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Animal Organization and Homeostasis

the need for a space suit to take a space walk reminds us that organ systems function best if the internal environment stays within normal limits. For example, a warm temperature speeds enzymatic reactions, a moderate blood pressure helps circulate blood, and a sufficient oxygen concentration facilitates ATP production. Working in harmony and under the coordination of the nervous and endocrine systems, healthy organ systems are capable of maintaining homeostasis, a dynamic equilibrium of the internal environment. Swim the English Channel, cross the Sahara Desert by camel, hike to the South Pole, or take a space walk—your body temperature will stay at just about 37°C as long as you take proper precautions. An astronaut depends on artificial systems in addition to natural systems to maintain homeostasis.

This chapter discusses homeostasis after a look at the body's organization. Just as in other complex animals, each organ system of the human body contains a particular set of organs. The circulatory system contains the heart and blood vessels and the nervous system contains the brain and nerves. Organs are composed of tissues, and each type of tissue has like cells that perform specific functions. We will begin the chapter by examining several of the major types of tissues.

An astronaut needs a special suit to take a walk outside his spaceship.

31.1 TYPES OF TISSUES

- Animals have these levels of organization: cells—tissues—organs—organ systems—organism. 578
- Animal tissues are categorized into four major types: epithelial, connective, muscular, and nervous tissues. 578
- Epithelial tissues, which line body cavities and cover surfaces, are specialized in structure and function. 578–79
- Connective tissues, which protect, support, and bind other tissues, include cartilage and bone and also blood, the only liquid tissue. 579–81
- Muscular tissues, which contract, make body parts move. 582
- Nervous tissues coordinate the activities of the other tissues and body parts. 582–83

31.2 ORGANS AND ORGAN SYSTEMS

- Organs usually contain several types of tissues. For example, although skin is composed primarily of epithelial tissue and connective tissue, it also contains muscle and nerve fibers. 585–87
- Organs, each with their own specialized functions, belong to an organ system, which has an overall function. 587
- The coelom, which arises during development, is later divided into various cavities where specific organs are located. 587

31.3 HOMEOSTASIS

- Homeostasis is the dynamic equilibrium of the internal environment. All organ systems contribute to homeostasis in animals. 588–89



31.1 Types of Tissues

Like all living things, animals are highly organized. Animals begin life as a single cell, the fertilized egg or zygote. The zygote undergoes cell division, and the cells differentiate into a variety of tissues that go on to become parts of organs. Several organs are found in an organ system. In this chapter, we consider the tissue, organ, and organ system levels of organization.

A **tissue** is composed of specialized cells of the same type that perform a common function in the body. The tissues of the human body can be categorized into four major types:

1. *Epithelial tissue* covers body surfaces, lines body cavities, and forms glands.
2. *Connective tissue* binds and supports body parts.
3. *Muscular tissue* moves the body and its parts.
4. *Nervous tissue* receives stimuli and transmits nerve impulses.

Epithelial Tissue

Epithelial tissue, also called epithelium (pl., epithelia), consists of tightly packed cells that form a continuous layer. Epithelial tissue covers surfaces and lines body cavities. Usually, it has a protective function, but it can also be modified to carry out secretion, absorption, excretion, and filtration.

Epithelial cells may be connected to one another by three types of junctions composed of proteins (see Fig. 5.14). Regions where proteins join them together are called tight junctions. In the intestine, the gastric juices stay out of the body, and in the kidneys, the urine stays within kidney tubules because epithelial cells are joined by tight junctions. For example, adhesion junctions in the skin allow epithelial cells to stretch and bend,

while gap junctions are protein channels that permit the passage of molecules between two adjacent cells.

Epithelial cells are exposed to the environment on one side, but on the other side they have a **basement membrane**. The basement membrane is simply a thin layer of various types of proteins that anchors the epithelium to the extracellular matrix, which is often a type of connective tissue. The basement membrane should not be confused with the plasma membrane or the body membranes we will be discussing.

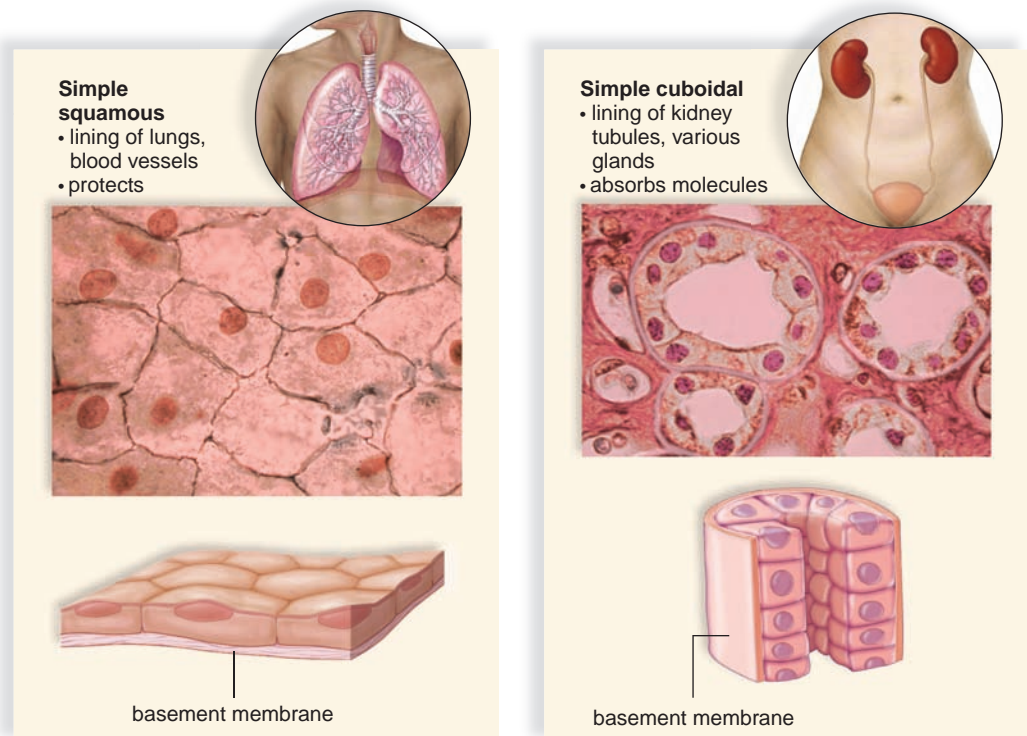
Simple Epithelia

Epithelial tissue is either simple or complex. Simple epithelia have only a single layer of cells (Fig. 31.1) and are classified according to cell type. **Squamous epithelium**, which is composed of flattened cells, is found lining blood vessels and the air sacs of lungs. **Cuboidal epithelium** contains cube-shaped cells and is found lining the kidney tubules and various glands. **Columnar epithelium** has cells resembling rectangular pillars or columns, with nuclei usually located near the bottom of each cell. This epithelium is found lining the digestive tract, where it efficiently absorbs nutrients from the small intestine because of minute cellular extensions called microvilli. Ciliated columnar epithelium is found lining the oviducts, where it propels the egg toward the uterus.

When an epithelium is pseudostratified, it appears to be layered, but true layers do not exist because each cell touches the basement membrane. The lining of the windpipe, or trachea, is pseudostratified ciliated columnar epithelium. A secreted covering of mucus traps foreign particles, and the upward motion of the cilia carries the mucus to the back of the throat, where it may be either swallowed or expectorated. Smoking can cause a change in mucus secretion and inhibit

FIGURE 31.1 Types of epithelial tissues in vertebrates.

Basic epithelial tissues found in vertebrates are shown, along with locations of the tissue and the primary function of the tissue at these locations.



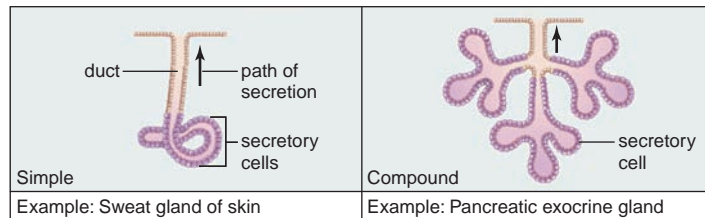
ciliary action, resulting in a chronic inflammatory condition called bronchitis.

Stratified Epithelia

Stratified epithelia have layers of cells piled one on top of the other. Only the bottom layer touches the basement membrane. The nose, mouth, esophagus, anal canal, and vagina are all lined with stratified squamous epithelium. As we shall see, the outer layer of skin is also stratified squamous epithelium, but the cells have been reinforced by keratin, a protein that provides strength. Stratified cuboidal and stratified columnar epithelia also occur in the body.

Glandular Epithelia

When an epithelium secretes a product, it is said to be glandular. A **gland** can be a single epithelial cell, as in the case of mucus-secreting goblet cells within the columnar epithelium lining the digestive tract, or a gland can contain many cells. Glands that secrete their product into ducts are called **exocrine glands**.



Glands that have no duct are appropriately known as **endocrine glands**. Endocrine glands (e.g., pituitary gland and thyroid) secrete hormones internally, so they are transported by the bloodstream.

Connective Tissue

Connective tissue is the most abundant and widely distributed tissue in complex animals. It is quite diverse in structure and function, but, even so, all types have three components: specialized cells, ground substance, and protein fibers (Fig. 31.2). The ground substance is a noncellular material that separates the cells and varies in consistency from solid to semifluid to fluid. The fibers are of three possible types. White **collagen fibers** contain collagen, a protein that gives them flexibility and strength. **Reticular fibers** are very thin collagen fibers that are highly branched and form delicate supporting networks. Yellow **elastic fibers** contain elastin, a protein that is not as strong as collagen but is more elastic.

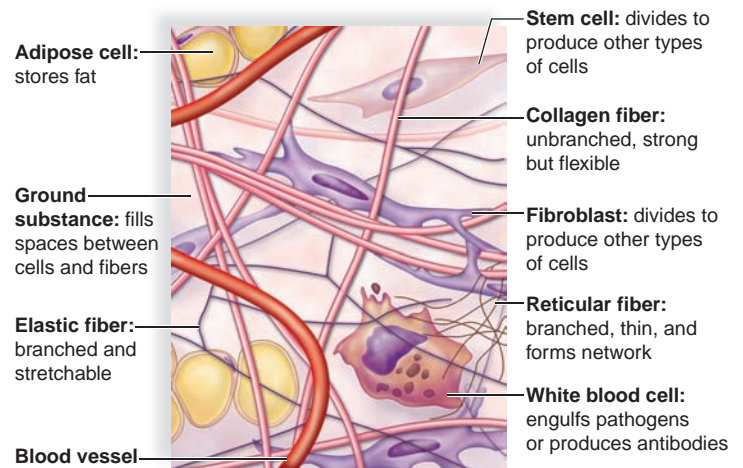
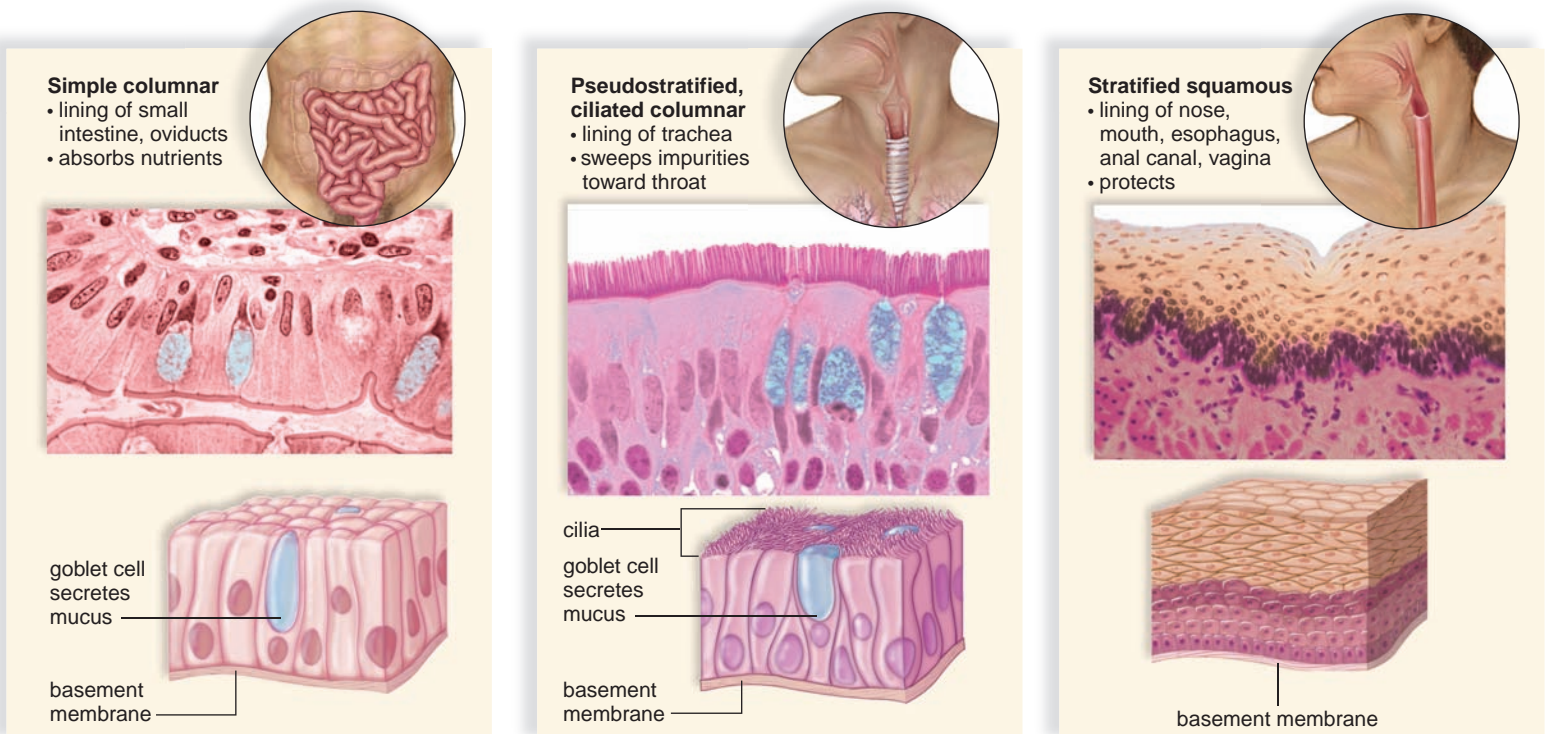


FIGURE 31.2 Diagram of fibrous connective tissue.



Connective tissue is classified into three categories: fibrous, supportive, and fluid. Each category includes a number of different types of tissues.

Fibrous Connective Tissue

Both loose fibrous and dense fibrous connective tissues have cells called **fibroblasts** [L. *fibra*, thread, and Gk. *blastos*, bud] that are located some distance from one another and are separated by a jellylike matrix containing white collagen fibers and yellow elastic fibers.

Loose fibrous connective tissue supports epithelium and also many internal organs (Fig. 31.3a). Its presence in lungs, arteries, and the urinary bladder allows these organs to expand. It forms a protective covering enclosing many internal organs, such as muscles, blood vessels, and nerves.

Adipose tissue [L. *adipalis*, fatty] serves as the body's primary energy reservoir (Fig. 31.3b). Adipose tissue also insulates the body, contributes to body contours, and provides cushioning. In mammals, adipose tissue is found particularly beneath the skin, around the kidneys, and on the surface of the heart. The number of adipose cells in an individual is fixed. When a person gains weight, the cells become larger, and when weight is lost, the cells shrink. In obese people, the individual cells called adipocytes may be up to five times larger than normal. Most adipocytes are white, but in fetuses, infants, and children, they may be brown due to mitochondria and be good at heat production.

Dense fibrous connective tissue contains many collagen fibers that are packed together (Fig. 31.3c). This type of tissue has more specific functions than does loose connective tissue. For example, dense fibrous connective tissue is found in **tendons** [L. *tendo*, stretch], which connect muscles to bones, and in **ligaments** [L. *ligamentum*, band], which connect bones to other bones at joints.

Supportive Connective Tissue

In **cartilage**, the cells lie in small chambers called lacunae (sing., **lacuna**), separated by a matrix that is solid yet flexible. Unfortunately, because this tissue lacks a direct blood supply, it heals very slowly. There are three types of cartilage, distinguished by the type of fiber in the matrix.

Hyaline cartilage (Fig. 31.3d), the most common type of cartilage, contains only very fine collagen fibers. The matrix has a white, translucent appearance. Hyaline cartilage is found in the nose and at the ends of the long bones and the ribs, and it forms rings in the walls of respiratory passages. The fetal skeleton also is made of this type of cartilage. Later, the cartilaginous fetal skeleton is replaced by bone.

Elastic cartilage has more elastic fibers than hyaline cartilage. For this reason, it is more flexible and is found, for example, in the framework of the outer ear.

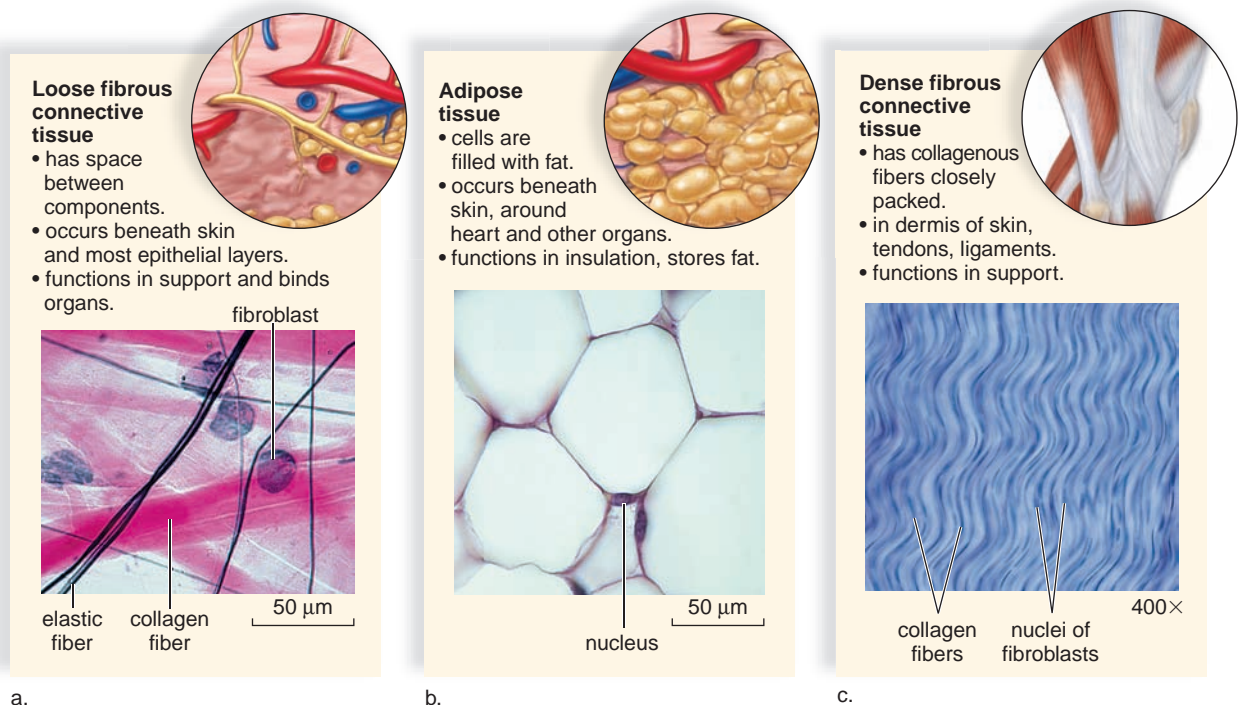
Fibrocartilage has a matrix containing strong collagen fibers. Fibrocartilage is found in structures that withstand tension and pressure, such as the pads between the vertebrae in the backbone and the wedges in the knee joint.

Bone. Of all the connective tissues, **bone** is the most rigid. It consists of an extremely hard matrix of inorganic salts, notably calcium salts, deposited around protein fibers, especially collagen fibers. The inorganic salts give bones rigidity, and the protein fibers provide elasticity and strength, much as steel rods do in reinforced concrete.

Compact bone makes up the shaft of a long bone (Fig. 31.3e). It consists of cylindrical structural units called osteons (Haversian systems). The central canal of each osteon is surrounded by rings of hard matrix. Bone cells are located in spaces called lacunae between the rings of matrix. Blood vessels in the central canal carry nutrients that allow bone to

FIGURE 31.3
Types of connective tissue in vertebrates.

Pertinent information about each type of connective tissue is given.



renew itself. Thin extensions of bone cells within canaliculi (minute canals) connect the cells to each other and to the central canal.

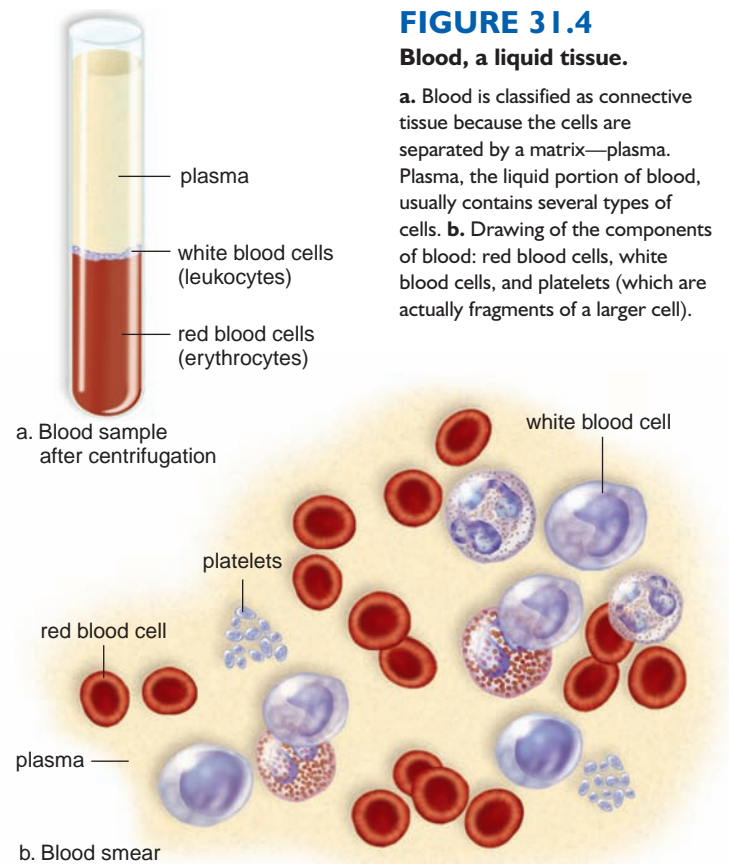
The ends of a long bone contain spongy bone, which has an entirely different structure. **Spongy bone** contains numerous bony bars and plates, separated by irregular spaces. Although lighter than compact bone, spongy bone is still designed for strength. Just as braces are used for support in buildings, the solid portions of spongy bone follow lines of stress.

Fluid Connective Tissues

Blood, which consists of formed elements and plasma, is a fluid connective tissue located in blood vessels (Fig. 31.4). In adults, the production of blood cells, known as hematopoiesis, occurs in the red bone marrow.

The internal environment of the body consists of blood and **tissue fluid**. The systems of the body help keep blood composition and chemistry within normal limits, and blood in turn creates tissue fluid. Blood transports nutrients and oxygen to tissue fluid and removes carbon dioxide and other wastes. It helps distribute heat and also plays a role in fluid, ion, and pH balance. The formed elements, discussed following, each have specific functions.

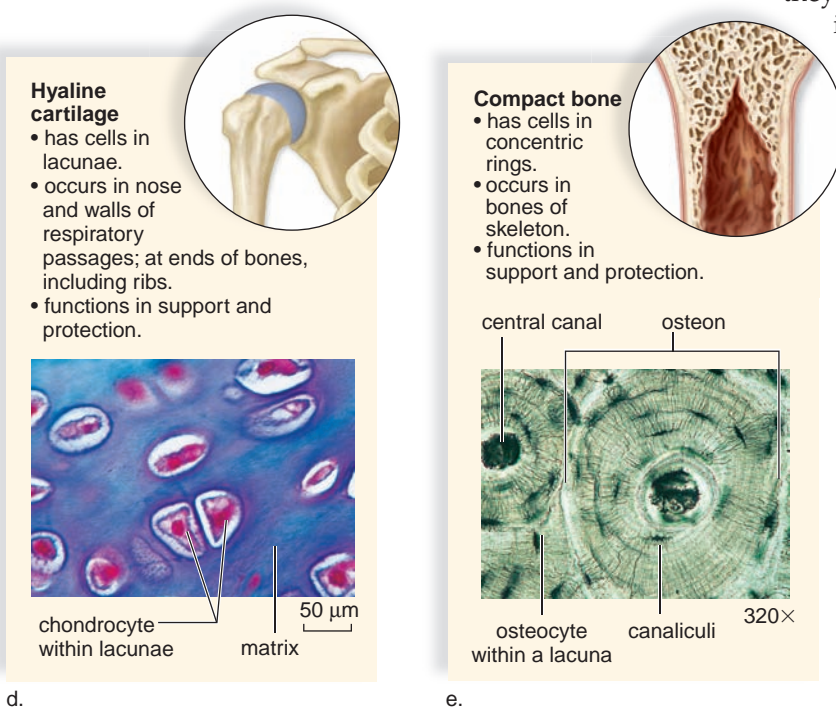
The **red blood cells** are small, biconcave, disk-shaped cells without nuclei. The absence of a nucleus makes the cells biconcave. The presence of the red pigment hemoglobin makes them red and, in turn, makes the blood red. Hemoglobin is composed of four units; each unit is composed of the protein globin and a complex iron-containing structure called heme. The iron forms a loose association with oxygen, and in this way red blood cells transport oxygen and readily give it up in the tissues.



White blood cells may be distinguished from red blood cells by the fact that they are usually larger, have a nucleus, and without staining would appear translucent. White blood cells characteristically look bluish because they have been stained that color. White blood cells fight infection, primarily in two ways. Some white blood cells are phagocytic and engulf infectious **pathogens**, while other white blood cells either produce antibodies, molecules that combine with foreign substances to inactivate them, or they kill cells outright.

Platelets are not complete cells; rather, they are fragments of giant cells present only in bone marrow. When a blood vessel is damaged, platelets form a plug that seals the vessel, and injured tissues release molecules that help the clotting process.

Lymph is a fluid connective tissue located in lymphatic vessels. Lymphatic vessels absorb excess tissue fluid and various dissolved solutes in the tissues and transport them to particular vessels of the cardiovascular system. Special lymphatic capillaries, called lacteals, absorb fat molecules from the small intestine. Lymph nodes, composed of fibrous connective tissue, occur along the length of lymphatic vessels. In particular, lymph is cleansed as it passes through lymph nodes because white blood cells congregate there. Lymph nodes enlarge when you have an infection.



Muscular Tissue

Muscular (contractile) tissue is composed of cells called muscle fibers. Muscle fibers contain actin filaments and myosin filaments, whose interaction accounts for movement. The muscles are also important in the generation of body heat. There are three distinct types of muscle tissue: skeletal, smooth, and cardiac. Each type differs in appearance, physiology, and function.

Skeletal muscle, also called voluntary muscle (Fig. 31.5a), is attached by tendons to the bones of the skeleton, and when it contracts, body parts move. Contraction of skeletal muscle is under voluntary control and occurs faster than in the other muscle types. Skeletal muscle fibers are cylindrical and quite long—sometimes they run the length of the muscle. They arise during development when several cells fuse, resulting in one fiber with multiple nuclei. The nuclei are located at the periphery of the cell, just inside the plasma membrane. The fibers have alternating light and dark bands that give them a **striated** appearance. These bands are due to the placement of actin filaments and myosin filaments in the cell.

