucosa*, which is composed of transitional epithelium that is adapted to the repeated stretching of the urinary bladder wall. The epithelium stretches, and its thickness decreases as the urinary bladder fills with urine.

The mucosa is supported by the underlying *submucosa* formed of areolar connective tissue containing an abundance of elastic fibers. Blood vessels and nerves supplying the urinary bladder are present in the submucosa.

Smooth muscle cells compose the third, and thickest, layer. These cells form a muscle called the *detrusor* (dē-trū′-sor). The detrusor is relaxed as the urinary bladder fills with urine, and it contracts as urine is expelled. Cells of the detrusor form an *internal urethral sphincter* at the junction of the urinary bladder and the urethra.

The external layer consists of the parietal peritoneum, but it covers only the superior portion of the urinary bladder. The remainder of the urinary bladder surface is coated with dense irregular connective tissue.

Urethra

The **urethra** is a thin-walled tube that carries urine from the urinary bladder to the external environment. The urethral wall contains smooth muscle cells and is supported by connective tissue. The internal lining is a mucosa that is continuous with the mucosa of the urinary bladder. An

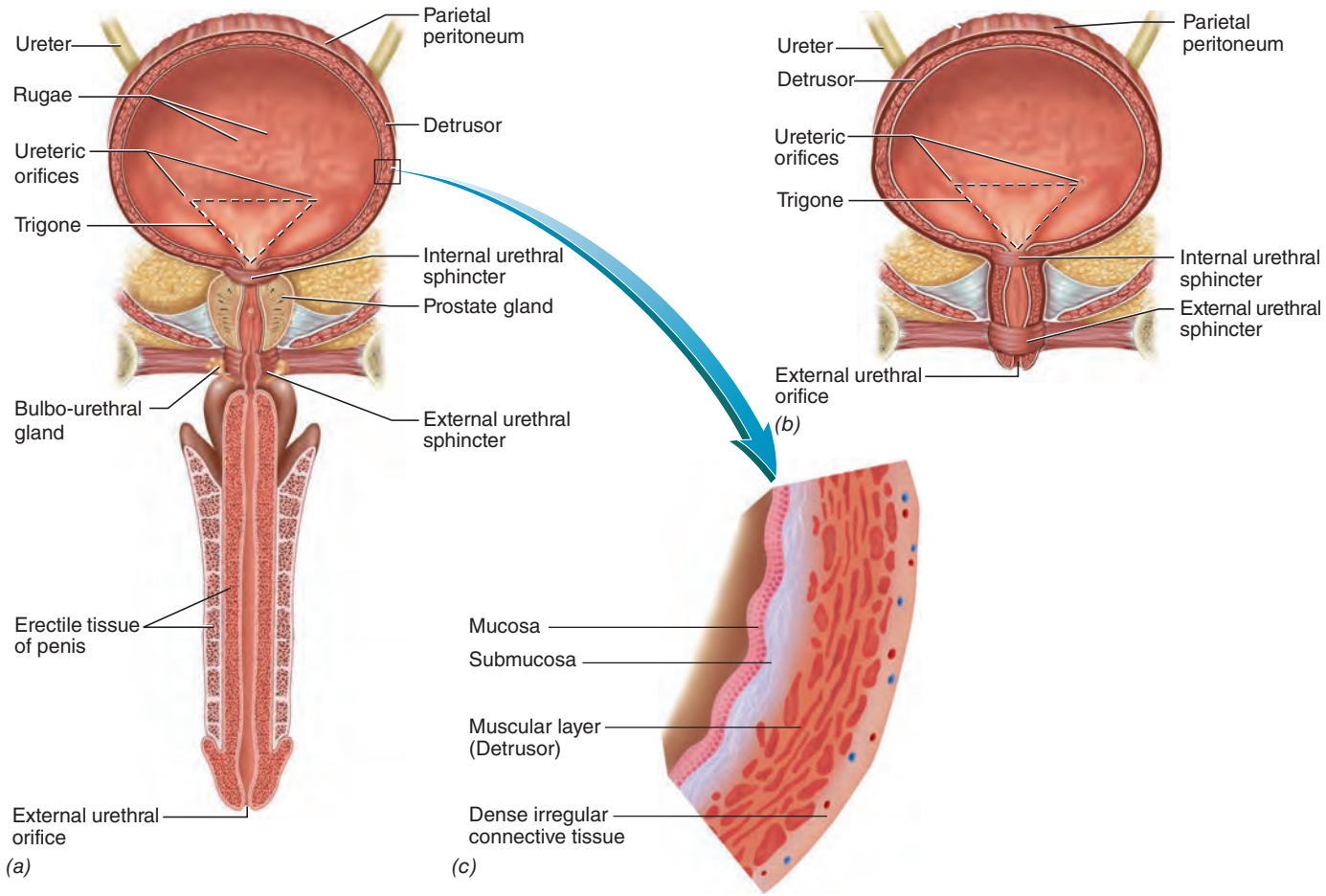


Figure 16.10 Urinary Bladder and Urethra in Frontal Section.
(a) Male. *(b)* Female. *(c)* Magnification of the wall of the urinary bladder.

external urethral sphincter, which is composed of skeletal muscle fibers, is located where the urethra penetrates the pelvic floor.

The female urethra is quite short, about 3 to 4 cm (1.5 in) in length. The external urethral orifice, its external opening, lies anterior to the vaginal orifice. The male urethra is much longer, about 16 to 20 cm (6–8 in) in length, because the urethra runs the length of the penis. The external urethral orifice is at the tip of the penis.

Micturition

Micturition (mik-tū-rish′un), or urination, is the act of expelling urine from the urinary bladder. Although the urinary bladder may hold up to 1,000 ml of urine, micturition usually occurs long before that volume is attained. When 200 to 400 ml of urine have accumulated in the urinary bladder, stretch receptors in the urinary bladder wall are stimulated and they trigger the *micturition reflex*. This reflex sends parasympathetic nerve impulses to the detrusor, causing rhythmic contractions. As this reflex continues, it causes the involuntarily controlled internal urethral sphincter to open and the person becomes aware of the desire to urinate. The act of urinating then becomes a consciously controlled process. If the voluntarily controlled external urethral sphincter is relaxed, micturition occurs; if it is not relaxed, micturition is postponed.