Smooth (visceral) muscle is so named because the cells lack striations. The spindle-shaped cells form layers in which the thick middle portion of one cell is opposite the thin ends of adjacent cells. Consequently, the nuclei form an irregular pattern in the tissue (Fig. 31.5b). Smooth muscle is not under voluntary control and therefore is said to be involuntary. Smooth muscle, found in the walls of viscera (intestine, stomach, and

other internal organs) and blood vessels, contracts more slowly than skeletal muscle but can remain contracted for a longer time. When the smooth muscle of the intestine contracts, food moves along its lumen (central cavity). When the smooth muscle of the blood vessels contracts, blood vessels constrict, helping to raise blood pressure. Small amounts of smooth muscle are also found in the iris of the eye and in the skin.

Cardiac muscle (Fig. 31.5c) makes up the walls of the heart. Its contraction pumps blood and accounts for the heartbeat. Cardiac muscle combines features of both smooth muscle and skeletal muscle. Like skeletal muscle, it has striations, but the contraction of the heart is involuntary for the most part. Cardiac muscle cells also differ from skeletal muscle cells in that they have a single, centrally placed nucleus. The cells are branched and seemingly fused one with the other, and the heart appears to be composed of one large interconnecting mass of muscle cells. Actually, cardiac muscle cells are separate and individual, but they are bound end to end at **intercalated disks**, areas where folded plasma membranes between two cells contain adhesion junctions and gap junctions.

Nervous Tissue

Nervous tissue contains nerve cells called neurons. An average person has about 1 trillion neurons. A **neuron** is a specialized cell that has three parts: dendrites, a cell body, and an axon (Fig. 31.6, top). A dendrite is a process that conducts signals toward

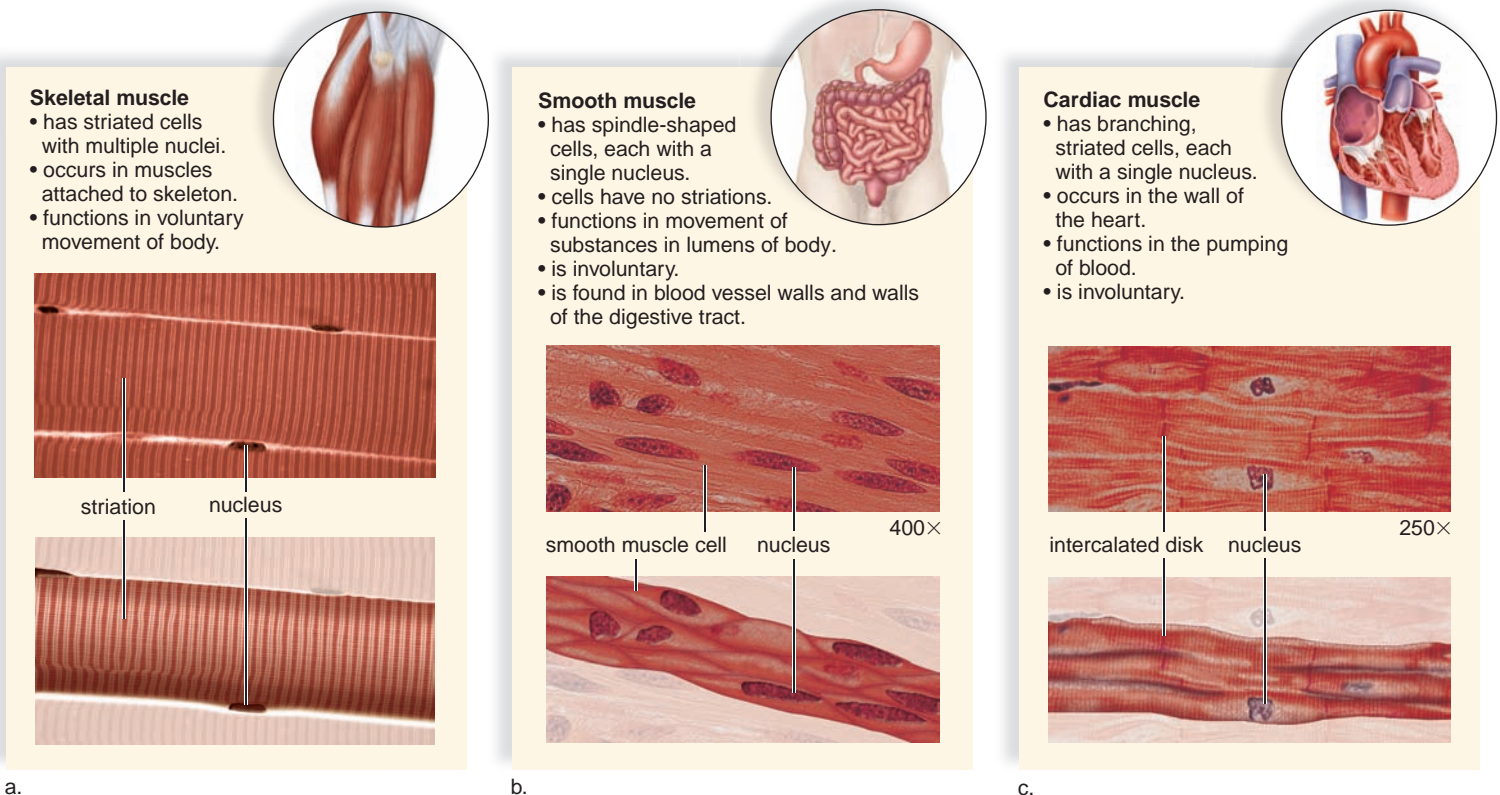


FIGURE 31.5 Muscular tissue.

a. Skeletal muscle is voluntary and striated. b. Smooth muscle is involuntary and nonstriated. c. Cardiac muscle is involuntary and striated. Cardiac muscle cells branch and fit together at intercalated disks.

the cell body. The cell body contains the major concentration of the cytoplasm and the nucleus of the neuron. An axon is a process that typically conducts nerve impulses away from the cell body. Long axons are covered by myelin, a white, fatty substance. The term *fiber*¹ is used here to refer to an axon along with its myelin sheath if it has one. Outside the brain and spinal cord, fibers bound by connective tissue form **nerves**.

The nervous system has just three functions: sensory input, integration of data, and motor output. Nerves conduct impulses from sensory receptors to the spinal cord and the brain, where integration occurs. The phenomenon called sensation occurs only in the brain, however. Nerves also conduct nerve impulses away from the spinal cord and brain to the muscles and glands, causing them to contract and secrete, respectively. In this way, a coordinated response to the stimulus is achieved.

In addition to neurons, nervous tissue contains neuroglia.

Neuroglia

Neuroglia are cells that outnumber neurons as much as 50 to 1, and take up more than half the volume of the brain. Although the primary function of neuroglia is to support and nourish neurons, research is currently being conducted to determine how much they directly contribute to brain function. Various types of neuroglia are found in the brain. Microglia, astrocytes, and oligodendrocytes are shown in Figure 31.6a. Microglia, in addition to supporting neurons, engulf bacterial and cellular debris. Astrocytes provide nutrients to neurons and produce a hormone known as glia-derived growth factor, which someday might be used as a cure for Parkinson disease and other diseases caused by neuron degeneration. Oligodendrocytes form myelin. Neuroglia do not have a long process, but even so, researchers are now beginning to gather evidence that they do communicate among themselves and with neurons!

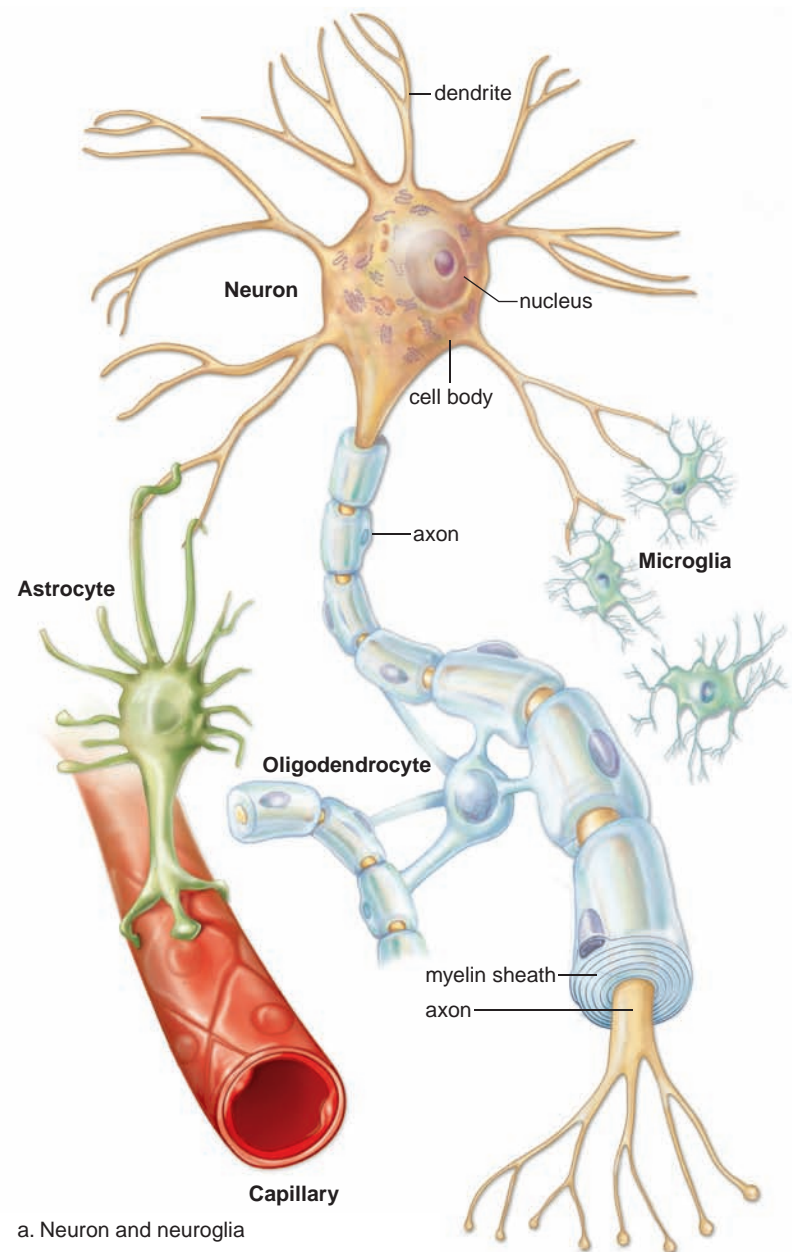
Mature neurons have little capacity for cell division and seldom form tumors. The majority of brain tumors in adults involve actively dividing neuroglia cells. Most brain tumors have to be treated with surgery or radiation therapy because of a blood-brain barrier.

Check Your Progress

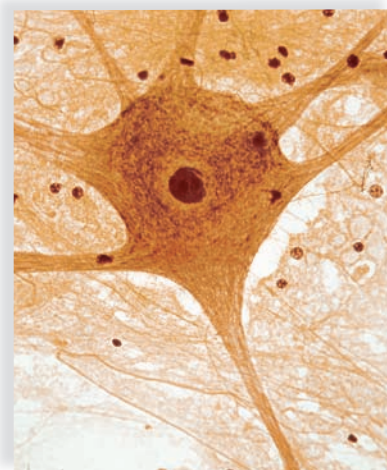
31.1

1. Distinguish between the three types of simple epithelium and give a location for each.
2. Compare and contrast the three types of connective tissue.
3. How does the structure and function of skeletal, smooth, and cardiac muscle differ?
4. What are the three parts of a neuron, and what does each part do?

¹ In connective tissue, a fiber is a component of the matrix; in muscular tissue, a fiber is a muscle cell; in nervous tissue, a nerve fiber is an axon and its myelin sheath.



a. Neuron and neuroglia



b. Micrograph of a neuron

200×

FIGURE 31.6

Neurons and neuroglia.

Neurons conduct nerve impulses. Neuroglia consist of cells that support and service neurons and have various functions: Microglia are a type of neuroglia that become mobile in response to inflammation and phagocytize debris. Astrocytes lie between neurons and a capillary; therefore, nutrients entering neurons from the blood must first pass through astrocytes. Oligodendrocytes form the myelin sheaths around fibers in the brain and spinal cord.

health focus

Nerve Regeneration

In humans, axons outside the brain and spinal cord can regenerate, but not those inside these organs. After injury, axons in the human central nervous system (CNS) degenerate, resulting in permanent loss of nervous function. Not so in cold-water fishes and amphibians, where axon regeneration in the CNS does occur. So far, investigators have identified several proteins that seem to be necessary to axon regeneration in the CNS of these animals (Fig. 31A), but it will be a long time before biochemistry can offer a way to bring about axon regeneration in the human CNS. It's possible, though, that one day these proteins will become drugs or that gene therapy might be used to cause humans to produce the same proteins when CNS injuries occur.

In the meantime, some accident victims are trying other ways to bring about a cure. In 1995, Christopher Reeve, best known for his acting role as "Superman," was thrown headfirst from his horse, crushing the spinal cord just below the neck's top two vertebrae. Immediately, his brain lost almost all communication with the portion of his body below the site of damage and he could not move his arms and legs. Many years later, Reeve could move his left index finger slightly and could take tiny steps while being held upright in a



a.

pool. He had sensation throughout his body and could feel his wife's touch.

Reeve's improvement was not the result of cutting-edge drugs or gene therapy—it was due to exercise (Fig. 31B)! Reeve exercised as much as five hours a day, especially using a recumbent

FIGURE 31B Treatment today for spinal cord injuries. a. Reeve suffered a spinal cord injury when horseback riding in 1995. b. He exercised many hours a day. Here he receives aqua therapy. Reeve died in 2004.



b.

bike outfitted with electrodes that made his leg muscles contract and relax. The bike cost him \$16,000. It could cost less if commonly used by spinal cord injury patients in their own homes. Reeve, who was an activist for the disabled, was pleased that insurance would pay for the bike about 50% of the time.

It's possible that Reeve's advances were the result of improved strength and bone density, which lead to stronger nerve signals. Normally, nerve cells are constantly signaling one another, but after a spinal cord injury, the signals cease. Perhaps Reeve's intensive exercise brought back some of the normal communication between nerve cells. Reeve's physician, John McDonald, a neurologist at Washington University in St. Louis, is convinced that his axons were regenerating. The neuroscientist Fred Gage at the Salk Institute in La Jolla, California, has shown that exercise does enhance the growth of new cells in adult brains.

For himself, Reeve was convinced that stem cell therapy would one day allow him to be off his ventilator and functioning normally; however, Reeve died in 2004. So far, researchers have shown that both embryonic stem cells and bone marrow stem cells can differentiate into neurons in the laboratory. Bone marrow stem cells apparently can also become neurons when injected into the body.

FIGURE 31A Researchers at work.

a. Some researchers are studying the activity of proteins that allow cold-bodied animals to regenerate axons in the CNS. b. Others are doing stem cell research. Stem cells might one day be used to cure people with spinal cord injuries.



a.



b.

31.2 Organs and Organ Systems

Specific tissues are associated with particular organs. For example, nervous tissue is associated with the brain. In actuality, an **organ** is composed of two or more types of tissues working together to perform particular functions. An **organ system** contains many different organs that cooperate to carry out a process, such as the digestion of food.

The integumentary system, consisting of the skin and its derivatives (hair, nails, and cutaneous glands), is the most conspicuous system in the body. Being the largest organ, the skin covers an area of 1.5–2 m² and accounts for nearly 15% of the weight of an average human.

Derivatives of the skin differ throughout the vertebrate world. Fishes possess a number of bony scales. Amphibians have smooth skin covered with mucous glands. Reptiles possess epidermal scales that vary in color and shape. Birds have scales on their legs, but most of the body is covered with feathers. Mammals are characterized by hair, nails, glands, and a number of sensory detectors.

Skin as an Organ

Human skin covers the body, protecting underlying parts from physical trauma, pathogen invasion, and water loss. The skin is also important in thermoregulation or regulating body temperature. Skin is equipped with a variety of

sensory structures that monitor touch, pressure, temperature, and pain. In addition, skin cells manufacture precursor molecules that are converted to vitamin D after exposure to UV (ultraviolet) light.

Regions of Skin

The **skin** has two regions: the epidermis and the dermis (Fig. 31.7). A **subcutaneous layer** known as the hypodermis is found between the skin and any underlying structures, such as muscle or bone.

The Epidermis

The **epidermis** [Gk. *epi*, over, and *derma*, skin] is made up of stratified squamous epithelium. Skin can be described as thin skin or thick skin based on the thickness of the epidermis. Thin skin covers most of the body and is associated with hair follicles, sebaceous (oil) glands, and sweat glands. Thick skin appears in regions of wear and tear, such as the palms of the hands and soles of the feet. Thick skin has sweat glands but no sebaceous glands or hair follicles. In both types of skin, new cells derived from stem (basal) cells become flattened and hardened as they push to the surface (Fig. 31.8a). Hardening takes place because the cells produce keratin, a waterproof protein. Dandruff occurs when the rate of keratinization in the skin of the scalp is two or three times the normal rate. A thick layer of dead keratinized cells, arranged

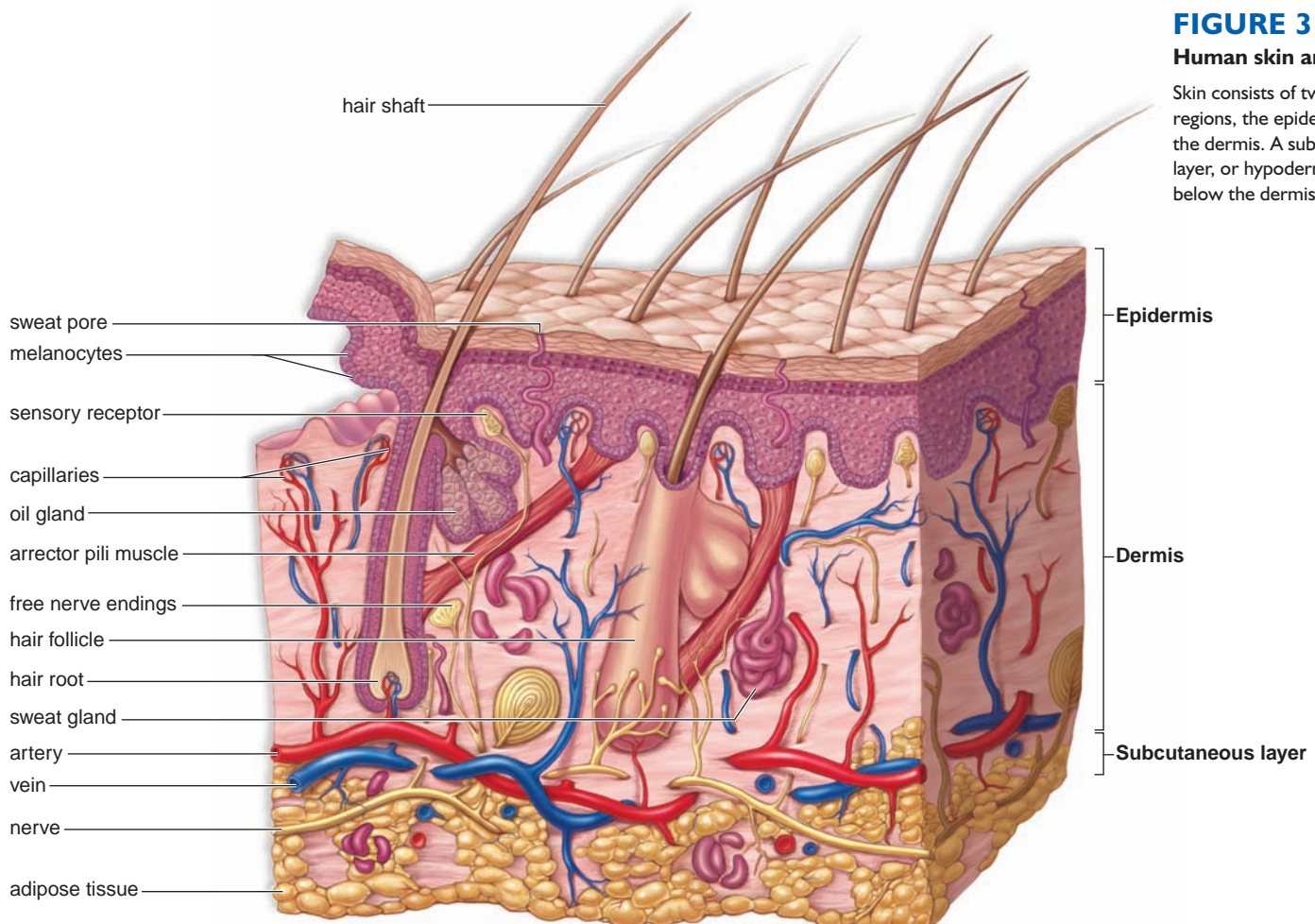


FIGURE 31.7
Human skin anatomy.

Skin consists of two regions, the epidermis and the dermis. A subcutaneous layer, or hypodermis, lies below the dermis.

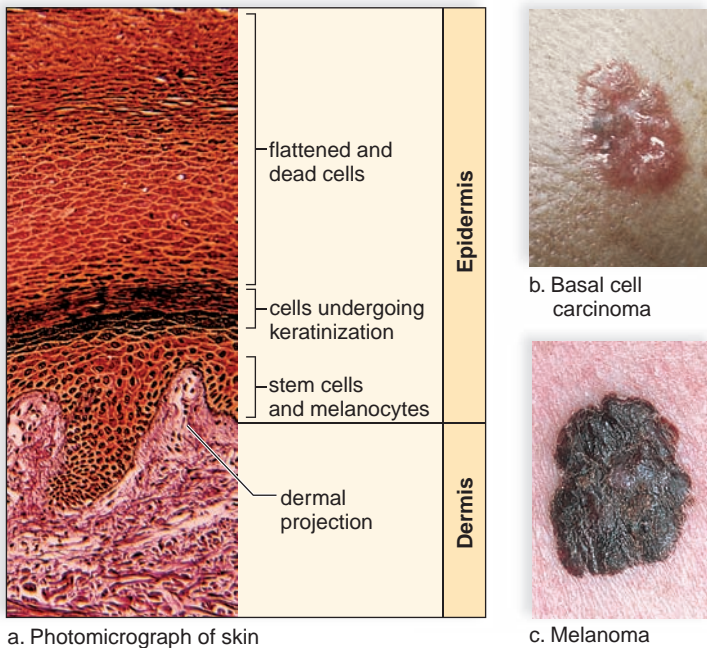


FIGURE 31.8 The epidermis.

a. Epidermal ridges following dermal projections are clearly visible. Stem cells and melanocytes are in this region. **b.** Basal cell carcinoma derived from stem cells and melanoma **(c)** derived from melanocytes are types of skin cancer. Remember the A, B, C, D rule when examining a questionable freckle or mole: A—asymmetrical shape; B—border irregularity; C—color change; D—diameter or sudden change in size.

in spiral and concentric patterns, forms fingerprints and footprints.

Specialized cells in the epidermis called **melanocytes** produce melanin, the pigment responsible for skin color. The amount of melanin varies throughout the body. It is concentrated in freckles and moles. Tanning occurs after a light-skinned person is exposed to sunlight because melanocytes produce more melanin, which is distributed to epidermal cells before they rise to the surface. While we tend to associate a tan with health, actually it signifies that the body is trying to protect itself from the dangerous rays of the sun. Some ultraviolet radiation does serve a purpose, however. As mentioned, certain cells in the epidermis convert a steroid related to cholesterol into **vitamin D** only with the aid of ultraviolet radiation. Vitamin D is required for proper bone growth.

Too much ultraviolet radiation is dangerous and can lead to skin cancer. Basal cell carcinoma (Fig. 31.8b) derived from stem cells gone awry is the more common type of skin cancer and the most curable. Melanoma (Fig. 31.8c), the type of skin cancer derived from melanocytes, is extremely serious.

The Dermis

The **dermis** [Gk. *derma*, skin] is a region of dense fibrous connective tissue beneath the epidermis. The dermis contains collagen and elastic fibers. The collagen fibers are flexible but offer great resistance to overstretching; they prevent the skin from being torn. Stretching of the dermis, as occurs in obesity and pregnancy, can produce stretch marks, or striae. The elastic fibers maintain normal skin tension but also stretch to allow movement of underlying muscles and joints. (The number of collagen

and elastic fibers decreases with age and with exposure to the sun, causing the skin to become less supple and more prone to wrinkling.) The dermis also contains blood vessels that nourish the skin. When blood rushes into these vessels, a person blushes, and when blood is minimal in them, a person turns “blue.”

Sensory receptors are specialized nerve endings in the dermis that respond to external stimuli. There are sensory receptors for touch, pressure, pain, and temperature. The fingertips contain the most touch receptors, and these add to our ability to use our fingers for delicate tasks.

The Subcutaneous Layer

Technically speaking, the subcutaneous layer (the hypodermis) beneath the dermis is not a part of skin. It is composed of loose connective tissue and adipose tissue, which stores fat. Fat is a stored source of energy in the body. Adipose tissue helps to thermally insulate the body from either gaining heat from the outside or losing heat from the inside. A well-developed subcutaneous layer gives the body a rounded appearance and provides protective padding against external assaults. Excessive development of the subcutaneous layer accompanies obesity.

Accessory Organs of the Skin

Nails, hair, and glands are structures of epidermal origin, even though some parts of hair and glands are largely found in the dermis.

Nails are a protective covering of the distal part of fingers and toes, collectively called digits. Nails grow from special epithelial cells at the base of the nail in the portion called the nail root. The cuticle is a fold of skin that hides the nail root. The whitish color of the half-moon-shaped base, or lunula, results from the thick layer of cells in this area. The cells of a nail become keratinized as they grow out over the nail bed. The appearance of nails can be medically important. For example, in clubbing of the nails, the nails turn down instead of lying flat. This condition is associated with a deficiency of oxygen in the blood.

Hair follicles begin in the dermis and continue through the epidermis, where the hair shaft extends beyond the skin. Contraction of the arrector pili muscles attached to hair follicles causes the hairs to “stand on end” and goose bumps to develop. Epidermal cells form the root of hair, and their division causes a hair to grow. The cells become keratinized and die as they are pushed farther from the root.

Hair, except for the root, is formed of dead, hardened epidermal cells; the root is alive and resides at the base of a follicle in the dermis. An average person has about 100,000 hair follicles on the scalp. The number of follicles varies from one body region to another. The texture of hair is dependent on the shape of the shaft. In wavy hair, the shaft is oval, and in straight hair, the shaft is round. Hair color is determined by pigmentation. Dark hair is due to melanin concentration, and blond hair has scanty amounts of melanin. Red hair is caused by an iron-containing pigment called trichosiderin. Gray or white hair results from a lack of pigment. A hair on the scalp grows about 1 mm every three days.

Each hair follicle has one or more **oil glands**, also called sebaceous glands, which secrete sebum, an oily substance that lubricates the hair within the follicle and the skin itself. If the

sebaceous glands fail to discharge the secretions collect and form “whiteheads” or “blackheads.” The color of blackheads is due to oxidized sebum. Acne is an inflammation of the sebaceous glands that most often occurs during adolescence due to hormonal changes.

Sweat glands, also called sudoriferous glands, are quite numerous and are present in all regions of skin. A sweat gland is a tubule that begins in the dermis and either opens into a hair follicle, or more often opens onto the surface of the skin. Sweat glands located all over the body play a role in modifying body temperature. When the body temperature starts to rise, sweat glands become active. Sweat absorbs body heat as it evaporates. Once the body temperature lowers, sweat glands are no longer active. Other sweat glands occur in the groin and axillary regions and are associated with distinct scents.

Organ Systems

In most animals, individual organs function as part of an organ system, the next higher level of animal organization. These same systems are found in all vertebrate animals. The organ systems of vertebrates carry out the life processes that are common to all animals, and indeed to all organisms.

Life Processes	Human Systems
Coordinate body activities	Nervous system Endocrine system
Acquire materials and energy (food)	Skeletal system Muscular system Digestive system
Maintain body shape	Skeletal system Muscular system
Exchange gases	Respiratory system
Transport materials	Cardiovascular system
Excrete wastes	Urinary system
Protect the body from disease	Lymphatic system Immune system
Produce offspring	Reproductive system

Body Cavities

Each organ system has a particular distribution within the human body. There are two main body cavities: the smaller dorsal cavity and the larger ventral cavity (Fig. 31.9a). The brain and the spinal cord are in the dorsal cavity.

During development, the ventral cavity develops from the coelom. In humans and other mammals, the coelom is divided by a muscular diaphragm that assists breathing. The heart (a pump for the cardiovascular system) and the lungs are located in the upper (thoracic or chest) cavity (Fig. 31.9b). The major portions of the digestive system, including the accessory organs (e.g., the liver and pancreas) are located in the abdominal cavity, as are the kidneys of the urinary system. The urinary bladder, the female reproductive organs, or certain of the male reproductive organs, are located in the pelvic cavity.

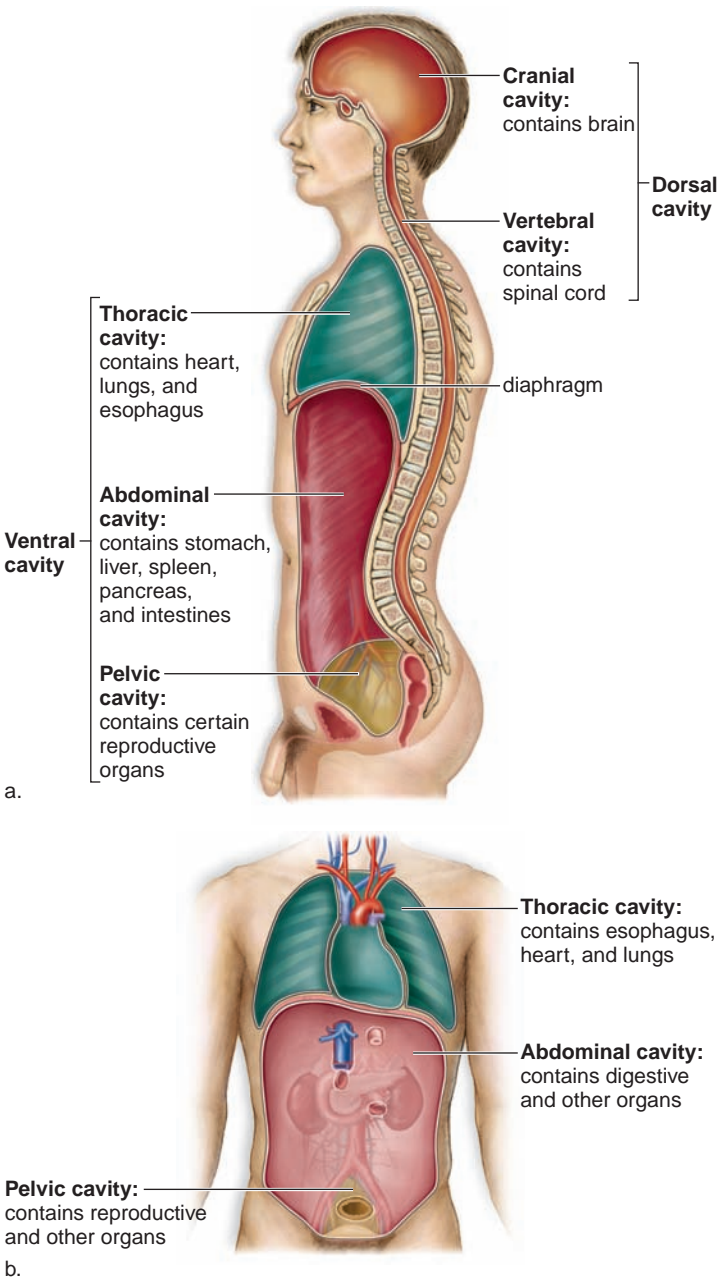


FIGURE 31.9 Mammalian body cavities.

a. Side view. The dorsal (toward the back) cavity contains the cranial cavity and the vertebral canal. The brain is in the cranial cavity, and the spinal cord is in the vertebral canal. The well-developed ventral (toward the front) cavity is divided by the diaphragm into the thoracic cavity and the abdominopelvic cavity (abdominal cavity and pelvic cavity). The heart and lungs are in the thoracic cavity, and most other internal organs are in the abdominal cavity. **b.** Frontal view of the thoracic cavity.

Check Your Progress

31.2

1. Compare the structure and function of the epidermis and dermis of the skin.
2. Contrast the location and function of sweat glands and oil glands.
3. What are the two major body cavities? What two cavities are in each of these?

31.3 Homeostasis

All type systems of the body contribute to **homeostasis**. The digestive system takes in and digests food, providing nutrient molecules that enter the blood and replace the nutrients that are constantly being used by the body cells. The respiratory system adds oxygen to the blood and removes carbon dioxide. The amount of oxygen taken in and carbon dioxide given off can be increased to meet body needs. The liver and the kidneys contribute greatly to homeostasis. For

example, immediately after glucose enters the blood, it can be removed by the liver and stored as glycogen. Later, glycogen is broken down to replace the glucose used by the body cells; in this way, the glucose composition of the blood remains constant. The hormone insulin, secreted by the pancreas, regulates glycogen storage. The kidneys are also under hormonal control as they excrete wastes and salts, substances that can affect the pH level of the blood.

Although homeostasis is, to a degree, controlled by hormones, it is ultimately controlled by the nervous system. In humans, the brain contains regulatory centers that control the function of other organs, maintaining homeostasis. These regulatory centers are often a part of a negative feedback system.

Negative Feedback

Negative feedback is the primary homeostatic mechanism that keeps a variable, such as the blood glucose level, close to a particular value, or set point. A homeostatic mechanism has at least two components: a sensor and a control center. The sensor detects a change in the internal environment; the control center then brings about an effect to bring conditions back to normal again. Now, the sensor is no longer activated. In other words, a negative feedback mechanism is present when the output of the system dampens the original stimulus. For example, when blood pressure rises, sensory receptors signal a control center in the brain. The center stops sending nerve impulses to the arterial walls, and they relax. Once the blood pressure drops, signals no longer go to the control center. A home heating system is often used to illustrate how a more complicated negative feedback mechanism works (Fig. 31.10). You set the thermostat at, say, 68°F. This is the *set point*. The thermostat contains a thermometer, a sensor that detects when the room temperature is above or below the set point. The thermostat also contains a control center; it turns the furnace off when the room is warm and turns it on when the room is cool. When the furnace is off, the room cools a bit, and when the furnace is on, the room warms a bit. In other words, typical of negative feedback mechanisms, there is a fluctuation above and below normal.

Human Example: Regulation of Body Temperature

The sensor and control center for body temperature is located in a part of the brain called the hypothalamus. Notice that a negative feedback mechanism prevents change in the same direction; body temperature does not get warmer and warmer because warmth brings about a change toward a lower body temperature. Also, body temperature does not get colder and colder because a body temperature below normal brings about a change toward a warmer body temperature.

Above Normal Temperature. When the body temperature is above normal, the control center directs the blood vessels of the skin to dilate. This allows more blood to flow near the surface of the body, where heat can be lost to the environment. In addition, the nervous system activates the sweat glands, and the evaporation of sweat helps lower body temperature. Gradually, body temperature decreases to 98.6°F.

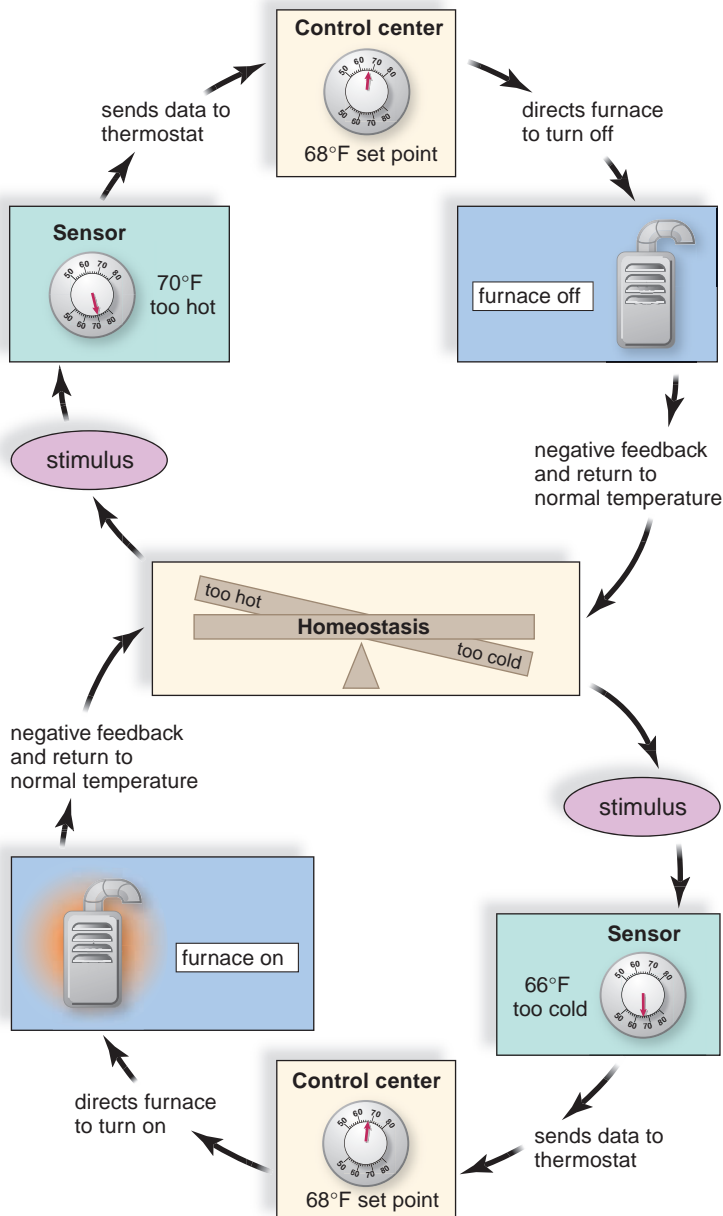


FIGURE 31.10 Regulation of room temperature.

This diagram shows how room temperature is returned to normal when the room becomes too hot (*above*) or too cold (*below*). The thermostat contains both the sensor and the control center. *Above*: The sensor detects that the room is too hot, and the control center turns the furnace off. The stimulus is no longer present when the temperature returns to normal. *Below*: The sensor detects that the room is too cold, and the control center turns the furnace on. The stimulus is no longer present when the temperature returns to normal.

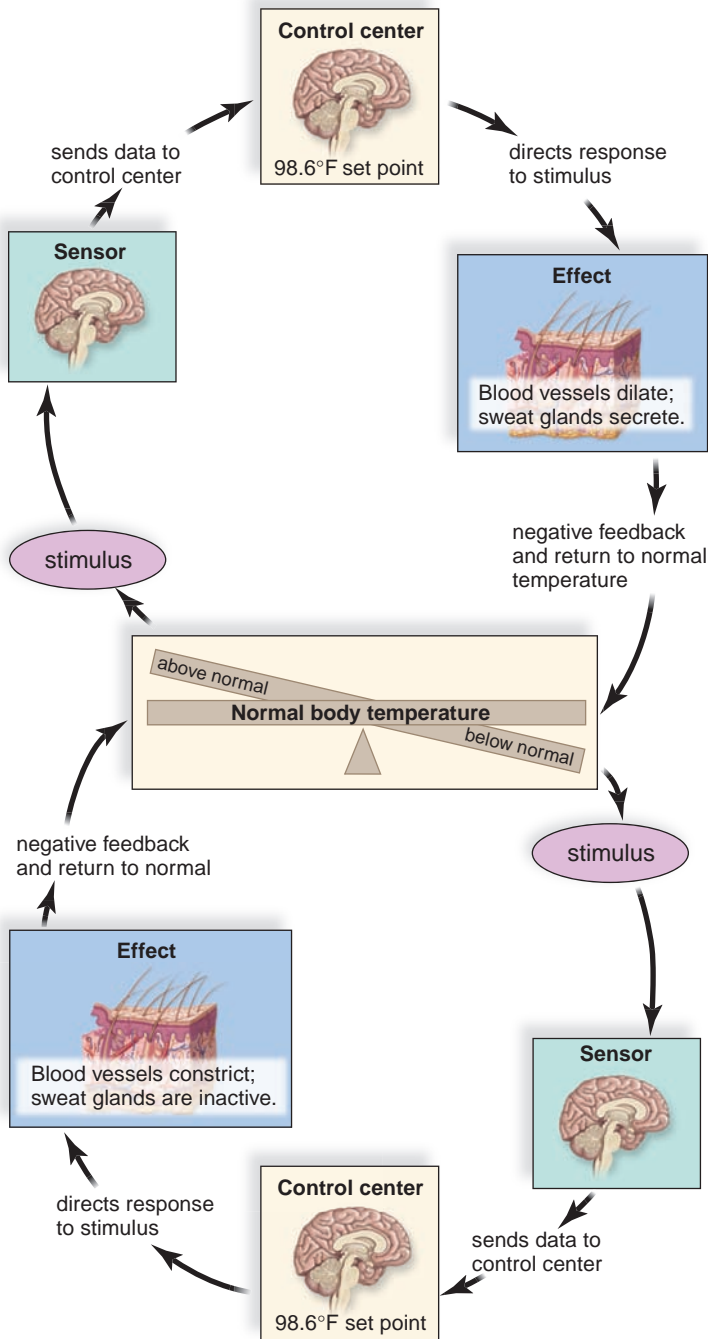


FIGURE 31.11 Regulation of body temperature.

Above: When body temperature rises above normal, the hypothalamus senses the change and causes blood vessels to dilate and sweat glands to secrete so that body temperature returns to normal. **Below:** When body temperature falls below normal, the hypothalamus senses the change and causes blood vessels to constrict. In addition, shivering may occur to bring body temperature back to normal. In this way, the original stimulus was removed.

Below Normal Temperature. When the body temperature falls below normal, the control center directs (via nerve impulses) the blood vessels of the skin to constrict (Fig. 31.11). This conserves heat. If body temperature falls even lower, the control center sends nerve impulses to the skeletal muscles, and shivering occurs. Shivering generates heat, and gradually body temperature rises to 98.6°C.

2. Signals cause pituitary gland to release the hormone oxytocin. As the level of oxytocin increases, so do uterine contractions until birth occurs.

1. Due to uterine contractions, baby's head presses on cervix, and signals are sent to brain.

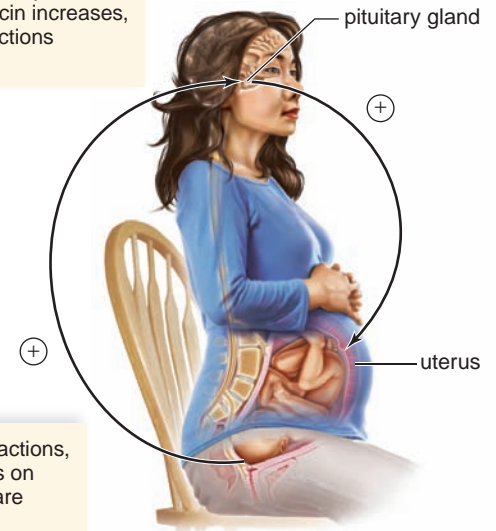


FIGURE 31.12 Positive feedback.

This diagram shows how positive feedback works. The signal causes a change in the same direction until there is a definite cutoff point, such as birth of a child.

When the temperature rises to normal, the control center is inactivated.

Positive Feedback

Positive feedback is a mechanism that brings about an ever greater change in the same direction (Fig. 31.12). When a woman is giving birth, the head of the baby begins to press against the cervix (opening to the birth canal) stimulating sensory receptors there. When nerve impulses reach the brain, the brain causes the pituitary gland to secrete the hormone oxytocin. Oxytocin travels in the blood and causes the uterus to contract. As labor continues, the cervix is ever more stimulated and uterine contractions become ever stronger until birth occurs.

A positive feedback mechanism can be harmful, as when a fever causes metabolic changes that push the fever still higher. Death occurs at a body temperature of 113°F because cellular proteins denature at this temperature and metabolism stops. Still, positive feedback loops such as those involved in childbirth, blood clotting, and the stomach's digestion of protein assist the body in completing a process that has a definite cutoff point.

Check Your Progress

31.3

1. What is homeostasis, and why is it important to body function?
2. How do the circulatory, respiratory, and urinary systems contribute to homeostasis?
3. How does negative feedback work?

Connecting the Concepts

In this chapter, we have concentrated on humans, but homeostasis occurs even in the simplest of animals. Homeostasis in unicellular organisms and thin invertebrate animals occurs only at the cellular level, and each cell must carry out its own exchanges with the external environment to maintain a relative constancy of cytoplasm.

In complex animals, such as humans, there are localized boundaries where materials are exchanged with the external environment. Gas exchange usually occurs within lungs, food is digested within a digestive tract, and kidneys collect and excrete metabolic wastes. Exchange boundaries are an effective way to regulate the internal environment if there is a transport system to carry materials from one body part to another. Circulation

in complex animals carries out this function (see p. 610).

Regulating mechanisms occur at all levels of organization. At the cellular level, the actions of enzymes are often controlled by feedback mechanisms. However, in animals with organ systems, the nervous and endocrine systems regulate the actions of organs. In addition, an animal's nervous system gathers and processes information about the external environment. Sensory receptors act as specialized boundaries through which external stimuli are received and converted into a form that can be processed by the nervous system. The information received and processed by the nervous system may then influence the organism's behavior in a way that contributes to homeostasis.

Homeostasis is so critical that without it the organism dies. Let us take a familiar example in humans. After eating, when the hormone insulin is present, glucose is removed from blood and stored in the liver as glycogen. In between eating, glycogen breakdown keeps the blood glucose level at just about 0.1%. When a person has type I diabetes, the pancreas fails to secrete insulin, and glucose is not stored in the liver. Worse yet, cells are unable to take up glucose even after eating, when there is a plentiful supply in the blood. Lacking glucose for cellular respiration, cells begin to break down fats with the result that acids are released in cells and enter the bloodstream. Now the person has acidosis—a low pH, which may hinder enzymatic activity to the point that cellular metabolism falters and the person dies.

summary

31.1 Types of Tissues

During development, the zygote divides to produce cells that go on to become tissues composed of similar cells specialized for a particular function. Tissues make up organs, and organ systems make up the organism. This sequence describes the levels of organization within an organism.

Tissues are categorized into four groups. Epithelial tissue, which covers the body and lines cavities, is of three types: squamous, cuboidal, and columnar epithelium. Each type can be simple or stratified; it can also be glandular or have modifications, such as cilia. Epithelial tissue protects, absorbs, secretes, and excretes.

Connective tissue has a matrix between cells. Loose fibrous connective tissue and dense fibrous connective tissue contain fibroblasts and fibers. Loose fibrous connective tissue has both collagen and elastic fibers. Dense fibrous connective tissue, like that of tendons and ligaments, contains closely packed collagen fibers. In adipose tissue, the cells enlarge and store fat.

Both cartilage and bone have cells within lacunae, but the matrix for cartilage is more flexible than that for bone, which contains calcium salts. In bone, the lacunae lie in concentric circles within an osteon (or Haversian system) about a central canal. Blood is a connective tissue in which the matrix is a liquid called plasma.

Muscular (contractile) tissue can be smooth or striated (skeletal and cardiac), and involuntary (smooth and cardiac) or voluntary (skeletal). In humans, skeletal muscle is attached to bone, smooth muscle is in the wall of internal organs, and cardiac muscle makes up the heart.

Nervous tissue has one main type of conducting cell, the neuron, and several types of neuroglia. The majority of neurons have dendrites, a cell body, and an axon. The brain and spinal cord contain complete neurons, while nerves contain only axons. Axons are specialized to conduct nerve impulses.

31.2 Organs and Organ Systems

Organs contain various tissues. Skin is an organ that has two regions. Epidermis (stratified squamous epithelium) overlies the dermis

(fibrous connective tissue containing sensory receptors, hair follicles, blood vessels, and nerves). A subcutaneous layer is composed of loose connective tissue.

Organ systems contain several organs. The organ systems of humans have specific functions and carry out the life processes that are common to all organisms.

The human body has two main cavities. The dorsal cavity contains the brain and spinal cord. The ventral cavity is divided into the thoracic cavity (heart and lungs) and the abdominal cavity (most other internal organs).

31.3 Homeostasis

Homeostasis is the dynamic equilibrium of the internal environment (blood and tissue fluid). All organ systems contribute to homeostasis, but special contributions are made by the liver, which keeps the blood glucose constant, and the kidneys, which regulate the pH. The nervous and hormonal systems regulate the other body systems. Both of these are controlled by negative feedback mechanisms, which result in slight fluctuations above and below desired levels. Body temperature is regulated by a center in the hypothalamus.

understanding the terms

adipose tissue	580	elastic cartilage	580
basement membrane	578	elastic fiber	579
blood	581	endocrine gland	579
bone	580	epidermis	585
cardiac muscle	582	epithelial tissue	578
cartilage	580	exocrine gland	579
collagen fiber	579	fibroblast	580
columnar epithelium	578	fibrocartilage	580
compact bone	580	gland	579
connective tissue	579	hair follicle	586
cuboidal epithelium	578	homeostasis	588
dense fibrous connective tissue	580	hyaline cartilage	580
dermis	586	intercalated disk	582
		lacuna	580

ligament 580	platelet 581
loose fibrous connective tissue 580	positive feedback 589
lymph 581	red blood cell 581
melanocyte 586	reticular fiber 579
muscular (contractile) tissue 582	skeletal muscle 582
nail 586	skin 585
negative feedback 588	smooth (visceral) muscle 582
nerve 583	spongy bone 581
nervous tissue 582	squamous epithelium 578
neuroglia 583	striated 582
neuron 582	subcutaneous layer 585
oil gland 586	sweat gland 587
organ 585	tendon 580
organ system 585	tissue 578
pathogen 581	tissue fluid 581
	vitamin D 586
	white blood cell 581

Match the terms to these definitions:

- _____ Fibrous connective tissue that joins bone to bone at a joint.
- _____ Outer region of the skin composed of stratified squamous epithelium.
- _____ Having striations, such as in cardiac and skeletal muscle.
- _____ Self-regulatory state in which imbalances result in a fluctuation above and below a mean.
- _____ Porous bone found at the ends of long bones where blood cells are formed.

reviewing this chapter

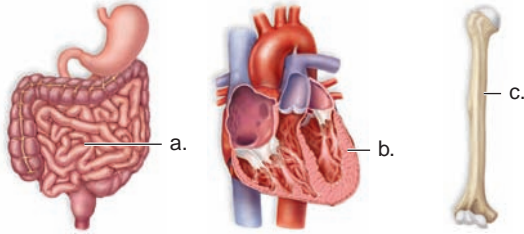
- Name the four major types of tissues. 578
- Describe the structure and the functions of three types of simple epithelial tissue. 578–79
- Describe the structure and the functions of six major types of connective tissue. 579–81
- Describe the structure and the functions of three types of muscular tissue. 582
- Nervous tissue contains what types of cells? 582–83
- Describe the structure of skin, and state at least two functions of this organ. 585–87
- In general terms, describe the locations of the human organ systems. 587
- Tell how the various systems of the body contribute to homeostasis. 588–89
- What is the function of sensors, the regulatory center, and effectors in a negative feedback mechanism? Why is it called negative feedback? 588–89

testing yourself

Choose the best answer for each question.

- Which of these pairs is incorrectly matched?
 - tissues—like cells
 - epithelial tissue—protection and absorption
 - muscular tissue—contraction and conduction
 - connective tissue—binding and support
 - nervous tissue—conduction and message sending
- Which of these is not a type of epithelial tissue?
 - simple cuboidal and stratified columnar
 - bone and cartilage
 - stratified squamous and simple squamous
 - pseudostratified and ciliated
 - All of these are epithelial tissue.
- Which tissue is more apt to line a lumen?
 - epithelial tissue
 - connective tissue
 - nervous tissue
 - muscular tissue
 - only smooth muscle
- Tendons and ligaments
 - are connective tissue.
 - are associated with the bones.
 - are found in vertebrates.
 - contain collagen.
 - All of these are correct.
- Which tissue has cells in lacunae?
 - epithelial tissue
 - cartilage
 - bone
 - smooth muscle
 - Both b and c are correct.
- Cardiac muscle is
 - striated.
 - involuntary.
 - smooth.
 - many fibers fused together.
 - Both a and b are correct.
- Which of these components of blood fights infection?
 - red blood cells
 - white blood cells
 - platelets
 - hydrogen ions
 - All of these are correct.
- Which of these body systems contribute to homeostasis?
 - digestive and urinary systems
 - respiratory and nervous systems
 - nervous and endocrine systems
 - immune and cardiovascular systems
 - All of these are correct.
- In a negative feedback mechanism,
 - the output cancels the input.
 - there is a fluctuation above and below the average.
 - there is self-regulation.
 - a regulatory center communicates with other body parts.
 - All of these are correct.
- When a human being is cold, the superficial blood vessels
 - dilate, and the sweat glands are inactive.
 - dilate, and the sweat glands are active.
 - constrict, and the sweat glands are inactive.
 - constrict, and the sweat glands are active.
 - contract so that shivering occurs.

11. Give the name, the location, and the function for each of these tissues in the human body.
- type of epithelial tissue _____
 - type of muscular tissue _____
 - type of connective tissue _____



12. Which of these is a function of skin?
- temperature regulation
 - manufacture of vitamin D
 - collection of sensory input
 - protection from invading pathogens
 - All of these are correct.
13. Which of these is an example of negative feedback?
- Air conditioning goes off when room temperature lowers.
 - Insulin decreases blood sugar levels after eating a meal.
 - Heart rate increases when blood pressure drops.
 - All of these are examples of negative feedback.
14. Which of these correctly describes a layer of the skin?
- The epidermis is simple squamous epithelium in which hair follicles develop and blood vessels expand when we are hot.
 - The subcutaneous layer lies between the epidermis and the dermis. It contains adipose tissue, which keeps us warm.
 - The dermis is a region of connective tissue that contains sensory receptors, nerve endings, and blood vessels.
 - The skin has a special layer, still unnamed, in which there are all the accessory structures such as nails, hair, and various glands.
15. The _____ separates the thoracic cavity from the abdominal cavity.
- liver
 - pancreas
 - diaphragm
 - pleural membrane
 - intestines

In questions 16–18, match each type of muscle tissue to as many terms in the key as possible.

KEY:

- voluntary
 - involuntary
 - striated
 - nonstriated
 - spindle-shaped cells
 - branched cells
 - long, cylindrical cells
16. skeletal muscle
17. smooth muscle
18. cardiac muscle

In questions 19–22, match each description to the tissues in the key.