Micturition may be postponed by keeping the external sphincter voluntarily closed, and in a few moments the urge to urinate subsides. After more urine enters the urinary bladder, the micturition reflex is activated again, and the urge to urinate returns. Micturition cannot be postponed for long periods of time. After a while, the reflex overwhelms voluntary control and micturition occurs, ready or not.

An infant is not able to be toilet trained until neural development allows control of the external urethral sphincter muscle. Voluntary control is possible shortly after two years of age.

Check My Understanding

7. How is micturition controlled?

16.5 Maintenance of Blood Plasma Composition

Learning Objectives

10. Explain how water balance is maintained in body fluids.
11. Explain how electrolyte balance is maintained in body fluids.
12. Explain how pH balance is maintained in body fluids.

The composition and volume of blood plasma are affected by diet, cellular metabolism, and urine production. The intake of food and liquids provides the body with water and a variety of nutrients, including minerals, that are absorbed into the blood. Cellular metabolism uses nutrients and produces waste products, including nitrogenous wastes. Urine production retains essential nutrients and minerals in the blood plasma but removes some water along with excess substances and nitrogenous wastes. In healthy people, the kidneys are able to keep the composition and volume of the blood plasma relatively constant in spite of variations in diet and cellular activity.

Water and Electrolyte Balance

Two important components of blood plasma and other body fluids are water and electrolytes, and their concentrations in body fluids must be maintained within normal limits. Recall that water is the solvent of body fluids in which the chemical reactions of life occur. Recall that electrolytes are substances that form ions when dissolved in water, and they are so named because they can conduct an electric current when dissolved in water. For example, sodium chloride is an electrolyte that forms sodium and chloride ions when dissolved in water.

The concentrations of water and electrolytes in body fluids are interrelated because the concentration of one affects the concentration of the other. For example, the concentration of electrolytes establishes the osmotic pressure that enables water to be reabsorbed by osmosis.

Water Balance

The intake of water is largely regulated by the *thirst center* located in the hypothalamus of the brain. The thirst center is activated when it detects an increase in solute concentration in the blood. It is also activated by angiotensin II when blood pressure declines significantly. An awareness of thirst stimulates water intake to replace water lost from body fluids. Water intake must balance water loss, and this averages about 2,500 ml per day.