KEY:

- loose fibrous connective tissue
 - hyaline cartilage
 - adipose tissue
 - compact bone
19. occurs in nose and walls of respiratory passages
20. occurs only within bones of skeleton
21. occurs beneath most epithelial layers
22. occurs beneath skin, and around organs, including the heart

thinking scientifically

- Many cancers develop from epithelial tissue. These include lung, colon, and skin cancers. What are two attributes of this tissue type that make cancer more likely to develop?
- Bacterial or viral infections can cause a fever. Fevers occur when the hypothalamus changes its temperature set point. Signaling of the hypothalamus could be direct (from the infectious agent itself) or indirect (from the immune system). Which of these would enable the hypothalamus to respond to the greatest variety of infectious agents? Is there any disadvantage to such a signaling system?

bioethical issue

Organ Transplants

Despite widespread efforts to convince people of the need for organ donors, supply continues to lag far behind demand. One proposed strategy to bring supply and demand into better balance is to develop an “insurance” program for organs. In this program, participants would pay the “premium” by promising to donate their organs at death. They, in turn, would receive priority for transplants as their “benefit.” To avoid the problem of too many high-risk people applying for this type of insurance, a medical exam would be required so that only people with a normal risk of requiring a transplant would be accepted. Do you suppose this system would be an improvement over the current system in which organ donation is voluntary, with no tangible benefit? Can you think of any other strategy that would be more effective for increasing organ donations?

Biology website

The companion website for *Biology* provides a wealth of information organized and integrated by chapter. You will find practice tests, animations, videos, and much more that will complement your learning and understanding of general biology.

<http://www.mhhe.com/maderbiology10>

32

Circulation and Cardiovascular Systems

blood is a lifeline for human beings because it is the means by which needed supplies are transported to the cells of the body. Ordinarily, red blood cells, which transport oxygen, are far more numerous than the white blood cells, which defend the body from infection. But when leukemia is present, white blood cells proliferate wildly (see inset) and are so numerous that blood can't carry out its many functions, even though the heart is still functioning as it should.

We shall see in this chapter that many animals have a cardiovascular system in which the heart pumps blood about the body to all organs. The pumping of the heart is merely an auxiliary function because it is blood that transports gases and nutrients to and carries waste away from the cells of all organs, including those such as the lungs, digestive tract, and kidneys, which carry out exchanges between the external environment and blood. These exchanges keep the composition of blood relatively constant.

Normally, red blood cells far outnumber white blood cells. When a cancer called leukemia is present, the blood cell composition is reversed (see inset).

32.1 TRANSPORT IN INVERTEBRATES

- Some invertebrates do not have a circulatory system, others have an open system, and still others have a closed system. 594–95

32.2 TRANSPORT IN VERTEBRATES

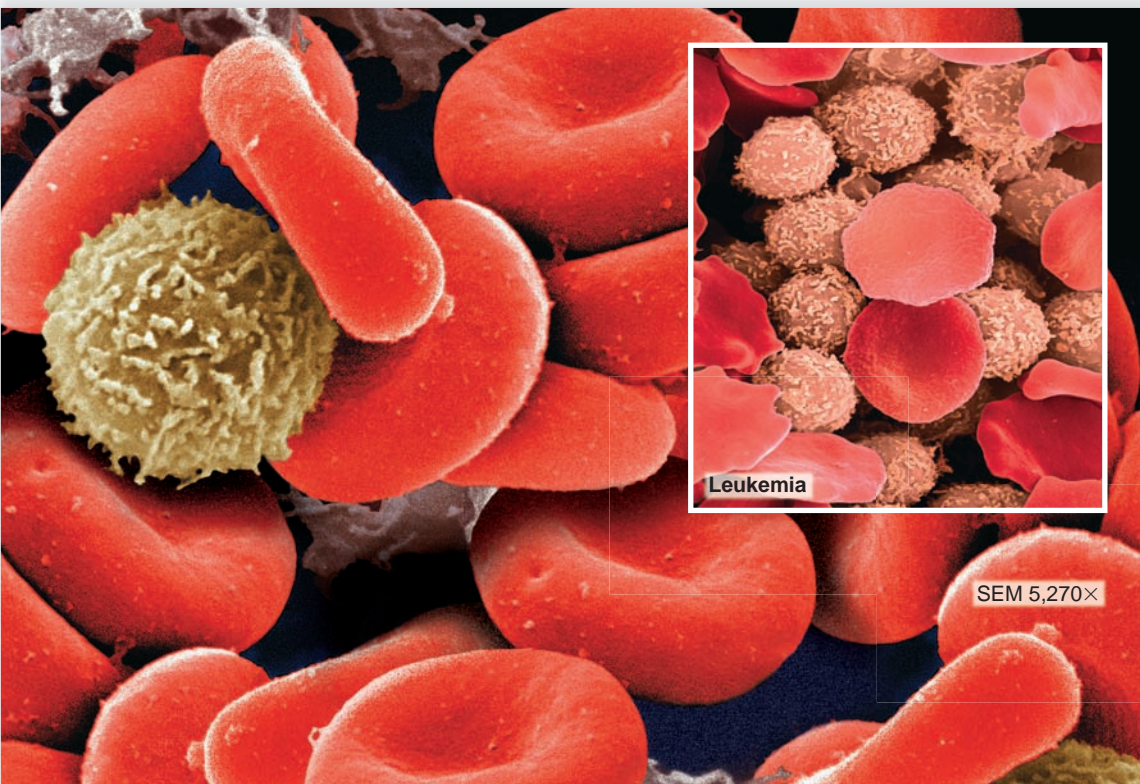
- Vertebrates have a closed circulatory system: Arteries take blood away from the heart to the capillaries, where exchange occurs, and veins take blood to the heart. 596–97
- Fishes have a single circulatory loop, whereas the other vertebrates have a double circulatory loop—from the heart to and from the lungs and also from the heart to and from the tissues. 597

32.3 TRANSPORT IN HUMANS

- In humans, the right side of the heart pumps blood to the lungs, and the left side pumps blood to the tissues. The conduction system of the heart keeps the heartbeat regular. 598–602
- Blood pressure causes blood to flow in the arteries and arterioles. Skeletal muscle contraction causes blood to flow in the veins and venules. In veins, valves prevent backflow of blood. 603
- Although the cardiovascular system is very efficient, it is still subject to degenerative disorders. 604–5

32.4 BLOOD, A TRANSPORT MEDIUM

- In humans, blood composed of cells and a fluid containing proteins and various other molecules and ions has many functions. 606–7
- Exchange of substances between blood and tissue fluid across capillary walls supplies cells with nutrients and removes wastes. 608
- Blood typing is necessary for safe blood transfusions. 609



32.1 Transport in Invertebrates

Some invertebrates such as sponges, cnidarians (e.g., hydras, sea anemones), and flatworms (e.g., planarians) do not have a circulatory system (Fig. 32.1*a, b*). Their thin body wall makes a circulatory system unnecessary. In hydras, cells are either part of an external layer, or they line the gastrovascular cavity. Each cell is exposed to water and can independently exchange gases and rid itself of wastes. The cells that line the gastrovascular cavity are specialized to complete the digestive process. They pass nutrient molecules to other cells by diffusion. In a planarian, a trilobed gastrovascular cavity branches throughout the small, flattened body. No cell is very far from one of the three digestive branches, so nutrient molecules can diffuse from cell to cell. Similarly, diffusion meets the respiratory and excretory needs of the cells.

Pseudocoelomate invertebrates, such as nematodes, use the coelomic fluid of their body cavity for transport purposes. The coelomate echinoderms also rely on movement of coelomic fluid within a body cavity as a circulatory system (Fig. 32.1*c*).

Invertebrates with a Circulatory System

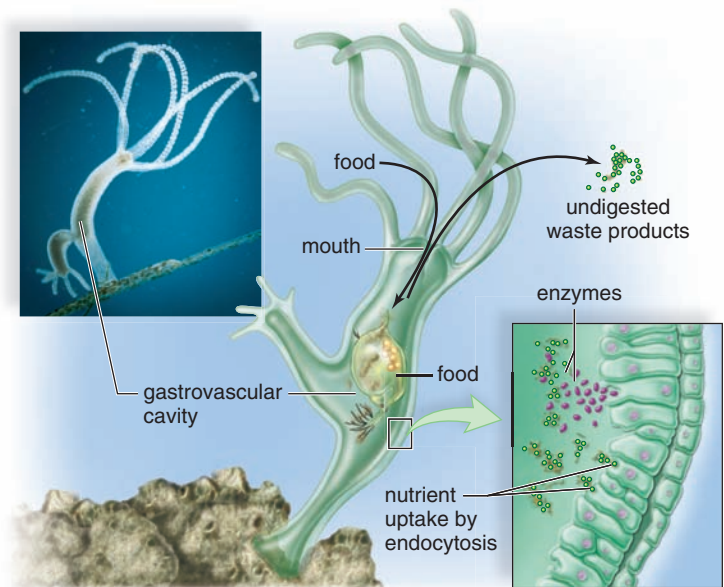
Most animals have a **circulatory system** that serves the needs of their cells. The circulatory system transports oxygen and nutrients, such as glucose and amino acids, to the cells. There it picks up wastes, which are later excreted from the body by the lungs or kidneys. There are two types of circulatory fluids: **blood**, which is always contained within blood vessels, and **hemolymph**, which flows into a body cavity called a hemocoel. Hemolymph is a mixture of blood and tissue fluid.

Open Circulatory System

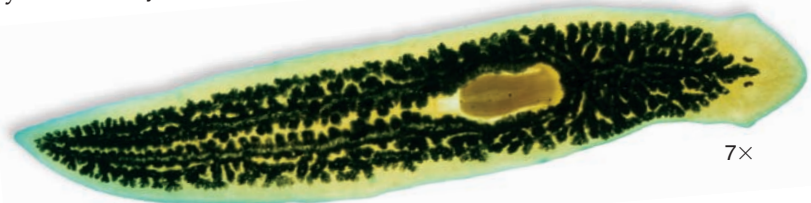
Hemolymph is seen in animals that have an **open circulatory system** that consists of blood vessels plus open spaces. For example, in most molluscs and arthropods, the heart pumps hemolymph via vessels into tissue spaces that are sometimes enlarged into saclike sinuses (Fig. 32.2*a*). Eventually, hemolymph drains back to the heart. In the grasshopper, an arthropod, the dorsal tubular heart pumps hemolymph into a dorsal aorta, which empties into the hemocoel. When the heart contracts, openings called ostia (sing., ostium) are closed; when the heart relaxes, the hemolymph is sucked back into the heart by way of the ostia. The hemolymph of a grasshopper is colorless because it does not contain hemoglobin or any other respiratory pigment. It carries nutrients but no oxygen. Oxygen is taken to cells, and carbon dioxide is removed from them by way of air tubes, called tracheae, which are found throughout the body. The tracheae provide efficient transport and delivery of respiratory gases, while at the same time restricting water loss.

Closed Circulatory System

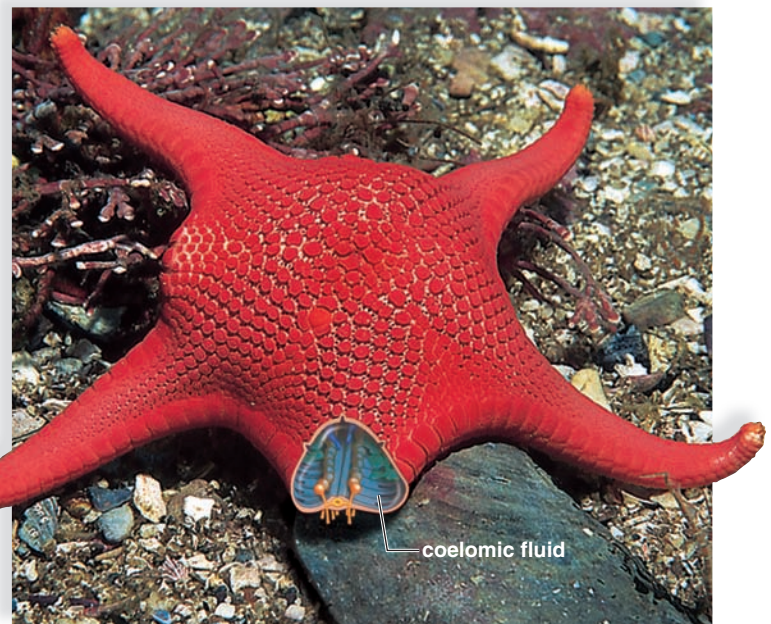
Blood is seen in animals that have a **closed circulatory system**, which consists of blood vessels only. For example, in annelids



a. Hydra



b. Flatworm



c. Red sea star, *Mediastar*

FIGURE 32.1 Aquatic organisms without a circulatory system.

a. In a hydra, a cnidarian, the gastrovascular cavity makes digested material available to the cells that line the cavity. These cells can also acquire oxygen from the watery contents of the cavity and discharge their wastes there. **b.** In a planarian, a flatworm, the gastrovascular cavity branches throughout the body, bringing nutrients to body cells. **c.** In a sea star, the coelomic fluid distributes oxygen and picks up wastes.

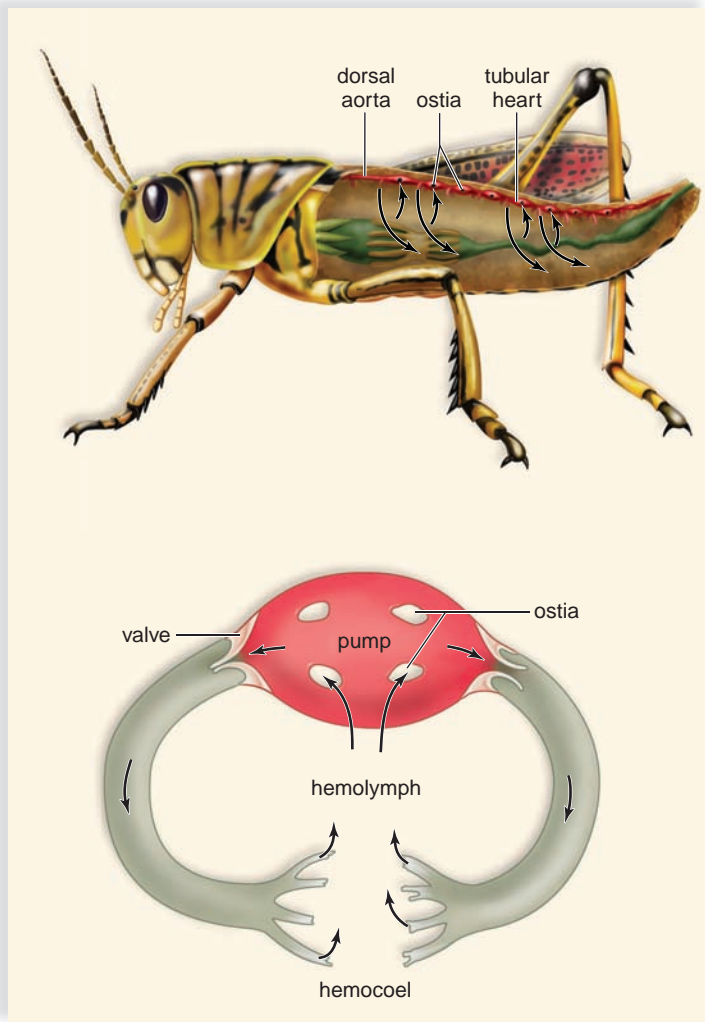
such as earthworms and in some molluscs such as squid and octopuses, blood, consisting of cells and plasma, (a liquid) is pumped by the heart into a system of blood vessels (Fig. 32.2*b*). Valves prevent the backward flow of blood. In the segmented earthworm, five pairs of anterior hearts (aortic arches) pump blood into the ventral blood vessel (an artery), which has a branch called a lateral vessel in every segment of the worm's body. Blood moves through these branches into capillaries, the thinnest of the blood vessels, where exchanges with tissue fluid take place. Both gas exchange and nutrient-for-waste exchange occur across the capillary walls. (No cell in the body of an animal with a closed circulatory system is far from a capillary.) In an earthworm, after leaving a capillary, blood moves from small veins into the dorsal blood vessel (a vein). This dorsal blood vessel returns blood to the heart for repumping.

The earthworm has red blood that contains the respiratory pigment hemoglobin. Hemoglobin is dissolved in the blood and is not contained within cells. The earthworm has no specialized organ, such as lungs, for gas exchange with the external environment. Gas exchange takes place across the body wall, which must always remain moist for this purpose.

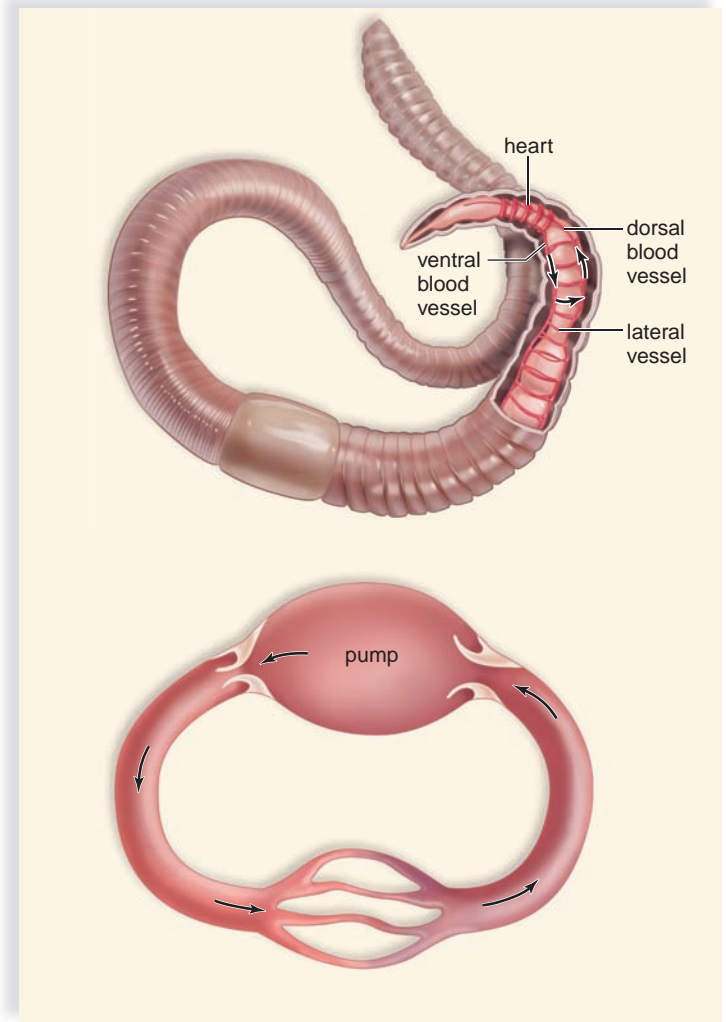
Check Your Progress

32.1

1. What is the primary function of a circulatory system?
2. Compare and contrast an open circulatory system of a grasshopper with a closed circulatory system of an earthworm. Why might it be advantageous for a grasshopper to use tracheae to transport oxygen to cells?



a. Open circulatory system



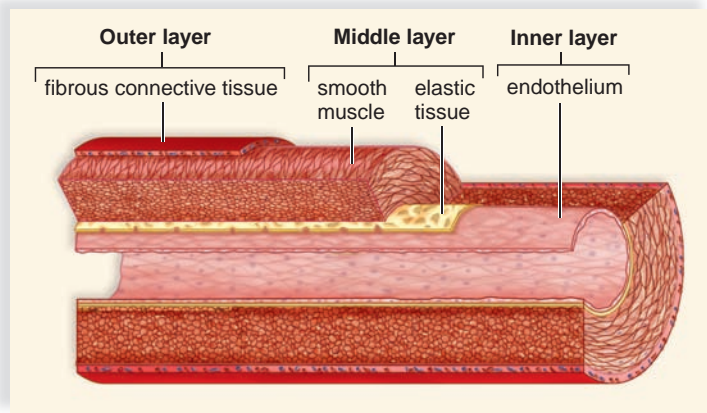
b. Closed circulatory system

FIGURE 32.2 Open versus closed circulatory systems.

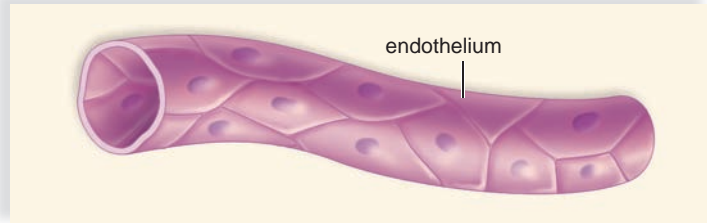
a. (above) The grasshopper, an arthropod, has an open circulatory system. (below) A hemocoel is a body cavity filled with hemolymph, which freely bathes the internal organs. The heart, a pump, sends hemolymph out through vessels and collects it through ostia (openings). This open system probably could not supply oxygen to wing muscles rapidly enough. These muscles receive oxygen directly from tracheae (air tubes). **b.** (above) The earthworm, an annelid, has a closed circulatory system. The dorsal and ventral blood vessels are joined by five pairs of anterior hearts, which pump blood. (below) The lateral vessels distribute blood to the rest of the worm.

32.2 Transport in Vertebrates

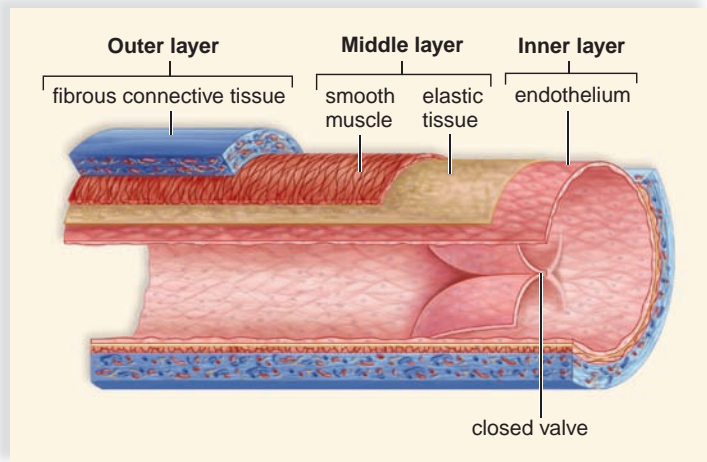
All vertebrate animals have a closed circulatory system, which is called a **cardiovascular system** [Gk. *kardia*, heart; L. *vascular*, vessel]. It consists of a strong, muscular heart in which the atria (sing., atrium) receive blood and the muscular ventricles pump blood through the blood vessels. There are three kinds of blood vessels: **arteries**, which carry blood away from the heart; **capillaries** [L. *capillus*, hair], which exchange materials with tissue fluid; and **veins** [L. *vena*, blood vessel], which return blood to the heart (Fig. 32.3).



a. Artery



b. Capillary



c. Vein

FIGURE 32.3 Transport in vertebrates.

a. Arteries have well-developed walls with a thick middle layer of elastic tissue and smooth muscle. b. Capillary walls are only one cell thick. c. Veins have flabby walls, particularly because the middle layer is not as thick as in arteries. Veins have valves, which ensure one-way flow of blood back to the heart.

An artery or a vein has three distinct layers (Fig. 32.3a, c). The outer layer consists of fibrous connective tissue, which is rich in elastic and collagen fibers. The middle layer is composed of smooth muscle and elastic tissue. The innermost layer, called the endothelium, is similar to squamous epithelium.

Arteries have thick walls, and those attached to the heart are resilient, meaning that they are able to expand and accommodate the sudden increase in blood volume that results after each heartbeat. **Arterioles** are small arteries whose diameter can be regulated by the nervous system. Arteriole constriction and dilation affect blood pressure in general. The greater the number of vessels dilated, the lower the blood pressure.

Arterioles branch into capillaries, which are extremely narrow, microscopic tubes with a wall composed of only one layer of cells. Capillary beds, which consist of many interconnected capillaries (Fig. 32.4), are so prevalent that in humans, all cells are within 60–80 μm of a capillary. But only about 5% of the capillary beds are open at the same time. After an animal has eaten, precapillary sphincters relax, and the capillary beds in the digestive tract are usually open. During muscular exercise, the capillary beds of the muscles are open. Capillaries, which are usually so narrow that red blood cells pass through in single file, allow exchange of nutrient and waste molecules across their thin walls.

Venules and veins collect blood from the capillary beds and take it to the heart. First, the venules drain the blood from the capillaries, and then they join to form a vein. The wall of a vein is much thinner than that of an artery, and this may be associated with a lower blood pressure in the veins. Valves within the veins point, or open, toward the heart, preventing a backflow of blood when they close (Fig. 32.3c).

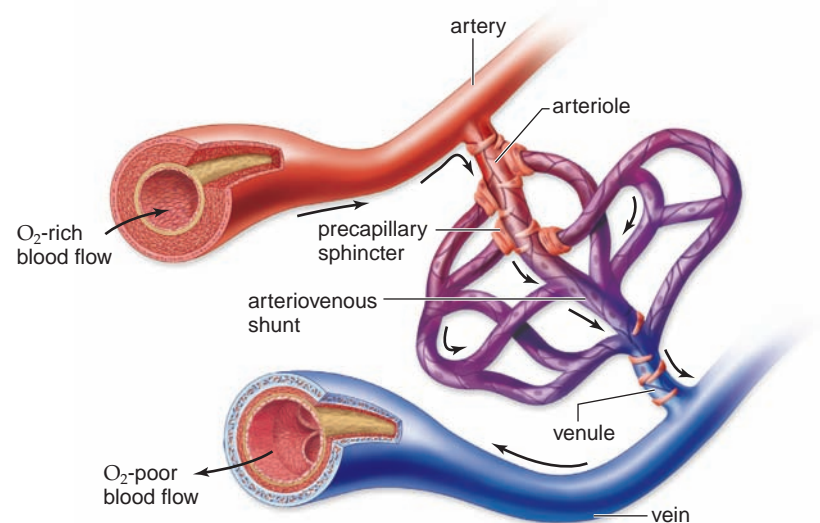


FIGURE 32.4 Anatomy of a capillary bed.

When a capillary bed is open, sphincter muscles are relaxed and blood flows through the capillaries. When precapillary sphincter muscles are contracted, the bed is closed and blood flows through an arteriovenous shunt that carries blood directly from an arteriole to a venule.