The body loses water in several ways, but about 60% of the total water loss occurs in urine. In addition, water is lost in the humidified air exhaled from the lungs, in feces, and in perspiration (figure 16.11). However, it is the kidneys that regulate the concentration of water in the blood plasma by controlling the volume of water lost in urine.

Clinical Insight

Substances that increase the production of urine are known as *diuretics*. Physicians often prescribe a diuretic to reduce the volume of body fluids in patients with edema or hypertension.

The volume of water lost in urine varies with both the volume of water lost by other means and the volume of water intake. These factors affect the action of the kidneys simultaneously, but we consider them separately to better understand how they influence kidney function.

In general, the more water that is lost through other means, the less water that is lost in urine. For example, if excessive water loss occurs through perspiration or diarrhea, more water is reabsorbed from the renal tubule and collecting duct. The result is a smaller volume of more concentrated urine. Conversely, if water loss through other means is minimal, water reabsorption is reduced, and a larger volume of more dilute urine is produced.

Similarly, the greater the intake of water, the less water is reabsorbed and a larger volume of more dilute urine is produced. Conversely, a lower water intake means more water is reabsorbed and a smaller volume of more concentrated urine is produced.

You can see that regulating water balance is a dynamic process and that water balance is largely controlled by the amount of water reabsorbed from renal tubules and collecting ducts into the blood plasma. Whether more or less water is reabsorbed is dependent upon ADH secreted by

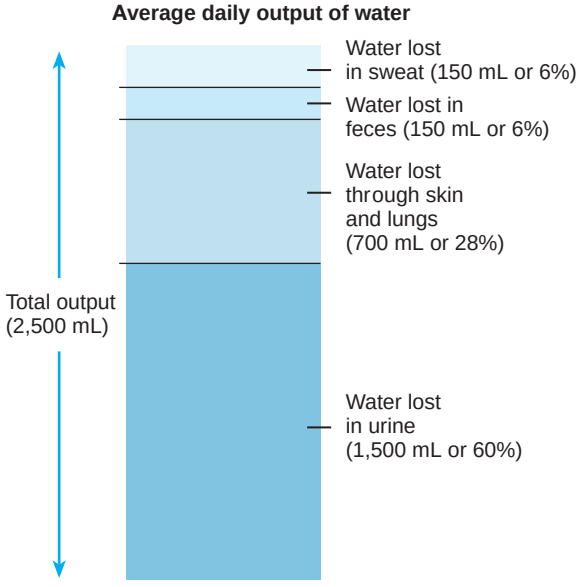


Figure 16.11 Pathways of water loss. Urine formation is the most important process that regulates water loss.

the posterior lobe of the pituitary gland. ADH promotes water reabsorption by increasing the permeability of the DCT and collecting ducts to water.

When the water concentration of blood is excessive, ANP is secreted and ADH secretion declines. The combined effect is that less water is reabsorbed and a greater volume of urine (and water) is excreted. The result is a decrease in water concentration in the blood. Conversely, when the water concentration of blood decreases, ANP is not secreted, ADH secretion is increased, more water is reabsorbed, and a smaller volume of urine is produced. ADH minimizes water loss in urine, but it cannot prevent it. Thus, water must be replenished daily by fluid intake.

Electrolyte Balance

Important electrolytes in body fluids include ions of sodium, potassium, calcium, chloride, phosphate, sulfate, and bicarbonate. Electrolytes are obtained from the intake of food and fluids. A craving for salt results when electrolytes are in low concentration in body fluids.

Electrolyte balance is regulated largely by active reabsorption of positively charged ions, which, in turn, secondarily controls the passive reabsorption of negatively charged ions by electrochemical attraction. Sodium ions are the most important ions to be regulated because they compose about 90% of the positively charged ions in extracellular fluids. Certain hormones play important roles in maintaining electrolyte balance.

Clinical Insight

If water loss significantly exceeds water intake for several days, extracellular fluids may become more concentrated, causing water to move out of the cells by osmosis. This condition, known as *cellular dehydration,* may lead to serious complications unless the water loss is quickly restored. In serious cases, dehydration may result in fever, mental confusion, or coma.

Aldosterone is a hormone that regulates the balance of sodium and potassium ions in the blood plasma by stimulating the active reabsorption of sodium ions and the active secretion of potassium ions by the DCT. Thus, aldosterone causes an exchange of sodium and potassium ions between the tubular fluid and the blood plasma until the blood concentrations of these two ions returns to normal. The adrenal cortex is stimulated to secrete aldosterone by (1) an increase of K^+ in the blood, (2) a decrease of Na^+ in the blood, and (3) angiotensin II. As long as blood concentrations of sodium and potassium ions are normal, aldosterone is not secreted. In contrast to aldosterone, ANP promotes the excretion of sodium ions and water by inhibiting sodium reabsorption, and thus osmosis, in the DCT and collecting duct when excess blood volume is detected by the atria of the heart.

The blood concentration of Ca^{2+} is regulated mainly by the actions of PTH and active vitamin D. When the blood Ca^{2+} concentration declines, the parathyroid glands are stimulated to secrete PTH. PTH promotes an increase in blood Ca^{2+} by stimulating three different processes: (1) the reabsorption of Ca^{2+} ions from the DCT, (2) the movement of Ca^{2+} from bones into the blood, and (3) the activation of vitamin D. Active vitamin D has the same actions as PTH; in addition, it increases the absorption of Ca^{2+} in foods by the small intestine. When the blood Ca^{2+} level returns to normal, PTH secretion is decreased. The lack of PTH is usually sufficient to decrease blood Ca^{2+} levels. Table 16.3 summarizes the effect of hormones that act on the kidneys.

During times of rapid bone remodeling, such as childhood or pregnancy, *calcitonin* is secreted by the thyroid gland. Calcitonin plays an antagonistic role to PTH by promoting the deposition of calcium in bones, which reduces the level of blood calcium.

Acid–Base Balance

The arterial blood pH must be maintained within rather narrow limits–pH 7.35 to pH 7.45–for body cells to function properly. Arterial blood pH below 7.35 is called **acidosis,** and arterial blood pH above 7.45 is called

Table 16.3 Hormones Acting on the Kidneys

Hormone	Source	Action
Aldosterone	Adrenal cortex	Stimulates reabsorption of Na^+ from the tubular fluid into the blood plasma; stimulates the secretion of K^+ from blood plasma into the tubular fluid
Antidiuretic hormone	Posterior lobe of pituitary	Stimulates the reabsorption of water from the tubular fluid into the blood plasma by making the DCT and collecting ducts more permeable to water; decreases the volume of urine produced
Atrial natriuretic peptide	Heart	Inhibits reabsorption of Na^+ from DCT and collecting ducts
Parathyroid hormone and active vitamin D	Parathyroid glands Liver and kidneys	Stimulates the reabsorption of Ca^{2+} from the tubular fluid into the blood plasma

alkalosis. Cellular metabolism produces products that tend to upset the acid-base balance. These products, such as lactic acid, phosphoric acid, and carbonic acid, tend to make the blood more acidic, as shown in figure 16.12.

Acids are substances that release hydrogen ions (H^+) when they are in water, which decreases the pH and increases the acidity of the liquid. Strong acids release more H^+ than weak acids. **Bases** are substances that, when placed in water, release ions that can combine with hydrogen ions, such as OH^- or HCO_3^-. Body fluids contain both acids and bases, and the balance between them determines pH. The balance of acids and bases in the body is regulated by three processes: (1) **buffers,** which act directly in the body fluids; (2) the **respiratory mechanism,** which controls carbonic acid levels; and (3) the **renal mechanism,** which regulates H^+ and HCO_3^- levels.

Buffers

The blood and other body fluids contain chemicals known as buffers (see chapter 2) that prevent significant changes in pH. Buffers are able to combine with or release H^+ ions as needed to stabilize the pH. If the H^+ concentration is excessive, buffers combine with some H^+ to reduce their concentration. Conversely, if too few H^+ are present,

Clinical Insight

The kidneys have a tremendous functional reserve. Renal insufficiency becomes evident only after about 75% of the renal functions have been lost. As the development of renal failure progresses, patients must rely on *hemodialysis* as a means of removing wastes and excessive substances from the blood. In hemodialysis, the patient's blood is pumped through selectively permeable tubes that are immersed in a dialyzing solution within a "kidney machine." Nitrogenous wastes and excessive electrolytes diffuse from the blood into the dialyzing solution, while certain needed substances, such as buffers, diffuse from the dialyzing solution into the blood. In this way, the concentration of wastes and electrolytes in the patient's blood are temporarily restored within normal limits. Hemodialysis may be required two to three times per week for patients with chronic kidney failure.