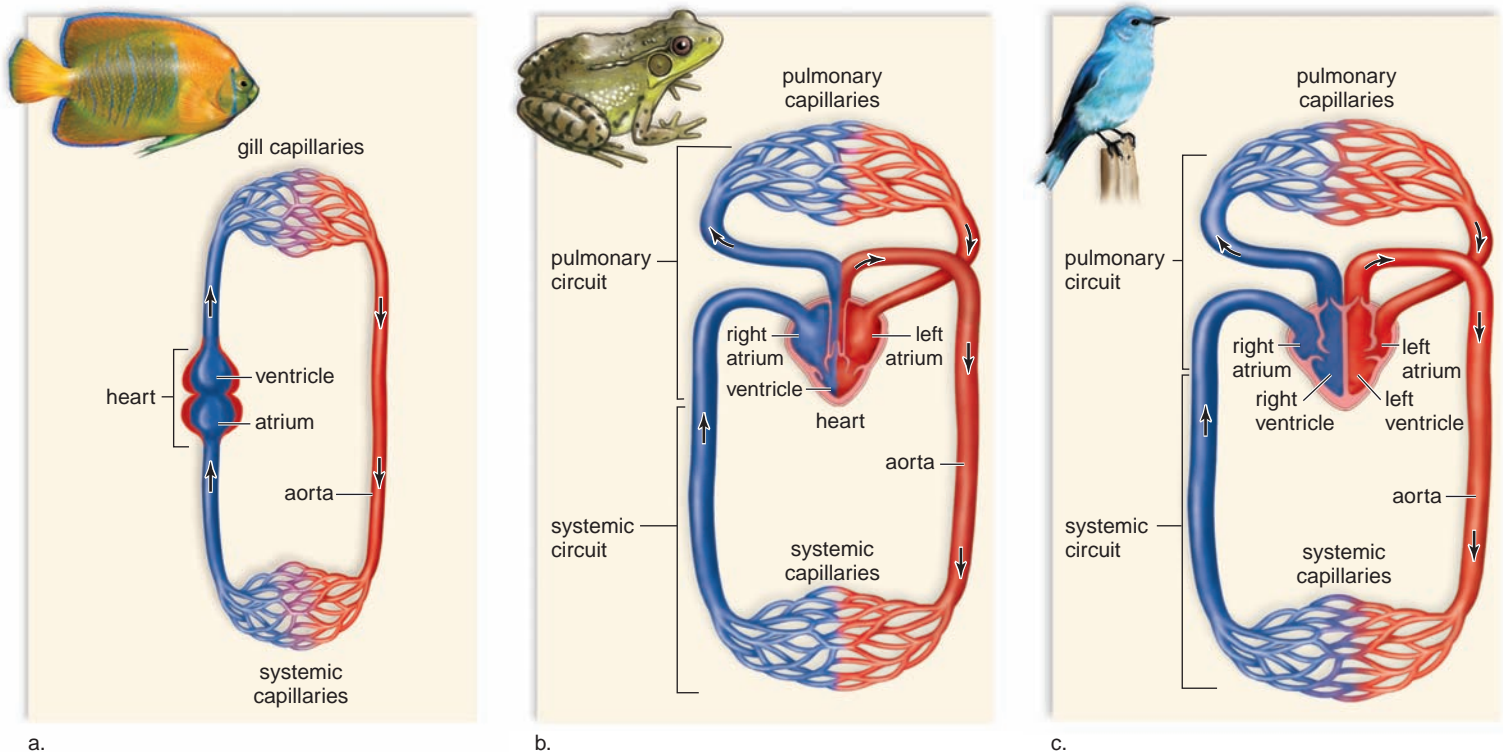


FIGURE 32.5 Comparison of circulatory circuits in vertebrates.

a. In fishes, the blood moves in a single circuit. Blood pressure created by the pumping of the heart is dissipated after the blood passes through the gill capillaries. This is a disadvantage of this one-circuit system. **b.** Amphibians and most reptiles have a two-circuit system in which the heart pumps blood to both the pulmonary capillaries in the lungs and the systemic capillaries in the body itself. Although there is a single ventricle, there is little mixing of O_2 -rich and O_2 -poor blood. **c.** The pulmonary and systemic circuits are completely separate in crocodiles (a reptile) and in birds and mammals, because the heart is divided by a septum into right and left halves. The right side pumps blood to the lungs, and the left side pumps blood to the body proper.

Comparison of Circulatory Pathways

Two different types of circulatory pathways are seen among vertebrate animals. In fishes, blood follows a one-circuit (single-loop) circulatory pathway through the body. The heart has a single atrium and a single ventricle (Fig. 32.5a). The pumping action of the ventricle sends blood under pressure to the gills, where gas exchange occurs. After passing through the gills, blood returns to the dorsal aorta, which distributes blood throughout the body. Veins return O_2 -poor blood to an enlarged chamber called the sinus venosus that leads to the atrium. The atrium pumps blood back to the ventricle. This single circulatory loop has an advantage in that the gill capillaries receive O_2 -poor blood and the capillaries of the body, called systemic capillaries, receive fully O_2 -rich blood. It is disadvantageous in that after leaving the gills the blood is under reduced pressure.

As a result of evolutionary changes, the other vertebrates have a two-circuit (double-loop) circulatory pathway. The heart pumps blood to the tissues, called a **systemic circuit**, and also pumps blood to the lungs, called a **pulmonary circuit** [*L. pulmonarius*, of the lungs]. This double pumping action is an adaptation to breathing air on land.

In amphibians, the heart has two atria and a single ventricle (Fig. 32.5b). The sinus venosus collects O_2 -poor blood returning via the veins and pumps it to the right atrium. O_2 -rich blood returning from the lungs passes to

the left atrium. Both of the atria empty into the single ventricle. O_2 -rich and O_2 -poor blood are kept somewhat separate because O_2 -poor blood is pumped out of the ventricle before O_2 -rich blood enters. The O_2 -rich blood is pumped out of the ventricle for distribution to the body. The O_2 -poor blood is delivered to the lungs and, perhaps, to the skin for recharging with oxygen.

In most reptiles, a septum partially divides the ventricle. In these animals, mixing of O_2 -rich and O_2 -poor blood is kept to a minimum. In crocodilians (alligators and crocodiles), the septum completely separates the ventricle. These reptiles have a four-chambered heart.

In all birds and mammals, as well as crocodilians, the heart is divided into left and right halves (Fig. 32.5c). The right ventricle pumps blood to the lungs, and the larger left ventricle pumps blood to the rest of the body. This arrangement provides adequate blood pressure for both the pulmonary and systemic circuits.

Check Your Progress

32.2

1. List and describe the functions of the three types of vessels in a cardiovascular system.
2. Contrast a one-circuit circulatory pathway with a two-circuit pathway.

32.3 Transport in Humans

In the cardiovascular system of humans, the pumping of the heart keeps blood moving primarily in the arteries. Skeletal muscle contraction pressing against veins is primarily responsible for the movement of blood in the veins.

The Human Heart

The **heart** is a cone-shaped, muscular organ about the size of a fist (Fig. 32.6). It is located between the lungs directly behind the sternum (breastbone) and is tilted so that the apex (the pointed end) is oriented to the left. The major portion of the heart, called the myocardium, consists largely of cardiac muscle tissue. Myocardium is serviced by the coronary artery and cardiac vein and not by the blood it pumps. The muscle fibers of the myocardium are branched and tightly joined to one another at intercalated disks. The heart lies within the pericardium, a thick, membranous sac that secretes a small quantity of lubricating liquid. The inner surface of the heart is lined with endocardium, a membrane composed of connective tissue and endothelial tissue. The lining is continuous with the endothelium lining of the blood vessels.

Internally, a wall called the **septum** separates the heart into a right side and a left side (Fig. 32.7). The heart has four chambers. The two upper, thin-walled atria (sing., **atrium**) have wrinkled, protruding appendages called auricles. The two lower chambers are the thick-walled **ventricles**, which pump the blood.

The heart also has four valves, which direct the flow of blood and prevent its backward movement. The two valves that lie between the atria and the ventricles are called the **atrioventricular valves**. These valves are supported by strong fibrous strings called chordae tendineae. The chordae, which are attached to muscular projections of the ventricular walls, support the valves and prevent them from inverting when the heart contracts. The atrioventricular valve on the right side is called the tricuspid valve because it has three flaps, or cusps. The valve on the left side is called the bicuspid (or the mitral) because it has two flaps. The remaining two valves are the **semilunar valves**, whose flaps resemble half-moons, between the ventricles and their attached vessels. The pulmonary semilunar valve lies between the right ventricle and the pulmonary trunk. The aortic semilunar valve lies between the left ventricle and the aorta.

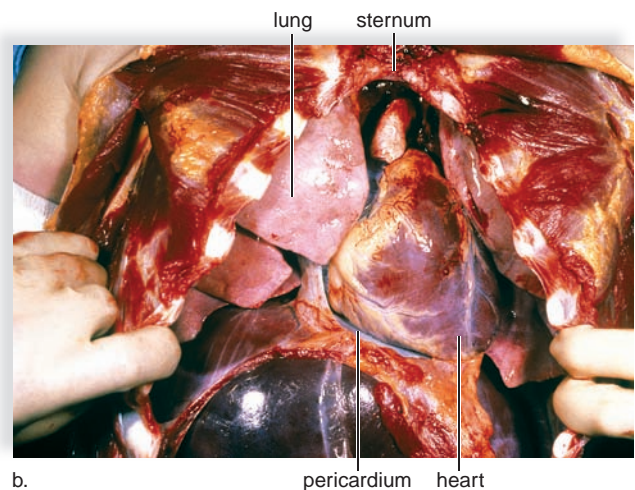
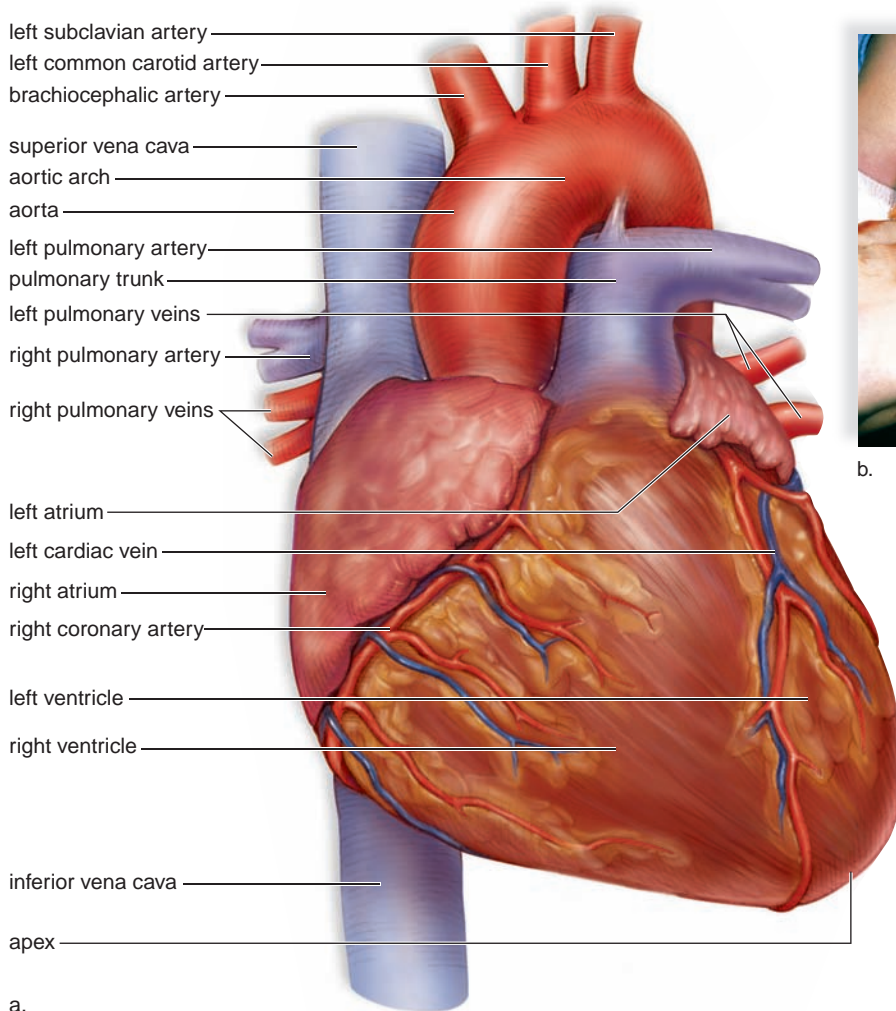


FIGURE 32.6 External heart anatomy.

a. The venae cavae and the pulmonary trunk are attached to the right side of the heart. The aorta and the pulmonary veins are attached to the left side of the heart. Blood vessels are colored red if they carry O_2 -rich blood and blue if they carry O_2 -poor blood. **b.** Photograph of a heart in its natural position in the chest.

Path of Blood Through the Heart

Even though the presence of intercalated disks (Fig. 32.7b) between cardiac muscle cells allows both atria and then both ventricles to contract simultaneously, we can travel the path of blood through the heart in the following manner:

- The superior vena cava and the inferior vena cava, which carry O_2 -poor blood that is relatively high in carbon dioxide, enter the right atrium.
- The right atrium sends blood through an atrioventricular valve (the tricuspid valve) to the right ventricle.
- The right ventricle sends blood through the pulmonary semilunar valve into the pulmonary trunk and the two pulmonary arteries to the lungs.
- Four pulmonary veins, which carry O_2 -rich blood, enter the left atrium.
- The left atrium sends blood through an atrioventricular valve (the bicuspid or mitral valve) to the left ventricle.
- The left ventricle sends blood through the aortic semilunar valve into the aorta to the body proper.

From this description, it is obvious that O_2 -poor blood never mixes with O_2 -rich blood and that blood must go through the lungs in order to pass from the right side to the left side of the heart. In fact, the heart is a double pump because the right ventricle of the heart sends blood into the pulmonary circuit, and the left ventricle sends blood into the systemic circuit. Since the left ventricle has the harder job of pumping blood to the entire body, its walls are thicker than those of the right ventricle, which pumps blood a relatively short distance to the lungs. Some people associate O_2 -rich blood with all arteries and O_2 -poor blood with all veins, but this idea is incorrect: Pulmonary arteries and pulmonary veins are just the reverse. That is why pulmonary arteries are colored blue and pulmonary veins are colored red in Figures 32.6 and 32.7.

The pumping of the heart sends blood out under pressure into the arteries. Because the left side of the heart is the stronger pump, blood pressure is greatest in the aorta. Blood pressure then decreases as the cross-sectional area of arteries and then arterioles increases. Therefore, a different mechanism is needed to move blood in the veins, as we shall discuss.

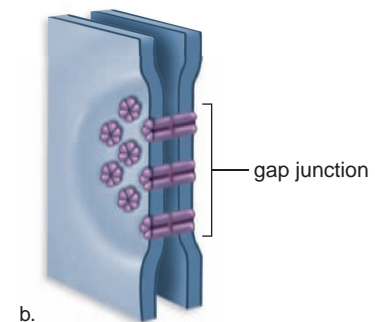
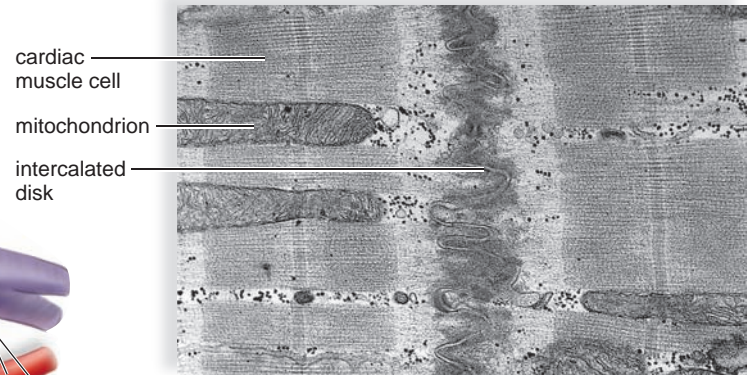
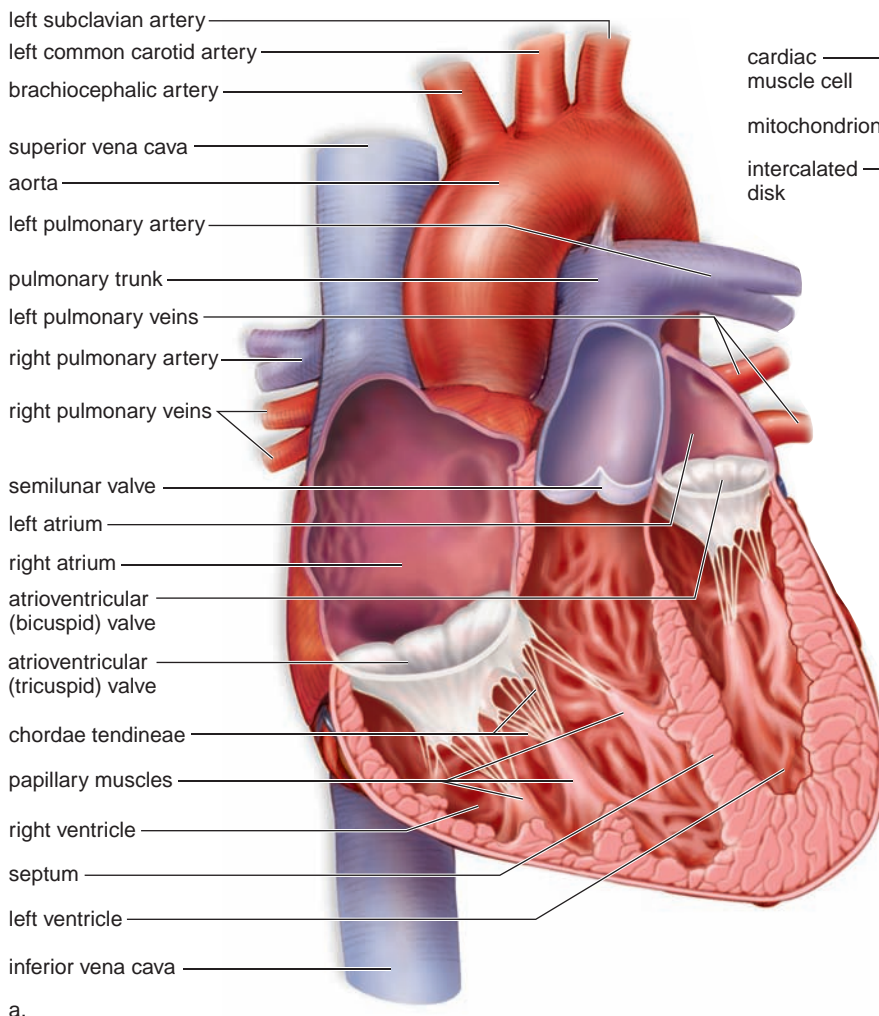


FIGURE 32.7 Internal view of the heart.

a. The heart has four chambers; the two chambers on the right are separated from the two chambers on the left by a septum. When the atrioventricular valves open, blood passes from the atria to the ventricles, and when the semilunar valves open, blood passes out of the heart. **b.** Intercalated disks contain gap junctions and these allow muscle cells to contract simultaneously. Desmosomes at the same location allow the cells to bend and stretch.

The Heartbeat

The average human heart contracts, or beats, about 70 times a minute, or 2.5 billion times in a lifetime, and each heartbeat lasts about 0.85 second. The term **systole** [Gk. *systole*, contraction] refers to contraction of the heart chambers, and the word **diastole** [Gk. *diastole*, dilation, spreading] refers to relaxation of these chambers. Each heartbeat, or **cardiac cycle**, consists of the following phases, which are also depicted in Figure 32.8:

Cardiac Cycle		
Time	Atria	Ventricles
0.15 sec	Systole	Diastole
0.30 sec	Diastole	Systole
0.40 sec	Diastole	Diastole

First the atria contract (while the ventricles relax), then the ventricles contract (while the atria relax), and then all chambers rest. Note that the heart is in diastole about 50% of the time. The short systole of the atria is appropriate since the atria send blood only into the ventricles. It is the

muscular ventricles that actually pump blood out into the cardiovascular system proper. When the word *systole* is used alone, it usually refers to the left ventricular systole. The volume of blood that the left ventricle pumps per minute into the systemic circuit is called the **cardiac output**. A person with a heartbeat of 70 beats per minute has a cardiac output of 5.25 liters a minute. This is almost equivalent to the amount of blood in the body. During heavy exercise, the cardiac output can increase manyfold.

When the heart beats, the familiar lub-dub sound is heard as the valves of the heart close. The longer and lower-pitched *lub* is caused by vibrations of the heart when the atrioventricular valves close due to ventricular contraction. The shorter and sharper *dub* is heard when the semilunar valves close due to back pressure of blood in the arteries. A heart murmur, a slight slush sound after the lub, is often due to ineffective valves, which allow blood to pass back into the atria after the atrioventricular valves have closed.

The **pulse** is a wave effect that passes down the walls of the arterial blood vessels when the aorta expands and then recoils following ventricular systole. Because there is one arterial pulse per ventricular systole, the arterial pulse rate can be used to determine the heart rate.

The rhythmic contraction of the heart is due to the **cardiac conduction system**. Nodal tissue, which has both

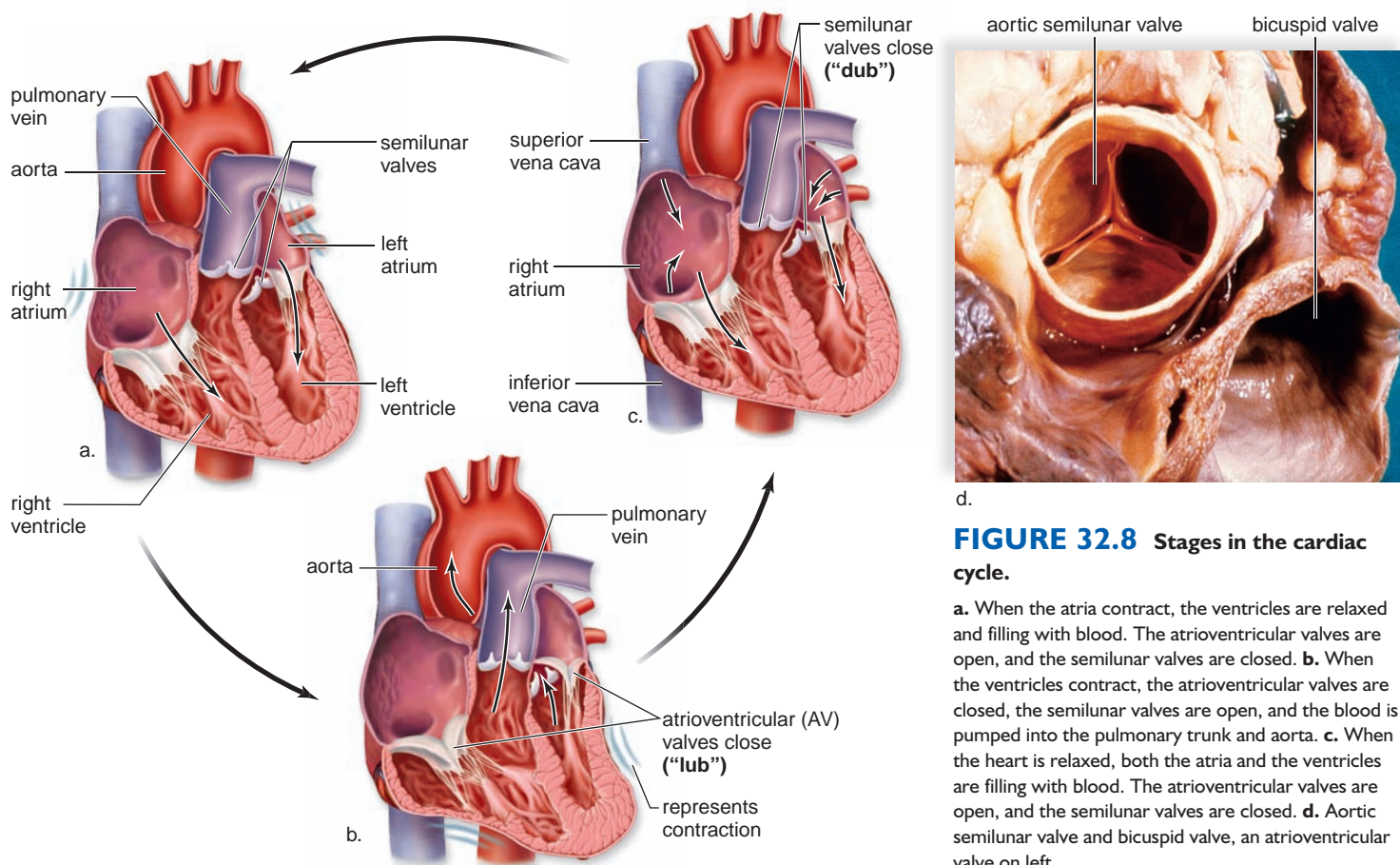


FIGURE 32.8 Stages in the cardiac cycle.

a. When the atria contract, the ventricles are relaxed and filling with blood. The atrioventricular valves are open, and the semilunar valves are closed. **b.** When the ventricles contract, the atrioventricular valves are closed, the semilunar valves are open, and the blood is pumped into the pulmonary trunk and aorta. **c.** When the heart is relaxed, both the atria and the ventricles are filling with blood. The atrioventricular valves are open, and the semilunar valves are closed. **d.** Aortic semilunar valve and bicuspid valve, an atrioventricular valve on left.

muscular and nervous characteristics, is a unique type of cardiac muscle located in two regions of the heart. The SA (sinoatrial) node is found in the upper dorsal wall of the right atrium; the AV (atrioventricular) node is found in the base of the right atrium very near the septum (Fig. 32.9a). The SA node initiates the heartbeat and every 0.85 second automatically sends out an excitation impulse, which causes the atria to contract. Therefore, the SA node is called the **cardiac pacemaker** because it usually keeps the heartbeat regular. When the impulse reaches the AV node, the AV node signals the ventricles to contract by way of large fibers terminating in the more numerous and smaller Purkinje fibers. Although the beat of the heart is intrinsic, it is regulated by the nervous system, which can increase or decrease the heartbeat rate. The hormones epinephrine and norepinephrine, which are released by the adrenal glands, also stimulate the heart. During exercise, for example, the heart pumps faster and stronger due to nervous stimulation and due to the release of epinephrine and norepinephrine.

The Electrocardiogram. An **electrocardiogram (ECG)** is a recording of the electrical changes that occur in the myocardium during a cardiac cycle. Body fluids contain ions

that conduct electrical currents, and therefore the electrical changes in the myocardium can be detected on the skin's surface. When an electrocardiogram is being taken, electrodes placed on the skin are connected by wires to an instrument that detects the myocardium's electrical changes. Thereafter, a pattern appears that reflects the contractions of the heart. Figure 32.9b depicts the pattern that results from a normal cardiac cycle.

When the SA node triggers an impulse, the atrial fibers produce an electrical change called the P wave. The P wave indicates that the atria are about to contract. After that, the QRS complex signals that the ventricles are about to contract and the atria are relaxing. The electrical changes that occur as the ventricular muscle fibers recover produce the T wave.

Various types of abnormalities can be detected by an electrocardiogram. One of these, called ventricular fibrillation, is caused by uncoordinated contraction of the ventricles (Fig. 32.9c). Ventricular fibrillation is of special interest because it can be caused by an injury or drug overdose. It is the most common cause of sudden cardiac death in a seemingly healthy person. Once the ventricles are fibrillating, they have to be defibrillated by applying a strong electric current for a short period of time. Then the SA node may be able to reestablish a coordinated beat.