An alternative method is called *continuous ambulatory peritoneal dialysis (CAPD).* In this technique, 1 to 3 liters of dialyzing fluid are introduced into the peritoneal cavity through an opening made in the abdominal wall. Waste products and excessive substances diffuse from blood vessels in the peritoneum into the dialyzing solution, which is drained after two to three hours. This technique is less costly, may be done at home, and allows the patient to move about during the procedure. However, it must be done more frequently than dialysis using a kidney machine, and there is a greater chance of serious infection.

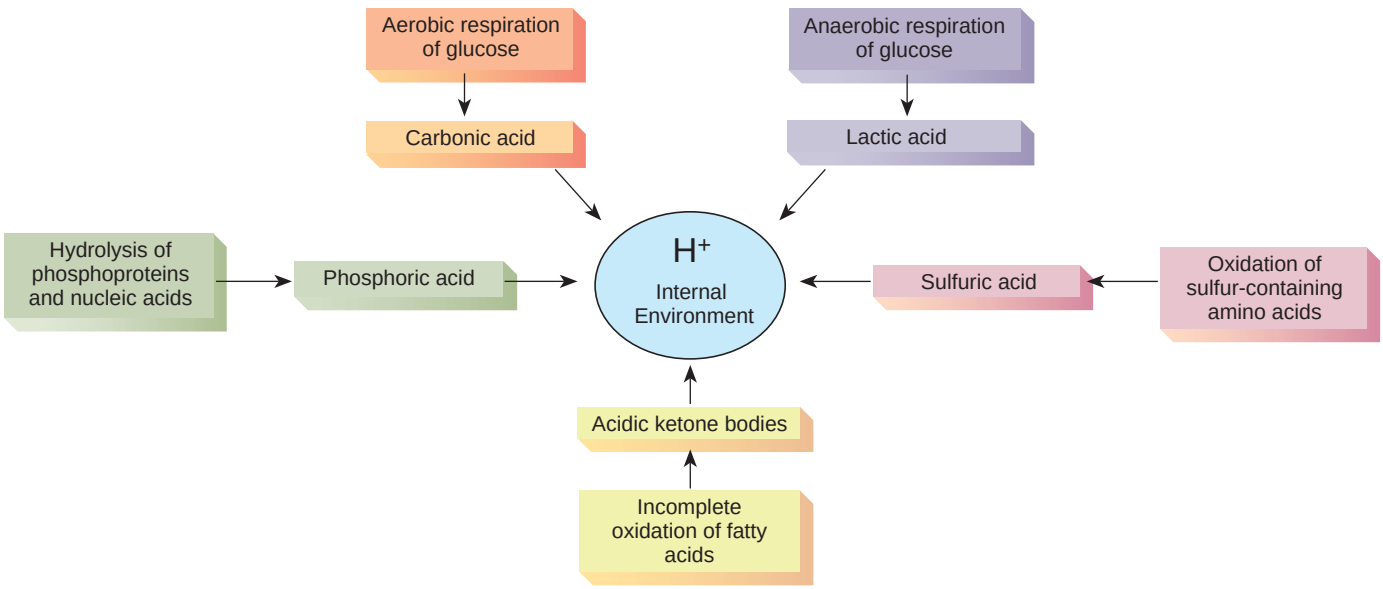


Figure 16.12 Examples of metabolic processes that increase the hydrogen ion concentration of body fluids.

buffers release some H^+ to increase their concentration to within normal limits. In this way, buffers help to keep the blood pH relatively constant.

The **bicarbonate buffer system** relies on a mixture of carbonic acid and HCO_3^-. Carbonic acid (H_2CO_3) forms by the hydration of carbon dioxide and then dissociates into HCO_3^- and H^+. The bicarbonate buffer system is particularly important in regulating the acid–base balance of extracellular fluids, such as blood. Additionally, as you will soon see, the respiratory mechanism and the renal mechanism directly influence the bicarbonate buffer system.