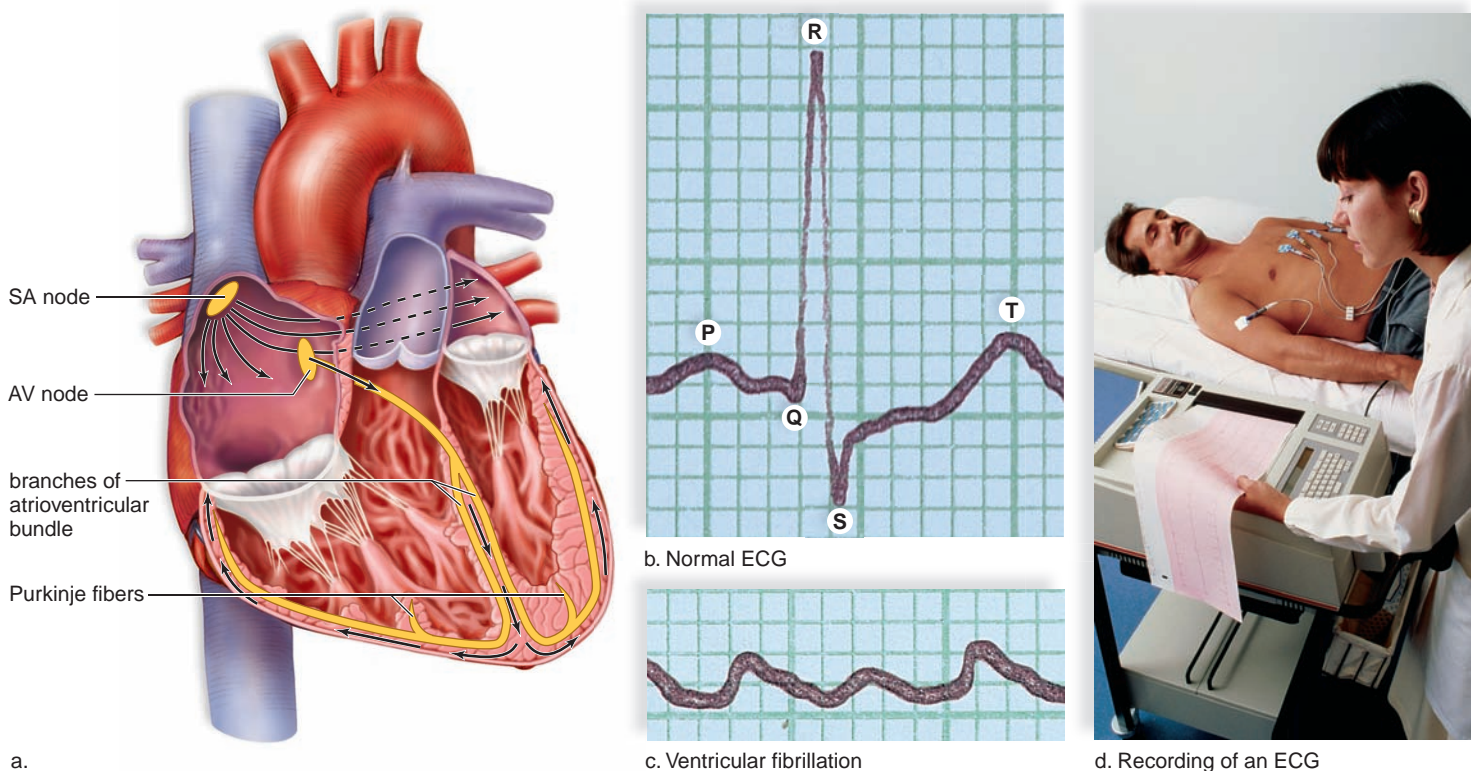


FIGURE 32.9 Conduction system of the heart.

a. The SA node sends out a stimulus (black arrows), which causes the atria to contract. When this stimulus reaches the AV node, it signals the ventricles to contract. Impulses pass down the two branches of the atrioventricular bundle to the Purkinje fibers, and thereafter the ventricles contract. **b.** A normal ECG usually indicates that the heart is functioning properly. The P wave occurs just prior to atrial contraction; the QRS complex occurs just prior to ventricular contraction; and the T wave occurs when the ventricles are recovering from contraction. **c.** Ventricular fibrillation produces an irregular electrocardiogram due to irregular stimulation of the ventricles. **d.** The recording of an ECG.

Vascular Pathways

The human cardiovascular system includes two major circular pathways, the pulmonary circuit and the systemic circuit (Fig. 32.10).

The Pulmonary Circuit

In the pulmonary circuit, the path of blood can be traced as follows: O_2 -poor blood from all regions of the body collects in the right atrium and then passes into the right ventricle, which pumps it into the pulmonary trunk. The pulmonary trunk divides into the right and left pulmonary arteries, which carry blood to the lungs. As blood passes through pulmonary capillaries, carbon dioxide is given off and oxygen is picked up. O_2 -rich blood returns to the left atrium of the heart, through pulmonary venules that join to form pulmonary veins.

The Systemic Circuit

The **aorta** [L. *aorte*, great artery] and the **venae cavae** (sing., vena cava) [L. *vena*, blood vessel, and *cavus*, hollow] are the major blood vessels in the systemic circuit. To trace the path of blood to any organ in the body, you need only start with the left ventricle, mention the aorta, the proper branch of the aorta, the organ, and the vein returning blood to the vena cava, which enters the right atrium. In the systemic circuit, arteries contain O_2 -rich blood and have a bright red color, but veins contain O_2 -poor blood and appear dull red or, when viewed through the skin, blue.

The coronary arteries are extremely important because they serve the heart muscle itself (see Fig. 32.6). The coronary arteries arise from the aorta just above the aortic semi-lunar valve. They lie on the exterior surface of the heart, where they branch into arterioles and then capillaries. In the capillary beds, nutrients, wastes, and gases are exchanged between the blood and the tissues. The capillary beds enter venules, which join to form the cardiac veins, and these empty into the right atrium.

A **portal system** [L. *porto*, carry, transport] is one that begins and ends in capillaries. The hepatic portal system takes blood from the intestines to the liver. The liver, an organ of homeostasis, modifies substances absorbed by the intestines, removes toxins and bacteria picked up from the intestines, and monitors the normal composition of the blood. Blood leaves the liver by way of the hepatic vein, which enters the inferior vena cava.

Tracing the Path of Blood. Branches from the aorta go to the organs and major body regions. For example, this is the path of blood to and from the lower legs:

left ventricle—aorta—common iliac artery—
femoral artery—lower leg capillaries—femoral
vein—common iliac vein—inferior vena cava—
right atrium

In most instances, the artery and the vein that serve the same region are given the same name. What happens in between the artery and the vein? Arterioles from the artery

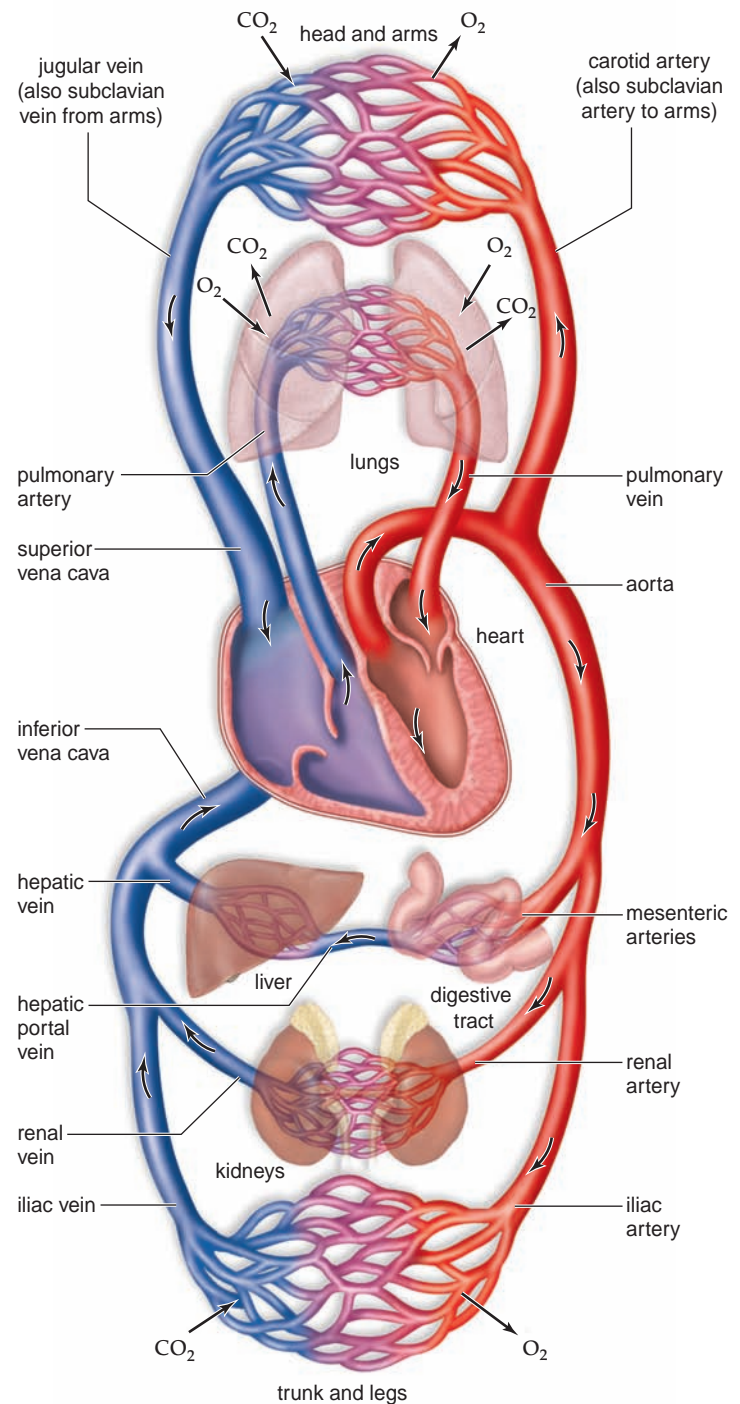


FIGURE 32.10 Path of blood.

When tracing blood from the right to the left side of the heart in the pulmonary circuit, you must mention the pulmonary vessels. When tracing blood from the digestive tract to the right atrium in the systemic circuit, you must mention the hepatic portal vein, the hepatic vein, and the inferior vena cava. The blue-colored vessels carry O_2 -poor blood, and the red-colored vessels carry O_2 -rich blood; the arrows indicate the flow of blood.

branch into capillaries, where exchange takes place, and then venules join to form the vein that enters a vena cava. An exception occurs between the digestive tract and the liver, because blood must pass through two sets of capillaries because of the hepatic portal system.

Blood Pressure

When the left ventricle contracts, blood is forced into the aorta and then other systemic arteries under pressure. Systolic pressure results from blood being forced into the arteries during ventricular systole, and diastolic pressure is the pressure in the arteries during ventricular diastole. Human **blood pressure** can be measured with a **sphygmomanometer**, which has a pressure cuff that determines the amount of pressure required to stop the flow of blood through an artery. Blood pressure is normally measured on the brachial artery, an artery in the upper arm. Today, digital manometers are often used to take one's blood pressure instead. Blood pressure is given in millimeters of mercury (mm Hg). A blood pressure reading consists of two numbers—for example, 120/80—that represent systolic and diastolic pressures, respectively.

As blood flows from the aorta into the various arteries and arterioles, blood pressure falls. Also, the difference between systolic and diastolic pressure gradually diminishes. In the capillaries, there is a slow, fairly even flow of blood. This may be related to the very high total cross-sectional area of the capillaries (Fig. 32.11). It has been calculated that if all the blood vessels in a human were connected end to

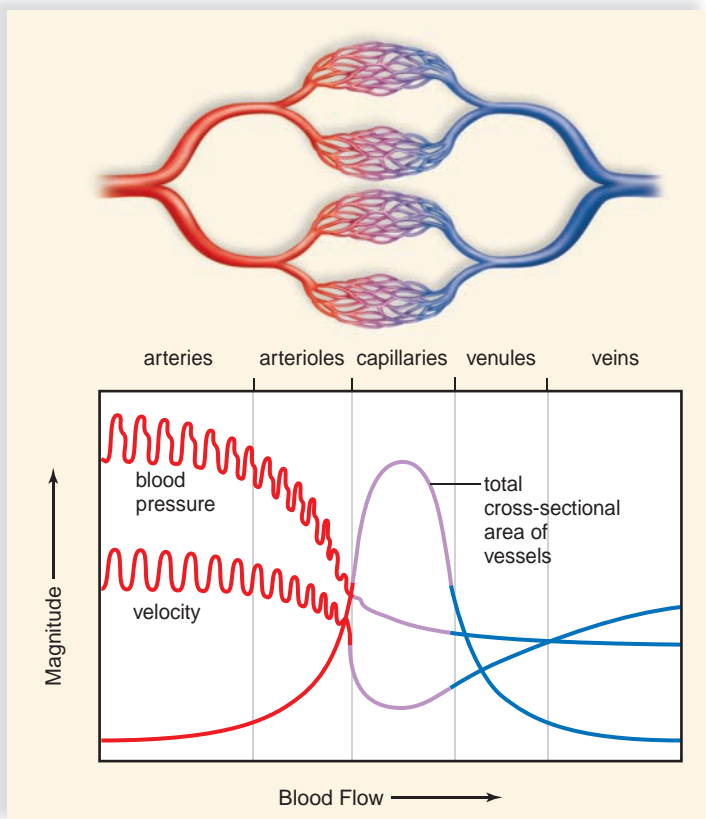
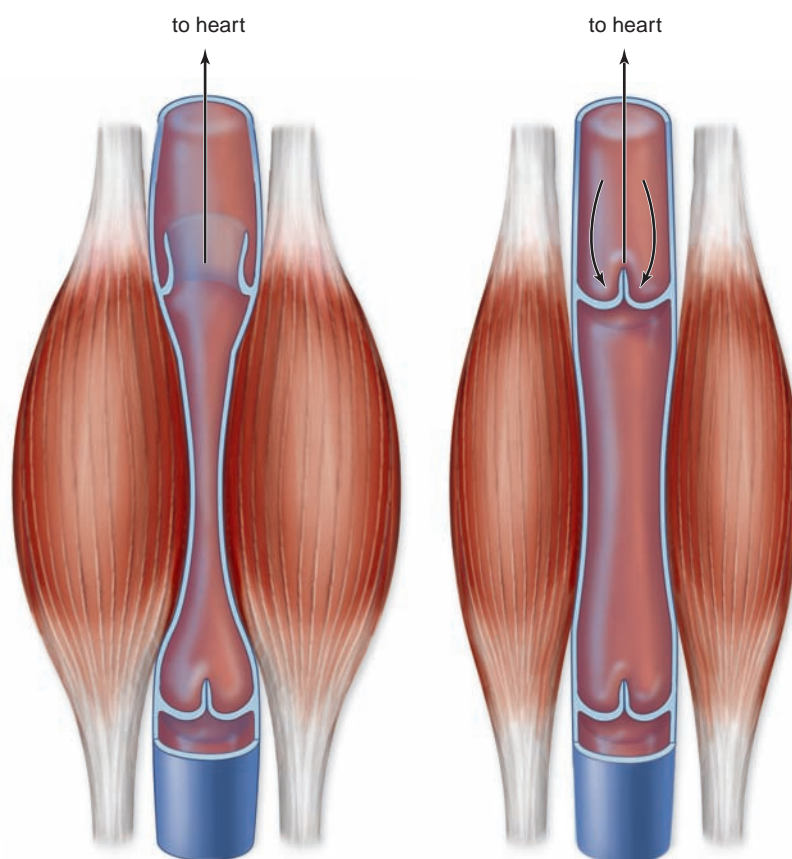


FIGURE 32.11 Velocity and blood pressure related to vascular cross-sectional area.

In capillaries, blood is under minimal pressure and has the least velocity. Blood pressure and velocity drop off because capillaries have a greater total cross-sectional area than arterioles.



a. Contracted skeletal muscle pushes blood past open valve.

b. Closed valve prevents backward flow of blood.

FIGURE 32.12 Cross section of a valve in a vein.

a. Pressure on the walls of a vein, exerted by skeletal muscles, increases blood pressure within the vein and forces a valve open. b. When external pressure is no longer applied to the vein, blood pressure decreases, and back pressure forces the valve closed. Closure of the valves prevents the blood from flowing in the opposite direction.

end, the total distance would reach around the Earth at the equator two times. A large portion of this distance would be due to the quantity of capillaries.

Blood pressure in the veins is low and cannot move blood back to the heart, especially from the limbs of the body. Venous return is dependent on these factors: (1) When skeletal muscles near veins contract, they put pressure on the collapsible walls of the veins and on blood contained in these vessels. (2) Veins have valves that prevent the backward flow of blood, and therefore pressure from muscle contraction is sufficient to move blood through veins toward the heart (Fig. 32.12). Varicose veins, abnormal dilations in superficial veins, develop when the valves of the veins become weak and ineffective due to a backward pressure of the blood. Varicose veins of the anal canal are known as hemorrhoids. (3) A respiratory pump works like this: When we inhale, the chest expands and this reduces pressure in the thoracic cavity. Blood will flow from the higher pressure (in the abdominal cavity) to lower pressure (in the thoracic cavity).

health focus

Prevention of Cardiovascular Disease

All of us can take steps to prevent cardiovascular disease, the most frequent cause of death in the United States. Certain genetic factors predispose an individual to cardiovascular disease, such as family history of heart attack under age 55, male gender, and ethnicity (African Americans are at greater risk). People with one or more of these risk factors need not despair, however. It means only that they should pay particular attention to the following guidelines for a heart-healthy lifestyle.

The Don'ts

Smoking

Hypertension is well recognized as a major contributor to cardiovascular disease. When a person smokes, the drug nicotine, present in cigarette smoke, enters the bloodstream. Nicotine causes the arterioles to constrict and the blood pressure to rise. Restricted blood flow and cold hands are associated with smoking in most people. More serious is the need for the heart to pump harder to propel the blood through the lungs at a time when the oxygen-carrying capacity of the blood is reduced.

Drug Abuse

Stimulants, such as cocaine and amphetamines, can cause an irregular heartbeat and lead to heart attacks and strokes in people

who are using drugs even for the first time. Intravenous drug use may result in a cerebral embolism.

Too much alcohol can destroy just about every organ in the body, the heart included. But investigators have discovered that people who take an occasional drink have a 20% lower risk of heart disease than do teetotalers. Two to four drinks a week is the recommended limit for men; one to three drinks for women.

Weight Gain

Hypertension is prevalent in persons who are more than 20% above the recommended weight for their height. In those who are overweight, more tissues require servicing, and the heart sends the extra blood out under greater pressure. It may be harder to lose weight once it is gained, and therefore it is recommended that weight control be a lifelong endeavor. Even a slight decrease in weight can bring with it a reduction in hypertension. A 4.5-kg weight (about 10 lbs) loss doubles the chance that blood pressure can be normalized without drugs.

The Dos

Healthy Diet

Diet influences the amount of cholesterol in the blood. Cholesterol is ferried by two types of plasma proteins, called LDL (low-density li-

poprotein) and HDL (high-density lipoprotein). LDL (called "bad" lipoprotein) takes cholesterol from the liver to the tissues, and HDL (called "good" lipoprotein) transports cholesterol out of the tissues to the liver. When the LDL level in blood is high or the HDL level is abnormally low, plaque, which interferes with circulation, accumulates on arterial walls (Fig. 32A).

Eating foods high in saturated fat (red meat, cream, and butter) and foods containing so-called trans-fats (most margarines, commercially baked goods, and deep-fried foods) raises the LDL-cholesterol level. Replacement of these harmful fats with healthier ones, such as monounsaturated fats (olive and canola oils) and polyunsaturated fats (corn, safflower, and soybean oils), is recommended. Cold water fish (e.g., halibut, sardines, tuna, and salmon) contain polyunsaturated fatty acids and especially omega-3 polyunsaturated fatty acids, which can reduce plaque.

Evidence is mounting to suggest a role for antioxidant vitamins (A, E, and C) in preventing cardiovascular disease. Antioxidants protect the body from free radicals that oxidize cholesterol and damage the lining of an artery, leading to a blood clot that can block blood vessels. Nutritionists believe that consuming at least five servings of fruits and vegetables a day may protect against cardiovascular disease.

Cardiovascular Disease

Cardiovascular disease (CVD) is the leading cause of untimely death in the Western countries. The Health Focus on this page emphasizes how to prevent CVD from developing.

Hypertension

It is estimated that about 20% of all Americans suffer from hypertension, which is high blood pressure. Under age 45, a reading above 130/90 is hypertensive, and beyond age 45, a reading above 140/95 is hypertensive. While both systolic and diastolic pressures are important, it is the diastolic pressure that is emphasized when medical treatment is being considered.

Atherosclerosis

Hypertension is also seen in individuals who have atherosclerosis (formerly called arteriosclerosis), an accumulation

of soft masses of fatty materials, particularly cholesterol, beneath the inner linings of arteries (see Fig. 32A). Such deposits are called plaque. As deposits occur, plaque tends to protrude into the lumen of the vessel, interfering with the flow of blood. Atherosclerosis begins in early adulthood and develops progressively through middle age, but symptoms may not appear until an individual is 50 or older. To prevent its onset and development, the American Heart Association and other organizations recommend a diet low in saturated fat and cholesterol and rich in fruits and vegetables.

Plaque can cause a clot to form on the irregular arterial wall. As long as the clot remains stationary, it is called a thrombus, but when and if it dislodges and moves along with the blood, it is called an embolus. If thromboembolism is not treated, complications can arise (see the following section).

In certain families, atherosclerosis is due to an inherited condition such as familial hypercholesterolemia. The presence

Cholesterol Profile

Starting at age 20, all adults are advised to have their cholesterol levels tested at least every five years. Even in healthy individuals, an LDL level above 160 mg/100 ml and an HDL level below 40 mg/100 ml are matters of concern. If a person has heart disease or is at risk for heart disease, an LDL level below 100 mg/100 ml is now recommended. Medications will most likely be prescribed for individuals who do not meet these minimum guidelines.

Exercise

People who exercise are less apt to have cardiovascular disease. One study found that moderately active men who spent an average of 48 minutes a day on a leisure-time activity such as gardening, bowling, or dancing had one-third fewer heart attacks than peers who spent an average of only 16 minutes each day being active. Exercise helps keep weight under control, may help minimize stress, and reduces hypertension. The heart

beats faster when exercising, but exercise slowly increases its capacity. This means that the heart can beat slower when we are at rest and still do the same amount of work. One physician recommends that cardiovascular patients walk for one hour, three times a week, and, in addition, practice meditation and yogalike stretching and breathing exercises to reduce stress.

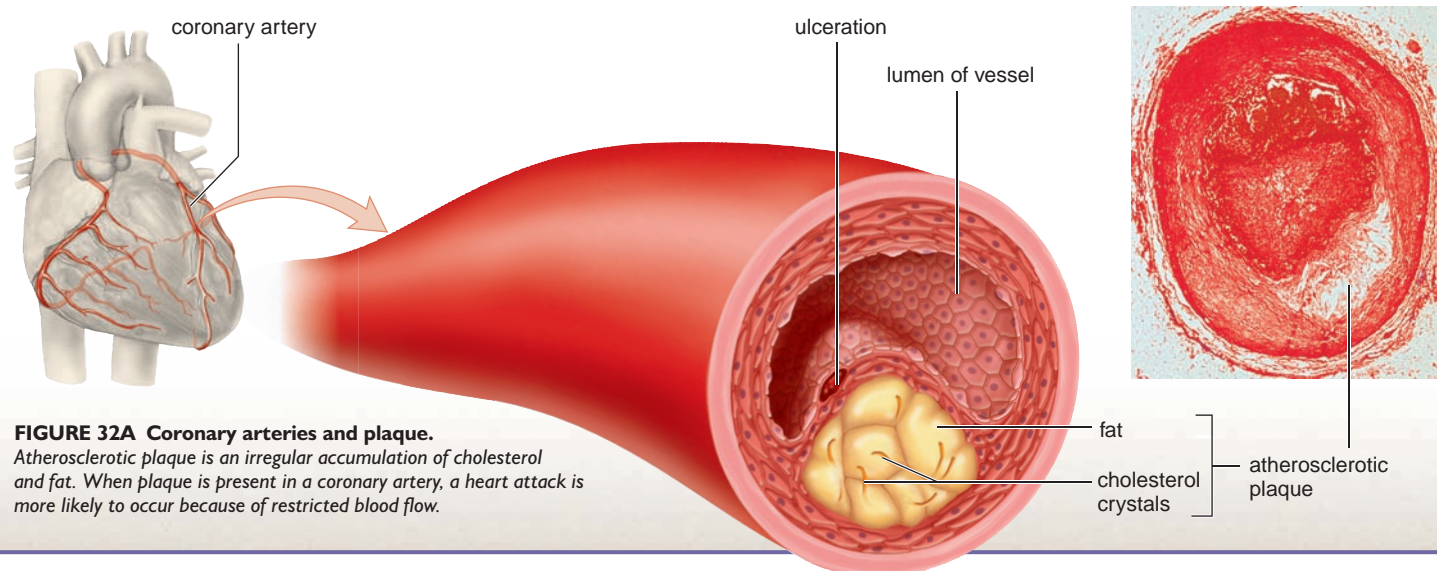


FIGURE 32A Coronary arteries and plaque.

Atherosclerotic plaque is an irregular accumulation of cholesterol and fat. When plaque is present in a coronary artery, a heart attack is more likely to occur because of restricted blood flow.

of the disease-associated mutation can be detected, and this information is helpful if measures are taken to prevent the occurrence of the disease.

Stroke and Heart Attack

Stroke, heart attack, and aneurysm are associated with hypertension and atherosclerosis. A cardiovascular accident, also called a **stroke**, often results when a small cranial arteriole bursts or is blocked by an embolus. A lack of oxygen causes a portion of the brain to die, and paralysis or death can result. A person is sometimes forewarned of a stroke by a feeling of numbness in the hands or the face, difficulty in speaking, or temporary blindness in one eye.

When a coronary artery is completely blocked, perhaps because of a thromboembolism, a portion of the heart muscle dies due to a lack of oxygen. This is a myocardial infarction, also called a **heart attack**. If a coronary artery becomes partially

blocked, the individual may suffer from **angina pectoris**, characterized as a squeezing sensation or a flash of burning. Nitroglycerin or related drugs dilate blood vessels and help relieve the pain.

Check Your Progress

32.3

1. Contrast the structure and function of the right and left ventricles.
2. Trace the path of blood through the heart from the venae cavae to the aorta.
3. Explain what happens during a heartbeat and what makes the familiar *lub-dub* sounds.
4. What conditions might occur as a result of hypertension and plaque?

32.4 Blood, a Transport Medium

The blood of mammals has numerous functions that help maintain homeostasis. Blood (1) transports gases, nutrients, waste products, and hormones throughout the body; (2) helps destroy pathogenic microorganisms; (3) distributes antibodies that are important in immunity; (4) aids in maintaining water balance and pH; (5) helps regulate body temperature; and (6) carries platelets and factors that ensure clotting and prevent blood loss.

In humans, blood has two main portions: the liquid portion, called plasma, and the formed elements, consisting of various cells and platelets (Fig. 32.13). **Plasma** [Gk. *plasma*, something molded] contains many types of molecules, including nutrients, wastes, salts, and proteins. The salts and proteins are involved in buffering the blood, effectively keeping the pH near 7.4. They also maintain the blood's osmotic pressure so that water has an automatic tendency to enter blood capillaries. Several plasma proteins are involved in blood clotting, and others transport large organic molecules in the blood. Albumin, the most plentiful of the plasma proteins, transports bilirubin, a breakdown product of hemoglobin. Globulins have various functions; among the globulins are the lipoproteins, which transport cholesterol.

Formed Elements

The formed elements are of three types: red blood cells, or erythrocytes [Gk. *erythros*, red, and *kytos*, cell]; white blood cells, or

leukocytes [Gk. *leukos*, white, and *kytos*, cell]; and platelets, or thrombocytes [Gk. *thrombos*, blood clot, and *kytos*, cell].

Red Blood Cells

Red blood cells are small, biconcave disks that at maturity lack a nucleus and contain the respiratory pigment hemoglobin. Approximately 25 trillion red blood cells exist in an average adult. There are 6 million red blood cells per cubic millimeter (mm^3) of whole blood, and each one of these cells contains about 250 million hemoglobin molecules.

Hemoglobin [Gk. *haima*, blood; L. *globus*, ball] contains four globin protein chains, each associated with heme, an iron-containing group. Iron combines loosely with oxygen, and in this way oxygen is carried in the blood. If there is an insufficient number of red blood cells, or if the cells do not have enough hemoglobin, the individual suffers from anemia and has a tired, run-down feeling.

Red blood cells are manufactured continuously in the red bone marrow of the skull, the ribs, the vertebrae, and the ends of the long bones. The hormone erythropoietin, which is produced by the kidneys, stimulates the production of red blood cells. Now available as a drug, erythropoietin is helpful to persons with anemia and is also sometimes abused by athletes who want to enhance their performance.

Before they are released from the bone marrow into blood, red blood cells lose their nuclei and synthesize hemoglobin. After living about 120 days, they are destroyed chiefly in the liver and the spleen, where they are engulfed by large phagocytic cells. When red blood cells are destroyed, hemoglobin is released. The iron is recovered and returned

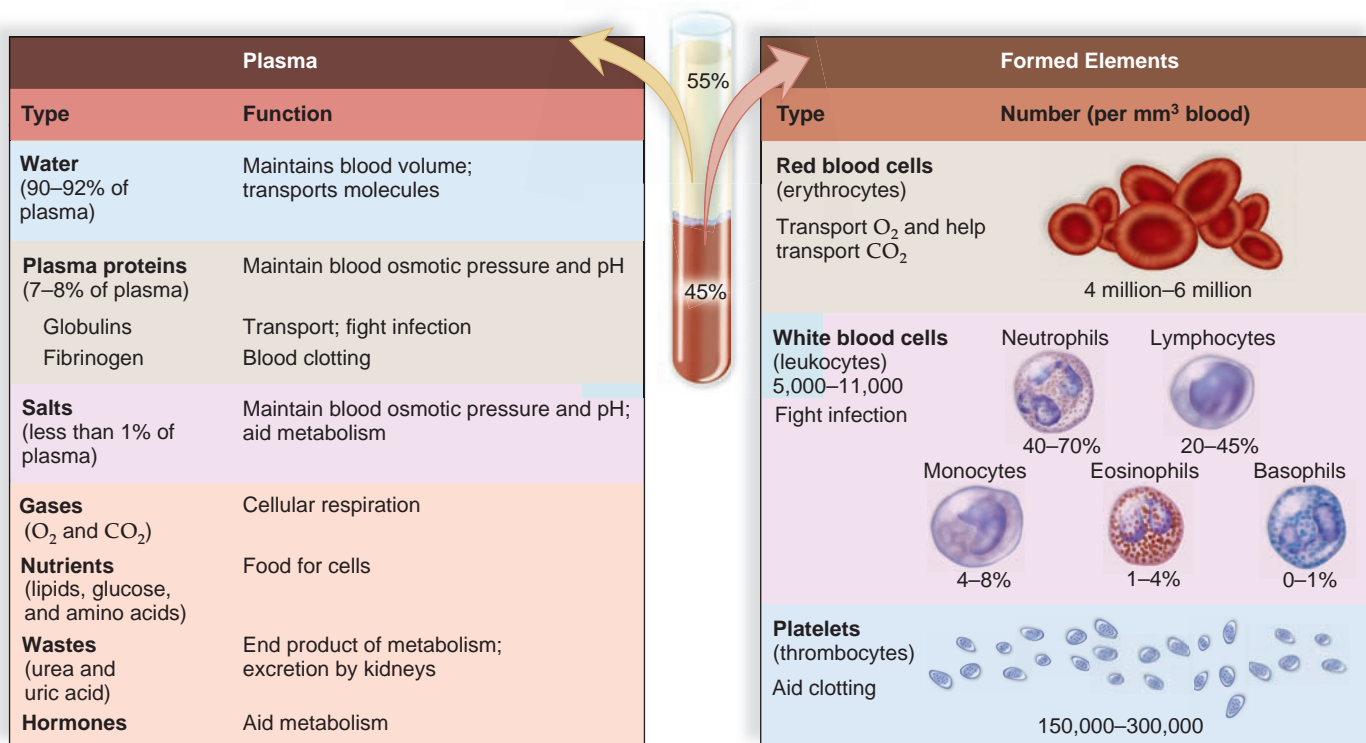


FIGURE 32.13 Composition of blood.

to the red bone marrow for reuse. The heme portions of the molecules undergo chemical degradation and are excreted by the liver as bile pigments in the bile. The bile pigments are primarily responsible for the color of feces.

White Blood Cells

White blood cells differ from red blood cells in that they are usually larger and have a nucleus, they lack hemoglobin, and, without staining, they appear translucent. With staining, white blood cells appear light blue unless they have granules that bind with certain stains. The following are granular leukocytes with a lobed nucleus: neutrophils, which have granules that stain slightly pink; eosinophils, which have granules that take up the red dye eosin; and basophils, which have granules that take up a basic dye, staining them a deep blue. The agranular leukocytes with no granules and a circular or indented nucleus are the larger monocytes and the smaller lymphocytes. There are approximately 5,000–11,000 white blood cells per mm^3 . Stem cell growth factor can be used to increase the production of all white blood cells, and various other growth factors are also available to stimulate the production of specific stem cells. These growth factors are helpful to people with low immunity, such as AIDS patients.

When microorganisms enter the body due to an injury, the response is called an inflammatory reaction because swelling and reddening occur at the injured site. Cells in the vicinity release substances that cause vasodilation (increase in the diameter of a vessel), and increased capillary permeability. **Neutrophils** [Gk. *neuter*, neither, and *phileo*, love], which are amoeboid, squeeze through the capillary wall and enter the tissue fluid, where they phagocytize foreign material. **Monocytes** appear and are transformed into **macrophages** [Gk. *makros*, long, and *phagein*, to eat], which are large phagocytizing cells that release white blood cell growth factors. Soon there is an explosive increase in the number of leukocytes. The thick, yellowish fluid called pus contains a large proportion of dead white blood cells that have fought the infection.

Lymphocytes [L. *lymph*a, clear water; Gk. *kytos*, cell] also play an important role in fighting infection. Certain lymphocytes called T cells attack infected cells that contain

viruses. Other lymphocytes called B cells produce antibodies. Each B cell produces just one type of antibody, which is specific for one type of antigen. An **antigen** [Gk. *anti*, against; L. *genitus*, forming, causing], which is most often a protein but sometimes a polysaccharide, causes the body to produce an antibody because the antigen doesn't belong to the body. Antigens are present in the outer covering of parasites or in their toxins. When **antibodies** [Gk. *anti*, against] combine with antigens, the complex is often phagocytized by a macrophage. An individual is actively immune when a large number of B cells are all producing the specific antibody needed for a particular infection.

The **eosinophils** are granular leukocytes that are important in releasing enzymes used in fighting parasites and destroying allergens. **Basophils** are the least common leukocyte. They contain the anticoagulant heparin, which prevents blood from clotting too quickly. Basophils also contain the vasodilator histamine, which promotes blood flow to tissues.

Platelets

Platelets (thrombocytes) result from fragmentation of certain large cells, called megakaryocytes, in the red bone marrow. Platelets are produced at a rate of 200 billion a day, and the blood contains 150,000–300,000 per mm^3 . These formed elements are involved in blood clotting, or coagulation.

Blood Clotting. When a blood vessel in the body is damaged, platelets clump at the site of the puncture and partially seal the leak. Platelets and the injured tissues release a clotting factor called prothrombin activator that converts prothrombin to thrombin. This reaction requires calcium ions (Ca^{2+}). *Thrombin*, in turn, acts as an enzyme that severs two short amino acid chains from each fibrinogen molecule. These activated fragments then join end to end, forming long threads of fibrin. Fibrin threads wind around the platelet plug in the damaged area of the blood vessel and provide the framework for the clot. Red blood cells also are trapped within the fibrin threads; these cells make a clot appear red (Fig. 32.14). A fibrin clot is present only temporarily. As soon as blood vessel repair is initiated, an enzyme called plasmin destroys the fibrin network and restores the fluidity of plasma.

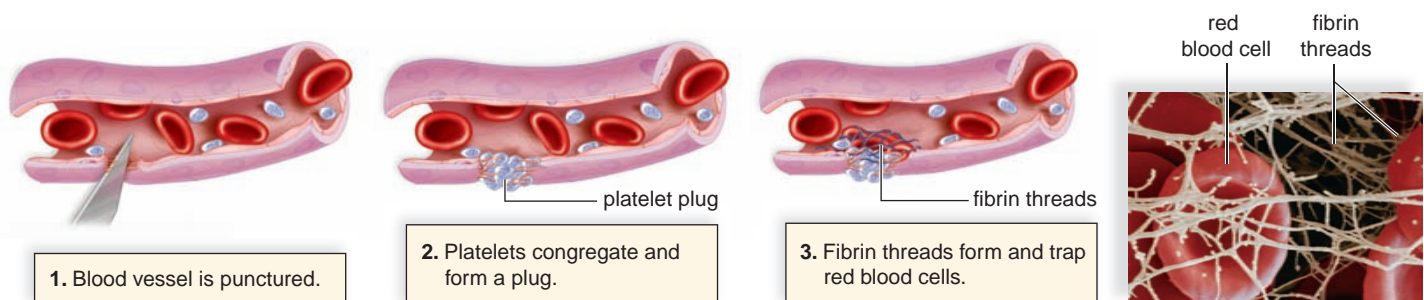


FIGURE 32.14 Blood clotting.

A number of plasma proteins participate in a series of enzymatic reactions that lead to the formation of fibrin threads.

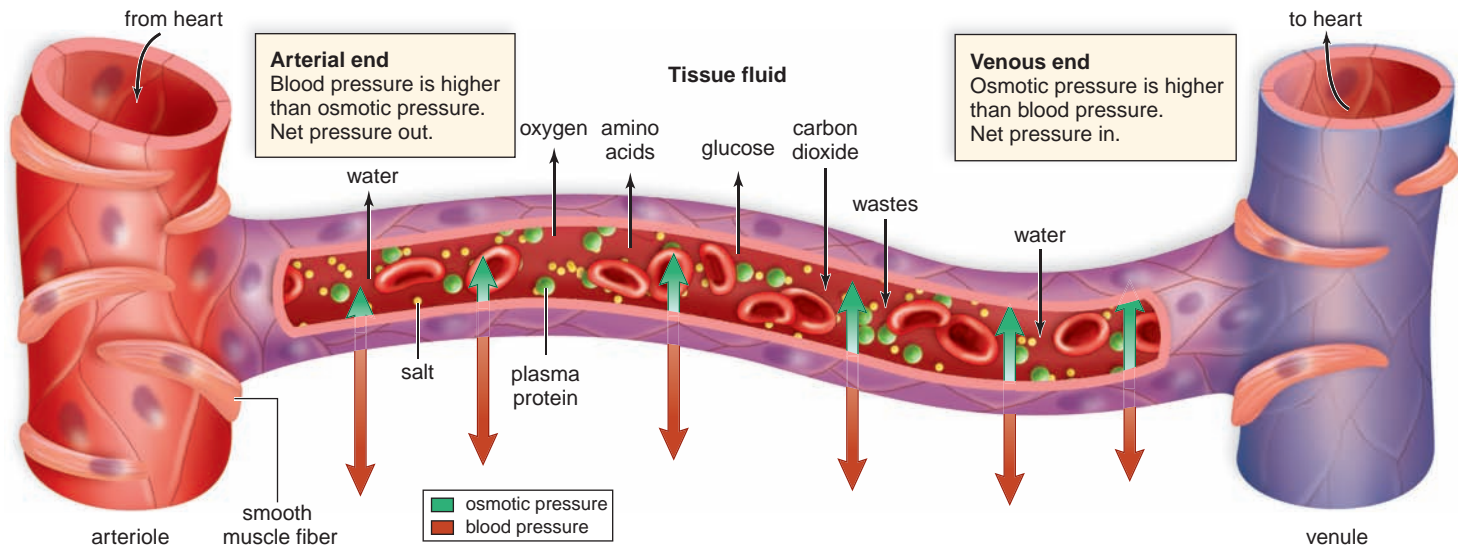


FIGURE 32.15 Capillary exchange.

A capillary, illustrating the exchanges that take place and the forces that aid the process. At the arterial end of a capillary, the blood pressure is higher than the osmotic pressure; therefore, water (H_2O) tends to leave the bloodstream. In the midsection, molecules, including oxygen (O_2) and carbon dioxide (CO_2), follow their concentration gradients. At the venous end of a capillary, the osmotic pressure is higher than the blood pressure; therefore, water tends to enter the bloodstream. Notice that the red blood cells and the plasma proteins are too large to exit a capillary.

Capillary Exchange

Figure 32.15 illustrates capillary exchange between a systemic capillary and tissue fluid, the fluid between the body's cells. Blood that enters a capillary at the arterial end is rich in oxygen and nutrients, and it is under pressure created by the pumping of the heart. Two forces primarily control movement of fluid through the capillary wall: osmotic pressure, which tends to cause water to move from tissue fluid to blood, and blood pressure, which tends to cause water to move in the opposite direction. At the arterial end of a capillary, blood pressure (30 mm Hg) is higher than the osmotic pressure of blood (21 mm Hg). Osmotic pressure is created by the presence of salts and the plasma proteins. Because blood pressure is higher than osmotic pressure at the arterial end of a capillary, water exits a capillary at this end.

Midway along the capillary, where blood pressure is lower, the two forces essentially cancel each other, and there is no net movement of water. Solutes now diffuse according to their concentration gradient: Oxygen and nutrients (glucose and amino acids) diffuse out of the capillary; carbon dioxide and wastes diffuse into the capillary. Red blood cells and almost all plasma proteins remain in the capillaries. The substances that leave a capillary contribute to **tissue fluid**, the fluid between the body's cells. Since plasma proteins are too large to readily pass out of the capillary, tissue fluid tends to contain all components of plasma except much lesser amounts of protein.

At the venule end of a capillary, where blood pressure has fallen even more, osmotic pressure is greater than blood pressure, and water tends to move into the capillary. Almost the same amount of fluid that left the capillary returns to it, although some excess tissue fluid is always collected by the lymphatic capillaries (Fig. 32.16). Tissue fluid contained within lymphatic vessels is called **lymph**. Lymph is returned to the

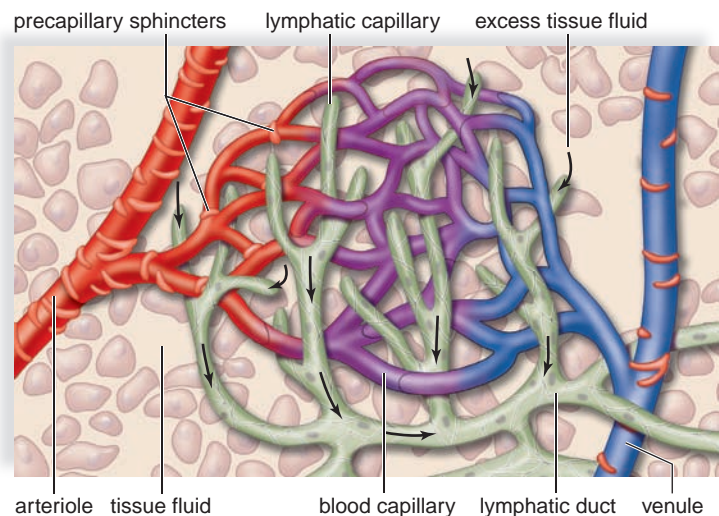


FIGURE 32.16 Capillary bed.

A lymphatic capillary bed lies near a blood capillary bed. When lymphatic capillaries take up excess tissue fluid, it becomes lymph. Precapillary sphincters can shut down a blood capillary, and blood then flows through the shunt.

systemic venous blood when the major lymphatic vessels enter the subclavian veins in the shoulder region.

Not all capillary beds are open at the same time. When the precapillary sphincters (circular muscles) shown in Figure 32.4 are relaxed, the capillary bed is open and blood flows through the capillaries. When precapillary sphincters are contracted, blood flows through a shunt that carries blood directly from an arteriole to a venule. In addition to nutrients and wastes, the blood distributes heat to body parts. When you are warm, many capillaries that serve the skin are open, and your face is flushed. This helps rid the body of excess heat. When you are cold, skin capillaries close, conserving heat, and your skin turns blue.

Blood Types

Many early blood transfusions resulted in illness and even death of some recipients. Eventually, it was discovered that only certain types of blood are compatible because red blood cell membranes carry specific proteins or carbohydrates that are antigens to blood recipients. An antigen is a foreign molecule, usually a protein, that the body reacts to. Several groups of red blood cell antigens exist, the most significant being the ABO system. Clinically, it is very important that the blood groups be properly cross-matched to avoid a potentially deadly transfusion reaction. In such a reaction, the recipient may die of kidney failure within a week.

ABO System

In the ABO system, the presence or absence of type A and type B antigens on red blood cells determines a person's blood type. For example, if a person has type A blood, the A antigen is on his or her red blood cells. This molecule is not an antigen to this individual, although it can be an antigen to a recipient who does not have type A blood.

In the ABO system, there are four types of blood: A, B, AB, and O. Within the plasma are antibodies to the antigens that are not present on the person's red blood cells. These antibodies are called anti-A and anti-B. This chart tells you what antibodies are present in the plasma of each blood type:

Blood Type	Antigen on Red Blood Cells	Antibody in Plasma
A	A	Anti-B
B	B	Anti-A
AB	A, B	None
O	None	Anti-A and anti-B

Because type A blood has anti-B and not anti-A antibodies in the plasma, a donor with type A blood can give blood to a recipient with type A blood (Fig. 32.17). However, if type A blood is given to a type B recipient, **agglutination** (Fig. 32.18), the clumping of red blood cells, occurs or it can

cause blood to stop circulating in small blood vessels, and this leads to organ damage.

Theoretically, which type blood would be accepted by all recipients? Type O blood has no antigens on the red blood cells and is sometimes called the universal donor. Which type blood could receive blood from any other blood type? Type AB blood has no anti-A or anti-B antibodies in the plasma and is sometimes called the universal recipient. In practice, however, it is not safe to rely solely on the ABO system when matching blood. Instead, samples of the two types of blood are physically mixed, and the result is microscopically examined before blood transfusions are done.

Rh System

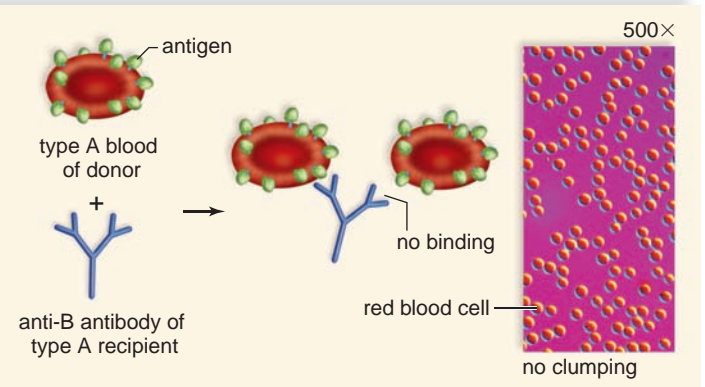
Another important antigen in matching blood types is the Rh factor. Eighty-five percent of the U.S. population has this particular antigen on the red blood cells and is called Rh positive. Fifteen percent does not have the antigen and is Rh negative. Rh-negative individuals normally do not have antibodies to the Rh factor, but they may make them when exposed to the Rh factor. The designation of blood type usually also includes whether the person has or does not have the Rh factor on the red blood cells.

During pregnancy, if the mother is Rh negative and the father is Rh positive, the child may be Rh positive. If the Rh-positive red blood cells leak across the placenta, the mother will produce anti-Rh antibodies. In this or a subsequent pregnancy with another Rh-positive baby, these antibodies may cross the placenta and destroy the child's red blood cells. This condition, called hemolytic disease of the newborn (HDN), can be fatal without an immediate blood transfusion.

Check Your Progress

32.4

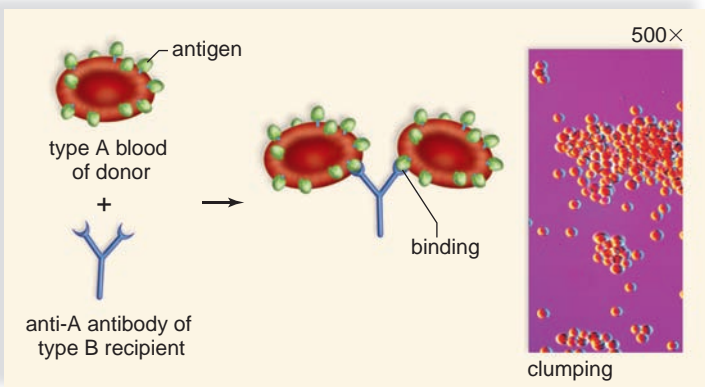
1. List the functions of blood.
2. Contrast red blood cells with white blood cells.
3. Describe how a blood clot forms.
4. Why can't you give type A blood to a type B recipient?



No agglutination

FIGURE 32.17 No agglutination.

No agglutination occurs when the donor and recipient have the same type blood.

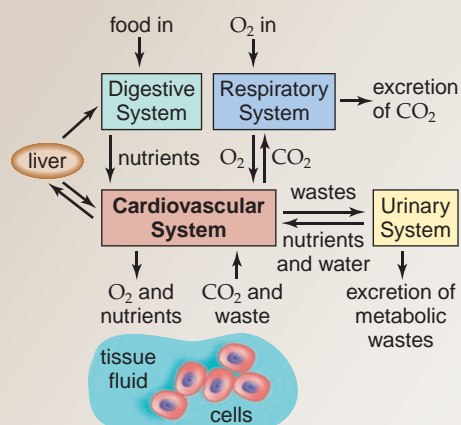


Agglutination

FIGURE 32.18 Agglutination.

Agglutination occurs because blood type B has anti-A antibodies in the plasma.

Connecting the Concepts



The cardiovascular system consists of the heart and the blood vessels, which can be likened to the streets of a town. Imagine that you have received birthday gifts and have decided to return some and pick up items you prefer. In a similar way, the cardiovascular system picks up nutrients at the intestinal tract, exchanges carbon dioxide for oxygen at the lungs, and deposits metabolic wastes at the kidneys. Therefore, the composition of the blood and the tissue fluid stays relatively constant. Tissue fluid, which surrounds the cells, makes exchanges with the blood, and if the composition of the blood stays constant,

tissue fluid will be able to supply the cells with the nutrients and oxygen they require and receive their metabolic wastes. In this way homeostasis, the relative constancy of the internal environment, will be maintained.

The pumping of the heart merely helps keep the blood moving so that it can continue to service the cells. While we tend to think of the body in terms of organs, it is the cells of the organs that do the work of keeping us alive and only if the cells are well cared for do we remain healthy. In Chapter 34, we consider the contribution of the digestive system to homeostasis.

summary

32.1 Transport in Invertebrates

Some invertebrates do not have a transport system. The presence of a gastrovascular cavity allows diffusion alone to supply the needs of cells in cnidarians and flatworms. Roundworms make use of their pseudocoelom in the same way that echinoderms use their coelom to circulate materials.

Other invertebrates do have a transport system. Insects have an open circulatory system, and earthworms have a closed one.

32.2 Transport in Vertebrates

Vertebrates have a closed system in which arteries carry blood away from the heart to capillaries, where exchange takes place, and veins carry blood to the heart.

Fishes have a one-circuit circulatory pathway because the heart, with the single atrium and ventricle, pumps blood only to the gills. The other vertebrates have both pulmonary and systemic circuits. Amphibians have two atria but a single ventricle. Crocodilians, birds, and mammals, including humans, have a heart with two atria and two ventricles, in which O₂-rich blood is always separate from O₂-poor blood.

32.3 Transport in Humans

The heartbeat in humans begins when the SA (sinoatrial) node (pacemaker) causes the two atria to contract, and blood moves through the atrioventricular valves to the two ventricles. The SA node also stimulates the AV (atrioventricular) node, which in turn causes the two ventricles to contract. Ventricular contraction sends blood through the semilunar valves to the pulmonary trunk and the aorta. Now all chambers rest. The heart sounds, lub-dub, are caused by the closing of the valves.

In the pulmonary circuit, blood can be traced to and from the lungs. In the systemic circuit, the aorta divides into blood vessels that serve the body's cells. The venae cavae return O₂-poor blood to the heart.

Blood pressure created by the beat of the heart accounts for the flow of blood in the arteries, but skeletal muscle contraction is largely responsible for the flow of blood in the veins, which have valves preventing a backward flow.

Hypertension and atherosclerosis are two circulatory disorders that lead to heart attack and to stroke. Following a heart-healthy diet, getting regular exercise, maintaining a proper weight, and not smoking cigarettes are protective against the development of these conditions.

32.4 Blood, a Transport Medium

Blood has two main parts: plasma and formed elements. Plasma contains mostly water (90–92%) and proteins (7–8%) but also contains nutrients and wastes.

The red blood cells contain hemoglobin and function in oxygen transport. Defense against disease depends on the various types of white blood cells. Neutrophils and monocytes are phagocytic and are very active during the inflammatory reaction. Lymphocytes are involved in the development of immunity to disease. Eosinophils are important in allergic reactions and parasitic infections, and basophils contain the anticoagulant heparin.

The platelets and two plasma proteins, prothrombin and fibrinogen, function in blood clotting, an enzymatic process that results in fibrin threads. Blood clotting is a complex process that includes three major events: (1) Platelets and injured tissue release prothrombin activator, which (2) enzymatically changes prothrombin to thrombin; (3) thrombin is an enzyme that causes fibrinogen to be converted to fibrin threads.

When blood reaches a capillary, water moves out at the arterial end, due to blood pressure. At the venous end, water moves in, due to osmotic pressure. In between, nutrients diffuse out of, and wastes diffuse into, the capillary.

The ABO system recognizes two possible antigens on the red blood cells (A and B) and two possible antibodies in the plasma, which are anti-A and anti-B. Type A blood cannot be given to a person with type B blood because the recipient's blood contains anti-A antibodies and agglutination will occur. Certain other combinations are also impossible.

understanding the terms

agglutination 609
 angina pectoris 605
 antibody 607
 antigen 607
 aorta 602
 arteriole 596
 artery 596
 atrioventricular valve 598
 atrium 598
 basophil 607
 blood 594

blood pressure 603
 capillary 596
 cardiac conduction system 600
 cardiac cycle 600
 cardiac output 600
 cardiac pacemaker 601
 circulatory (or cardiovascular) system 594, 596
 closed circulatory system 594
 diastole 600

electrocardiogram (ECG) 601	pulmonary circuit 597
eosinophil 607	pulse 600
heart 598	red blood cell 606
heart attack 605	semilunar valve 598
hemoglobin 606	septum 598
hemolymph 594	sphygmomanometer 603
lymph 608	stroke 605
lymphocyte 607	systemic circuit 597
macrophage 607	systole 600
monocyte 607	tissue fluid 608
neutrophil 607	vein 596
open circulatory system 594	vena cava 602
plasma 606	ventricle 598
platelet 607	venule 596
portal system 602	white blood cell 607

Match the terms to these definitions:

- _____ Blood vessel that transports blood away from the heart.
- _____ Cell fragment that is necessary to blood clotting.
- _____ The liquid portion of blood; contains nutrients, wastes, salts, and proteins.
- _____ The major systemic veins that take blood to the heart from the tissues.
- _____ Iron-containing respiratory pigment occurring in vertebrate red blood cells and in the blood plasma of many invertebrates.

reviewing this chapter

- Describe transport in invertebrates that have no circulatory system; in those that have an open circulatory system; and in those that have a closed circulatory system. 594–95
- Compare the circulatory systems of a fish, an amphibian, and a mammal. 597
- Trace the path of blood in humans from the right ventricle to the left atrium; from the left ventricle to the kidneys and to the right atrium; from the left ventricle to the small intestine and to the right atrium. 599
- Describe the mechanism of a heartbeat, mentioning all the factors that account for this repetitive process. Describe how the heartbeat affects blood flow. What other factors are involved in blood flow? 600–601
- Define these terms: pulmonary circuit, systemic circuit, and portal system. 601–2
- Discuss the life cycle and function of red blood cells. 606–7
- How are white blood cells classified? What are the functions of neutrophils, monocytes, and lymphocytes? 607
- Name the steps that take place when blood clots. Which substances are present in blood at all times, and which appear during the clotting process? 607
- What forces facilitate exchange of molecules across the capillary wall? 608
- Explain the ABO system of typing blood. 609

testing yourself

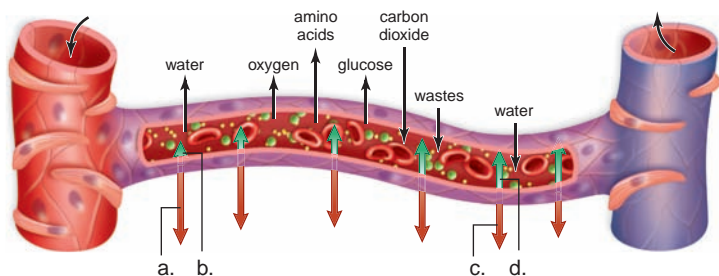
Choose the best answer for each question.