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

The **phosphate buffer system** relies on a mixture of HPO_4^- and $H_2PO_4^-$. The phosphate buffer system is most important in regulating the acid–base balance of intracellular fluid. The following reaction can proceed to the right to release H^+ and decrease pH, or it can proceed to the left to bind H^+ and increase pH.

$$H_2PO_4^- \leftrightarrow HPO_4^{2-} + H^+$$

The most abundant and powerful buffer system in the body is the **protein buffer system.** Proteins are able to act as buffers because amino acids have acidic (–COOH) side groups, which release H^+ when pH is elevated and decrease the pH, and amino acids also have amine ($–NH_2$) side groups that bind H^+ when pH is decreased and elevate the pH. Below are the reactions of the protein buffer system.

$$–COOH \rightarrow –COO^- + H^+ \quad \text{and} \quad –NH_2 + H^+ \rightarrow –NH_3$$

Respiratory Mechanism

The respiratory system also plays a significant role in regulating H^+ concentration of body fluids. The respiratory mechanism alters the bicarbonate buffer system by changing the levels of CO_2 in the body. Recall that the production of CO_2 results in the formation of carbonic acid, which dissociates to release H^+. When CO_2 production increases and blood pH decreases, the respiratory rhythmicity center in the medulla oblongata stimulates an increase in the rate and depth of breathing to remove the excess CO_2. Conversely, when the H^+ concentration of the blood is decreased, the rate and depth of breathing are decreased until the blood H^+ concentration increases to normal.

Renal Mechanism

The renal mechanism is able to control the bicarbonate buffer system. By selectively excreting excess H^+ or HCO_3^- in urine, kidneys help to maintain the normal pH of body fluids. The kidneys also have the ability to produce HCO_3^- and H^+ from carbon dioxide in times of shortage.

Check My Understanding

8. How do ADH, aldosterone, PTH, and ANP regulate water and electrolyte concentrations in blood?
9. What are the three buffer systems?
10. How does the kidney adjust blood pH?

16.6 Disorders of the Urinary System

Learning Objective

13. Describe the common disorders of the urinary system.

Inflammatory Disorders

Cystitis (sis-tī′-tis) is the inflammation of the urinary bladder. It is often caused by bacterial infection. Females are more prone to cystitis because their shorter urethra makes it easier for bacteria to reach the urinary bladder.

Glomerulonephritis (glō-mer-ū-lō-ne-frī′-tis) is the inflammation of a kidney involving the glomeruli. It may be caused by bacteria or bacterial toxins. The inflamed glomeruli become more permeable, allowing formed elements and proteins to leak into the glomerular filtrate and remain in the urine.

Pyelonephritis (pī-e-lō-ne-frī′-tis) is the inflammation of the renal pelvis and nephrons. If only the renal pelvis is involved, the condition is called *pyelitis*. These infections result from bacteria carried by blood from other places in the body or by migration of bacteria from distal portions of the urinary tract.

Urethritis is the inflammation of the urethra. It may be caused by several types of bacteria, but the bacterium *Escherichia coli* is the most common. Urethritis is more common in females.

Noninflammatory Disorders

Diuresis, or polyuria, is the excessive production of urine. It results from inadequate tubular reabsorption of water and is characteristic of diabetes insipidus and diabetes mellitus.

Renal calculi (kal′-kū-li), or kidney stones, result from crystallization of uric acid or of calcium or magnesium salts in the renal pelvis. They can cause extreme pain, especially when moving through a ureter by peristalsis. Ultrasound waves can be used to break up the stones, as an alternative to surgery.

Renal failure is characterized by a reduction in urine production and a failure to maintain the normal volume and composition of body fluids. It may occur suddenly (acute) or gradually (chronic). Renal failure leads to *uremia*, a toxic condition caused by excessive nitrogenous wastes in the blood, and ultimately to *anuria*, a cessation of urine production. Hemodialysis and/or a kidney transplant may be necessary.

Chapter Summary

16.1 Functions of the Urinary System

- The functions of the urinary system are the maintenance of blood plasma composition, the secretion of renin and erythropoietin, and the excretion of nitrogenous wastes.
- A major function of the kidneys is the removal of excess nitrogenous wastes—urea, uric acid, and creatinine–in order to keep their concentrations in the blood within normal limits.

16.2 Anatomy of the Kidneys

- The paired kidneys are located against the superior posterior abdominal wall.
- Internal structure of a kidney consists of two recognizable functional parts: a superficial renal cortex, and a deep renal medulla composed of renal pyramids.
- Nephrons are the functional units of the kidneys. Each nephron consists of a renal corpuscle and a renal tubule. A renal corpuscle is composed of a glomerulus and a glomerular capsule. A renal tubule is composed of a proximal convoluted tubule, the nephron loop, and a distal convoluted tubule.
- Each nephron joins with a collecting duct that empties into a minor calyx of the renal pelvis.
- The blood supply for each kidney is provided by a renal artery and drainage is through the renal vein.
- An afferent glomerular arteriole brings blood to a glomerulus. Blood exits the glomerulus via an efferent glomerular arteriole and flows through either the peritubular capillaries, which surround the cortical portion of the renal tubule or vasa recta, which surround the medullary portion of the nephron loop.
- The juxtaglomerular complex consists of modified cells of the afferent and efferent glomerular arterioles and the ascending limb of the nephron loop at their point of contact.

16.3 Urine Formation

- The process of urine formation regulates the composition and volume of blood plasma by removing excess nitrogenous wastes and surplus substances from the blood plasma.
- Urine is formed by four sequential processes: glomerular filtration, tubular reabsorption, tubular secretion, and water conservation.
- In glomerular filtration, water and dissolved substances (except plasma proteins and formed elements) in blood plasma are filtered from the glomerulus into the glomerular capsule. Glomerular filtration results from the increased permeability of glomerular capillaries and the elevated blood pressure within the glomerulus.
- About 180 liters of glomerular filtrate are formed in a 24-hour period.
- Glomerular filtration rate is proportional to the glomerular blood pressure. Glomerular blood pressure is maintained by mechanisms that control the diameters of the afferent and efferent glomerular arterioles.
- Glomerular blood pressure generally varies directly with systemic blood pressure.
- Glomerular filtration rate is regulated by renal autoregulation, sympathetic control, and the renin-angiotensin mechanism.
- In tubular reabsorption, needed substances are reabsorbed back into the blood plasma of the peritubular capillaries and vasa recta by either active or passive transport.
- Positively charged ions are actively reabsorbed. Negatively charged ions are passively reabsorbed by electrochemical attraction to the positively charged ions. Water is passively reabsorbed by osmosis.
- Most tubular reabsorption occurs in the PCT, especially of nutrients such as amino acids and glucose, but other portions of the renal tubule are also involved.
- In tubular secretion, certain substances are actively or passively secreted into the tubular fluid from the blood plasma. Uric acid and hydrogen ions are actively secreted. Potassium ions are secreted both actively and passively. Most tubular secretion occurs in the DCT.
- The nephron loop selectively reabsorbs water in the descending limb and Na^+ and Cl^- in the ascending limb, creating an osmotic gradient in the renal medulla.
- Urine is concentrated by water reabsorption from the collecting duct (water conservation), so it is hypertonic to blood plasma.
- The daily production of urine is 1.5 to 2.0 liters. Normal urine is a clear, pale yellow to amber fluid with a characteristic odor. The color is due to the presence of urochrome.
- Urine is usually slightly acidic but the pH may range from 4.8 to 7.5.
- Urine is heavier than water due to the dissolved substances that it contains.
- Abnormal substances that may be in urine are glucose, proteins, formed elements, hemoglobin, and bile pigments.

16.4 Excretion of Urine

- A ureter is a slender tube that carries urine by peristalsis into the urinary bladder.
- Urine is temporarily held in the urinary bladder. The urinary bladder is located posterior to the pubic symphysis in the pelvic cavity.
- The wall of the urinary bladder consists of the mucosa, submucosa, muscular layer, and dense irregular connective tissue. The parietal peritoneum covers only its superior surface. The muscular layer consists of smooth muscle cells forming the detrusor.
- A thickening of the detrusor at the urinary bladder-urethra junction forms the internal urethral sphincter. The external urethral sphincter in both genders is formed of skeletal muscle fibers in the floor of the pelvis.
- Micturition is the process of voiding urine from the urinary bladder. Urine is expelled from the urinary bladder through the urethra.
- When the urinary bladder contains 200 to 400 ml of urine, the micturition reflex is triggered, causing the detrusor to contract rhythmically. Continued contractions open the involuntarily controlled internal urethral sphincter. If the voluntarily controlled external urethral sphincter is relaxed, micturition occurs. If not, micturition is postponed.

16.5 Maintenance of Blood Plasma Composition

- The prime function of the kidneys is to maintain the volume and composition of the blood plasma in spite of variations in diet and metabolic processes.
- Water intake must equal water loss. Most water is lost in urine, but other avenues include exhaled air, perspiration, and feces.
- The volume of water lost in urine is decreased when water loss via other means is increased, and vice versa.
- Antidiuretic hormone, which is released from the posterior lobe of the pituitary gland, increases the permeability of DCT and collecting ducts to water and thereby promotes water reabsorption by osmosis.
- Electrolyte intake must replace electrolyte loss. Electrolytes are conserved largely by the active reabsorption of positively charged ions that passively pull along negatively charged ions by electrochemical attraction.
- Aldosterone regulates the blood concentration of sodium and potassium ions by stimulating the active reabsorption of sodium ions from and the active secretion of potassium ions into the DCT.
- Atrial natriuretic peptide promotes the excretion of sodium ions from the DCT and collecting duct.
- The concentration of calcium ions in the blood is regulated by the actions of two hormones acting in the DCT.
- Parathyroid hormone stimulates the reabsorption of calcium from bones into the blood and the reabsorption of calcium ions by the kidneys. Active vitamin D assists PTH and also increases the absorption of calcium by the small intestine. In contrast, calcitonin promotes the deposition of calcium in bones.
- The maintenance of the blood pH between 7.35 and 7.45 includes three major mechanisms: buffers in the blood either combine with or release hydrogen ions as needed; carbon dioxide is removed by the lungs; and renal tubules regulate the rate of hydrogen and bicarbonate ions secreted into the tubular fluid.
- Arterial blood pH less than 7.35 is called acidosis. Arterial blood pH greater than 7.45 is called alkalosis.

16.6 Disorders of the Urinary System

- Inflammatory disorders include cystitis, glomerulonephritis, pyelonephritis, and urethritis.
- Noninflammatory disorders include diuresis, renal calculi, and renal failure.

Self-Review

Answers are located in appendix B.

1. Renal corpuscles, proximal convoluted tubules, and distal convoluted tubules are located in the _____ of a kidney.
2. Renal pyramids are located in the _____ of a kidney and are composed mostly of _____, which collect urine from the nephrons.
3. The functional units of the kidneys are called _____.
4. The force powering glomerular filtration is _____ blood pressure, which in turn is primarily determined by the _____ blood pressure.
5. In glomerular filtration, water and dissolved substances are forced from blood plasma in the glomerulus into the _____, where the fluid is called _____.
6. In tubular reabsorption in the PCT, certain substances pass from the _____ in the renal tubules into blood plasma in the _____.
7. Glucose, amino acids, and positively charged ions are _____ reabsorbed, while water is _____ reabsorbed by _____.
8. Fluid in the collecting duct is called _____.
9. A severe drop in blood pressure causes the juxtaglomerular complex to secrete _____, which triggers a mechanism to raise blood pressure by chemical means.
10. _____ hormone promotes the reabsorption of water by making the DCT and _____ more permeable to water.
11. The hormone _____ promotes the reabsorption of sodium ions and secretion of _____ ions.
12. Water lost in urine composes about _____% of the total water loss from the body.
13. The _____ carry urine to the urinary bladder by _____.
14. Urine is voided from the urinary bladder through the _____.
15. The _____ urethral sphincter is involuntarily controlled, while the _____ sphincter is voluntarily controlled.

Critical Thinking

1. Predict the consequences of a problem with the granular cells.
2. How would perspiring heavily on a hot day affect a person's urine production?
3. How does kidney failure affect RBC production?
4. Why might kidney failure lead to hyperventilation?
5. Why does kidney failure usually lead to cardiovascular disorders, and vice versa?