- Which one of these would you expect to be part of a closed, but not an open, circulatory system?
 - ostia
 - capillary beds
 - hemocoel
 - heart
 - All of these are correct.
- In a one-circuit circulatory pathway, blood pressure
 - is constant throughout the system.
 - drops significantly after gas exchange has taken place.
 - is higher at the intestinal capillaries than at the gill capillaries.
 - brings O₂-rich blood directly to the heart.
 - does not occur in the animal kingdom.
- In which animal does aortic blood have less oxygen than blood in the pulmonary vein?
 - frog
 - chicken
 - monkey
 - fish
 - All of these are correct.
- Which of these factors has little effect on blood flow in arteries?
 - heartbeat
 - blood pressure
 - total cross-sectional area of vessels
 - skeletal muscle contraction
 - the amount of blood leaving the heart
- In humans, blood returning to the heart from the lungs returns to
 - the right ventricle.
 - the right atrium.
 - the left ventricle.
 - the left atrium.
 - both the right and left sides of the heart.
- Systole refers to the contraction of the
 - major arteries.
 - SA node.
 - atria and ventricles.
 - major veins.
 - All of these are correct.
- Which of these is an incorrect association?
 - white blood cells—infection fighting
 - red blood cells—blood clotting
 - plasma—water, nutrients, and wastes
 - red blood cells—hemoglobin
 - platelets—blood clotting
- Water enters capillaries on the venous end as a result of
 - active transport from tissue fluid.
 - an osmotic pressure gradient.
 - higher blood pressure on the venous end.
 - higher blood pressure on the arterial side.
 - higher red blood cell concentration on the venous end.
- The last step in blood clotting
 - is the only step that requires calcium ions.
 - occurs outside the bloodstream.
 - is the same as the first step.
 - converts prothrombin to thrombin.
 - converts fibrinogen to fibrin.
- Macrophages are derived from
 - basophils.
 - eosinophils.
 - neutrophils.
 - lymphocytes.
 - monocytes.
- Which of the following is not a formed element of blood?
 - leukocyte
 - eosinophil
 - fibrinogen
 - platelet
- Which of these is an incorrect statement concerning the heartbeat?
 - The atria contract at the same time.
 - The ventricles relax at the same time.
 - The atrioventricular valves open at the same time.
 - The semilunar valves open at the same time.
 - First, the right side contracts, and then the left side contracts.

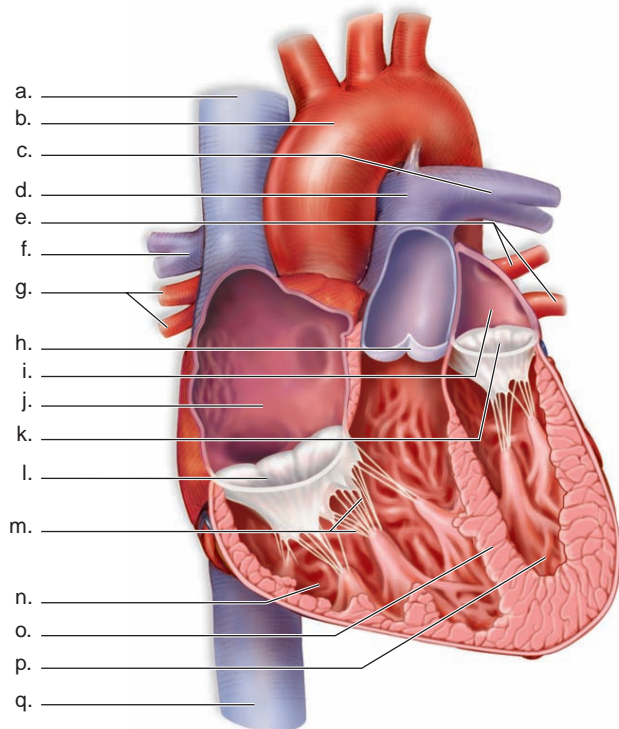
13. All arteries in the body contain O_2 -rich blood, with the exception of the
- aorta.
 - pulmonary arteries.
 - renal arteries.
 - coronary arteries.
14. The cardiac veins directly enter
- the inferior vena cava.
 - the superior vena cava.
 - the right atrium.
 - the left atrium.
15. The “lub,” the first heart sound, is produced by the closing of
- the aortic semilunar valve.
 - the pulmonary semilunar valve.
 - the right (atrioventricular) tricuspid valve.
 - the left (atrioventricular) bicuspid valve, or mitral valve.
 - both atrioventricular valves.

For questions 16–19, indicate whether the statement is true (T) or false (F).

16. Carbon dioxide exits the arterial end of the capillary, and oxygen enters the venous end of the capillary. _____
17. Platelets form a plug by sticking to each other. _____
18. Another term for blood clotting is agglutination. _____
19. SA node impulses cause the atria to contract. _____
20. Label portions of these arrows a–d as either blood pressure or osmotic pressure.



21. Label this diagram of the heart.



thinking scientifically

- For several years, researchers have attempted to produce an artificial blood for transfusions. Artificial blood would most likely be safer and more readily available than human blood. While artificial blood might not have all the characteristics of human blood, it would be useful on the battlefield and in emergency situations. Which characteristics of normal blood must artificial blood have to be useful, and which would probably be too difficult to reproduce?
- You have to stand in front of the class to give a report. You are nervous, and your heart is pounding. How would your ECG appear?

bioethical issue

A Healthy Lifestyle

Many deaths a year could be prevented if people adopted the healthy lifestyle described in the Health Focus on page 604. Tobacco, lack of exercise, and a high-fat diet probably cost the nation about \$200 billion per year in health-care costs. To what lengths should we go to prevent these deaths and reduce health-care costs?

E. A. Miller, a meatpacking entity of ConAgra in Hyrum, Utah, charges extra for medical coverage of employees who smoke. Eric Falk, Miller's director of human resources, says, "We want to teach employees to be responsible for their behavior." Anthem Blue Cross–Blue Shield of Cincinnati, Ohio, takes a more positive approach. They give insurance plan participants \$240 a year in extra benefits, such as additional vacation days, if they get good scores in five out of seven health-related categories. The University of Alabama, Birmingham, School of Nursing has a health-and-wellness program that counsels employees about how to get into shape in order to keep their insurance coverage. Audrey Brantley, who is in the program, has mixed feelings. She says, "It seems like they are trying to control us, but then, on the other hand, I know of folks who found out they had high blood pressure or were borderline diabetics and didn't know it."

Does it really work? Turner Broadcasting System in Atlanta has a policy that affects all employees hired after 1986. They will be fired if caught smoking—whether at work or at home—but some admit they still manage to sneak a smoke. What steps do you think are ethical to encourage people to adopt a healthy lifestyle?

Biology website

The companion website for *Biology* provides a wealth of information organized and integrated by chapter. You will find practice tests, animations, videos, and much more that will complement your learning and understanding of general biology.

<http://www.mhhe.com/maderbiology10>

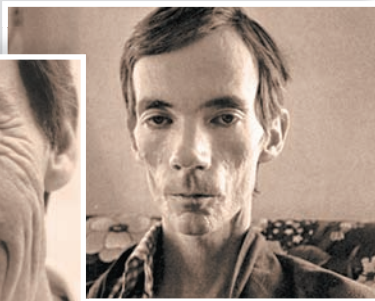
33

Lymph Transport and Immunity

the immunodeficiency virus (HIV) attacks the immune system and prevents it from mounting an organized defense. An HIV infection terminates in AIDS (acquired immunodeficiency syndrome), an illness characterized by weight loss, innumerable infections including herpes, and life-threatening illnesses from pneumonia to cancer. HIV is sexually transmitted, and everyone should follow certain guidelines to prevent an HIV infection because presently there is no cure: Either abstain or have a monogamous relationship with a person free of STDs (sexually transmitted diseases); don't inject drugs and be wary of a relationship with an intravenous drug user; always use a condom and avoid both anal intercourse and oral sex because HIV can be transmitted in these ways also.

This chapter begins with the lymphatic system, which has an intimate connection with immunity, and then it reviews the mechanisms the immune system ordinarily uses to keep us healthy. Finally, we will consider various illnesses that beset us when immunity falters.

A patient with AIDS. These photos show how the health of a patient with AIDS deteriorates.



33.1 THE LYMPHATIC SYSTEM

- The lymphatic vessels form a one-way system, which transports lymph from the tissues and fat from the digestive tract to certain cardiovascular veins. 614
- The lymphatic organs (lymph nodes, tonsils, spleen, thymus gland, red bone marrow) play critical roles in defense mechanisms. 614–15

33.2 NONSPECIFIC DEFENSE AGAINST DISEASE

- Nonspecific defenses consist of barriers to entry, the inflammatory response, phagocytes and natural killer cells, and protective proteins. 616–18
- Nonspecific defense is also called innate immunity because the responses are fully functional without previous exposure to a disease agent.

33.3 SPECIFIC DEFENSE AGAINST DISEASE

- Specific defenses require two types of lymphocytes: B lymphocytes and T lymphocytes. 619–25
- Specific defense is also called acquired immunity because the responses develop after exposure to a disease agent, whether the exposure is due to infection or vaccination.
- Active immunity, which occurs due to the production of antibodies following an illness or vaccine administration, is long lasting. Passive immunity, which occurs when antibodies are administered, is short-lived. 620–21

33.4 IMMUNITY SIDE EFFECTS

- While immunity preserves life, it is also responsible for certain undesirable effects, such as allergies, blood type incompatibility, tissue rejection, and autoimmune diseases. 628–29

33.1 The Lymphatic System

The **lymphatic system**, which is closely associated with the cardiovascular system, has four main functions that contribute to homeostasis:

- Lymphatic capillaries absorb excess tissue fluid and return it to the bloodstream.
- In the small intestines, lymphatic capillaries called lacteals absorb fats in the form of lipoproteins and transport them to the bloodstream.
- The lymphatic system is responsible for the production, maintenance, and distribution of lymphocytes.
- The lymphatic system helps defend the body against pathogens.

Lymphatic Vessels

Lymphatic vessels form a one-way system that begins with lymphatic capillaries (Fig. 33.1). Most regions of the body are richly supplied with lymph-

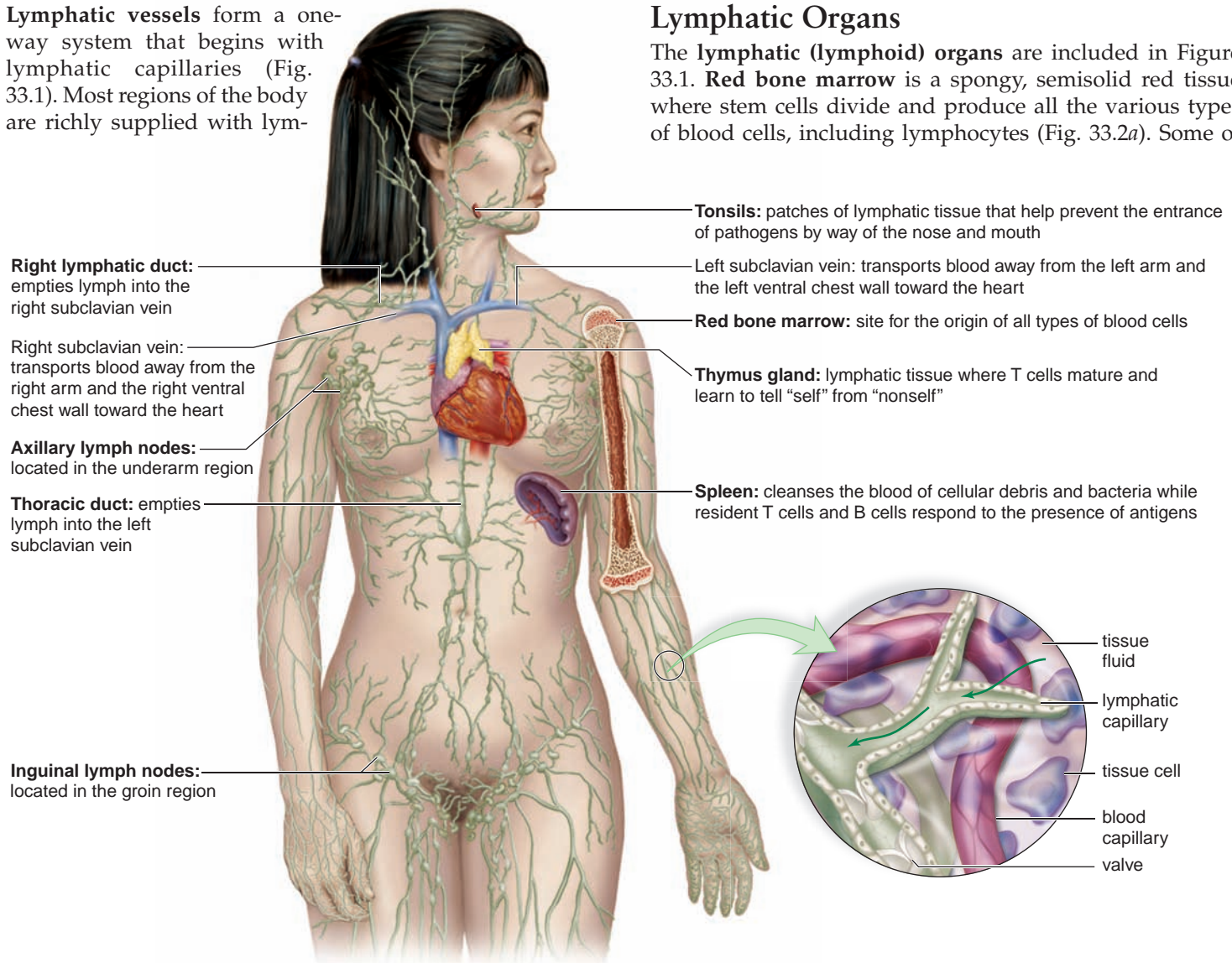


FIGURE 33.1 Lymphatic system.

Lymphatic vessels drain excess fluid from the tissues and return it to the cardiovascular system. The enlargement shows that lymphatic vessels, like cardiovascular veins, have valves to prevent backward flow. The lymph nodes, spleen, thymus gland, and red bone marrow are the main lymphatic organs that assist immunity.

phatic capillaries—tiny, closed-ended vessels. Lymphatic capillaries take up excess tissue fluid. The fluid inside lymphatic capillaries is called **lymph**. In addition to water and fat molecules, lymph contains the same ions, nutrients, gases, and proteins that are present in tissue fluid. It also contains defense molecules called antibodies, which are produced by lymphocytes.

The lymphatic capillaries join to form lymphatic vessels that merge before entering one of two ducts: the thoracic duct or the right lymphatic duct. The larger thoracic duct returns lymph to the left subclavian vein. The right lymphatic duct returns lymph to the right subclavian vein.

The construction of the larger lymphatic vessels is similar to that of cardiovascular veins, including the presence of valves. Skeletal muscle contraction forces lymph through lymphatic vessels, and then it is prevented from flowing backward by the one-way valves.

Lymphatic Organs

The **lymphatic (lymphoid) organs** are included in Figure 33.1. **Red bone marrow** is a spongy, semisolid red tissue where stem cells divide and produce all the various types of blood cells, including lymphocytes (Fig. 33.2a). Some of

these become mature **B cells**, a major type of lymphocyte, in the bone marrow. In a child, most of the bones have red bone marrow, but in an adult, it is present only in the bones of the skull, the sternum (breastbone), the ribs, the clavicle (collarbone), the pelvic bones, the vertebral column, and the proximal heads of the femur and humerus.

The red bone marrow consists of a network of connective tissue fibers that supports the stem cells and their progeny. They are packed around thin-walled sinuses filled with venous blood. Differentiated blood cells enter the bloodstream at these sinuses.

The soft, bilobed **thymus gland** is located in the thoracic cavity between the trachea and the sternum ventral to the heart (see Fig. 33.1). Immature **T cells**, the other major type of lymphocyte, migrate from the bone marrow through the bloodstream to the thymus, where they mature. The thymus also produces thymic hormones, such as thymosin, that are thought to aid in the maturation of T cells. The thymus varies in size, but it is largest in children and shrinks as we get older. In the elderly, it is barely detectable. When well developed, it contains many lobules (Fig. 33.2b).

Lymph nodes are small (about 1–25 mm in diameter), ovoid structures occurring along lymphatic vessels. Lymph nodes are named for their location. For example, inguinal lymph nodes are in the groin, and axillary lymph nodes are in the armpits. Physicians often feel for the presence of swollen, tender lymph nodes in the neck as evidence that the body is fighting an infection.

As lymph courses through the sinuses (open spaces) of the medulla (Fig. 33.2c), it is cleansed by macrophages, which engulf debris and pathogens. The many B and T cells also present help the immune system destroy pathogens.

Unfortunately, cancer cells sometimes enter lymphatic vessels and congregate in lymph nodes. Therefore, when a person undergoes surgery for cancer, it is a routine procedure to remove some lymph nodes and examine them to determine whether the cancer has spread to other regions of the body.

The **spleen**, an oval organ with a dull purplish color, is located in the upper left side of the abdominal cavity posterior to the stomach. Most of the spleen is red pulp that filters and cleanses the blood. Red pulp consists of blood vessels and sinuses, where macrophages remove old and defective blood cells. The spleen also has white pulp that is inside the red pulp and consists of little lumps of lymphatic tissue where B and T cells congregate (Fig. 33.2d).

The spleen's outer capsule is relatively thin, and an infection or a blow can cause the spleen to burst. Although the spleen's functions can be largely replaced by other organs, a person without a spleen is often slightly more susceptible to infections and may require antibiotic therapy indefinitely.

Patches of lymphatic tissue in the body include the **tonsils**, located in the pharynx; **Peyer patches**, located in the intestinal wall; and the vermiform appendix, attached to the cecum. These structures encounter pathogens and antigens that enter the body by way of the mouth.

Check Your Progress

33.1

1. Give a brief description of the lymphatic system.
2. Summarize the functions of the lymphatic system.
3. Briefly describe the general appearance, location, and function of the lymphatic organs.

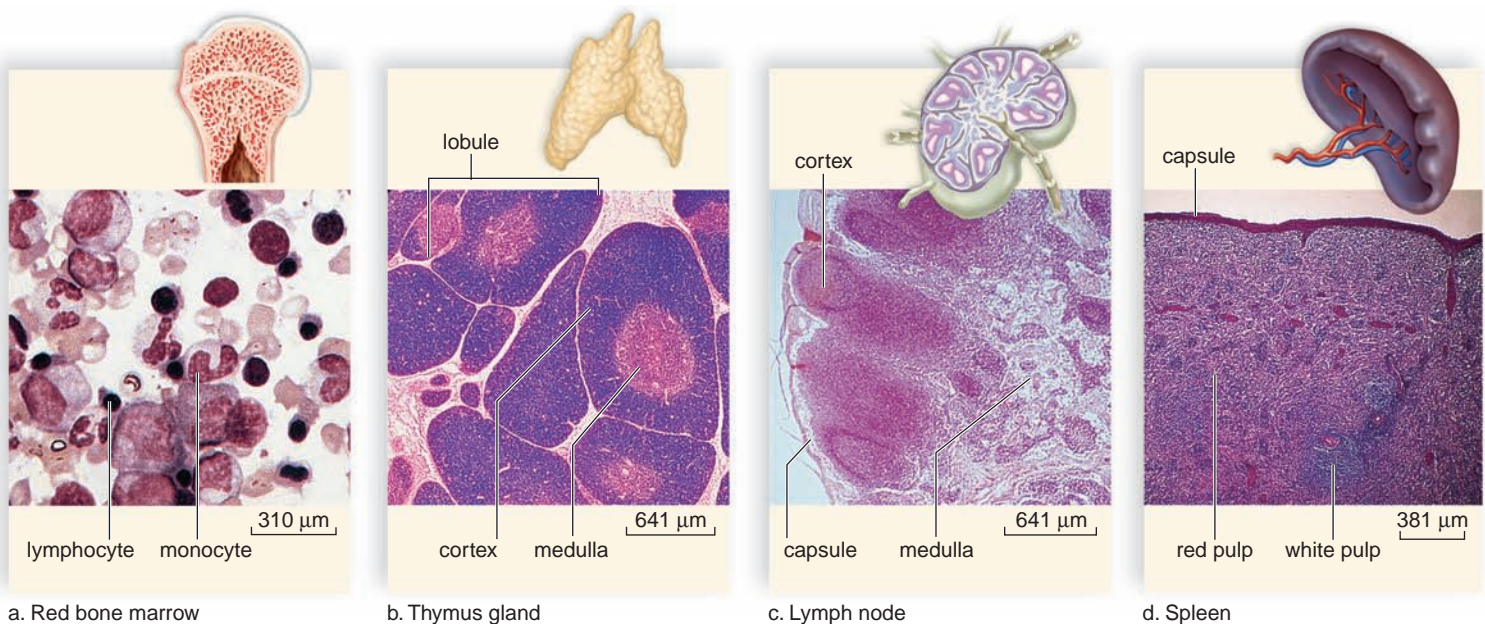


FIGURE 33.2 The lymphatic organs.

a. Blood cells, including lymphocytes, are produced in red bone marrow. B cells mature in the bone marrow, but **(b)** T cells mature in the thymus. **c.** Lymph is cleansed in lymph nodes, while **(d)** blood is cleansed in the spleen.

33.2 Nonspecific Defense Against Disease

We are constantly exposed to pathogens in our food and drink and as we breathe air or touch objects, both living and inanimate, in our environment. The warm temperature and constant supply of nutrients in our bodies make them an ideal place for pathogens to flourish. Without a means of defense, we would be unable to prevent invasions by all sorts of pathogens and would soon die. Fortunately, our body provides us with nonspecific defenses and specific defenses. Other organisms also have this ability to defend themselves, but none have been studied as much as humans because our defense mechanisms are very important to the field of medicine.

Immunity begins with the nonspecific defenses, which are summarized in Figure 33.3. They include (1) barriers to entry such as the skin, (2) protective proteins such as complement and interferons, (3) phagocytes and natural killer cells, and (4) the inflammatory response. Because nonspecific defenses occur automatically, the term *innate immunity* is preferred by some. With this type of immunity, there is no rec-

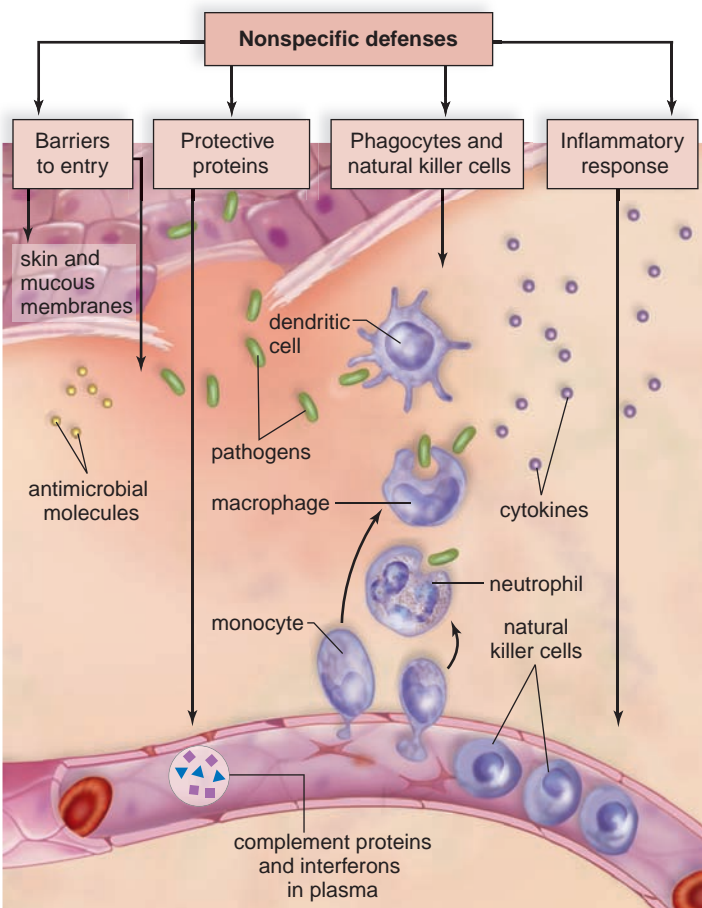


FIGURE 33.3 Overview of nonspecific defenses.

Nonspecific defenses act rapidly to detect and respond to an infection by any and all pathogens and cancer cells. Nonspecific defenses include barriers to entry, protective proteins, phagocytes and natural killer cells, and the inflammatory response.

ognition that an intruder has attacked before. Later, we will discuss specific defenses, which are directed against particular pathogens and do exhibit memory.

Barriers to Entry

Barriers to entry by pathogens include non-chemical, mechanical barriers, such as the skin and the mucous membranes lining the respiratory, digestive, and urinary tracts. For example, the upper layers of our skin are composed of dead, keratinized cells that form an impermeable barrier. But when the skin has been injured, one of the first concerns is the possibility of an infection. We are also familiar with the importance of sterility before an injection is given. The injection needle and the skin must be free of pathogens. This testifies to the importance of skin as a defense against invasion by a pathogen.

The mucus of mucous membranes physically ensnares microbes. The upper respiratory tract is lined by ciliated cells that sweep mucus and trapped particles up into the throat, where they can be swallowed or expectorated (coughed out). In addition, the various bacteria that normally reside in the intestine and other areas, such as the vagina, prevent pathogens from taking up residence.

Barriers to entry also include antimicrobial molecules. Oil gland secretions contain chemicals that weaken or kill certain bacteria on the skin; mucous membranes secrete lysozyme, an enzyme that can lyse bacteria; and the stomach has an acidic pH, which inhibits the growth of many types of bacteria, or may even kill them.

Inflammatory Response

Whenever tissue is damaged by physical or chemical agents or by pathogens, a series of events occurs that is known as the **inflammatory response**.

An inflamed area has four outward signs: redness, heat, swelling, and pain. All of these signs are due to capillary changes in the damaged area. Figure 33.4 illustrates the participants in the inflammatory response. Chemical mediators, such as **histamine**, released by damaged tissue cells, and mast cells cause the capillaries to dilate and become more permeable. Excess blood flow, due to enlarged capillaries, causes the skin to redden and become warm. Increased permeability of the capillaries allows proteins and fluids to escape into the tissues, resulting in swelling. The swollen area stimulates free nerve endings, causing the sensation of pain.

Migration of phagocytes, namely neutrophils and monocytes, also occurs during the inflammatory response. Neutrophils and monocytes are amoeboid and can change shape to squeeze through capillary walls and enter tissue fluid. Also present are dendritic cells, notably in the skin and mucous membranes, and macrophages, both of which are able to devour many pathogens and still survive (Fig. 33.5). Macrophages also release colony-stimulating factors, cytokines that pass by way of the blood to the red bone marrow, where they stimulate the production and release of white blood cells, primarily neutrophils. As the infection is being

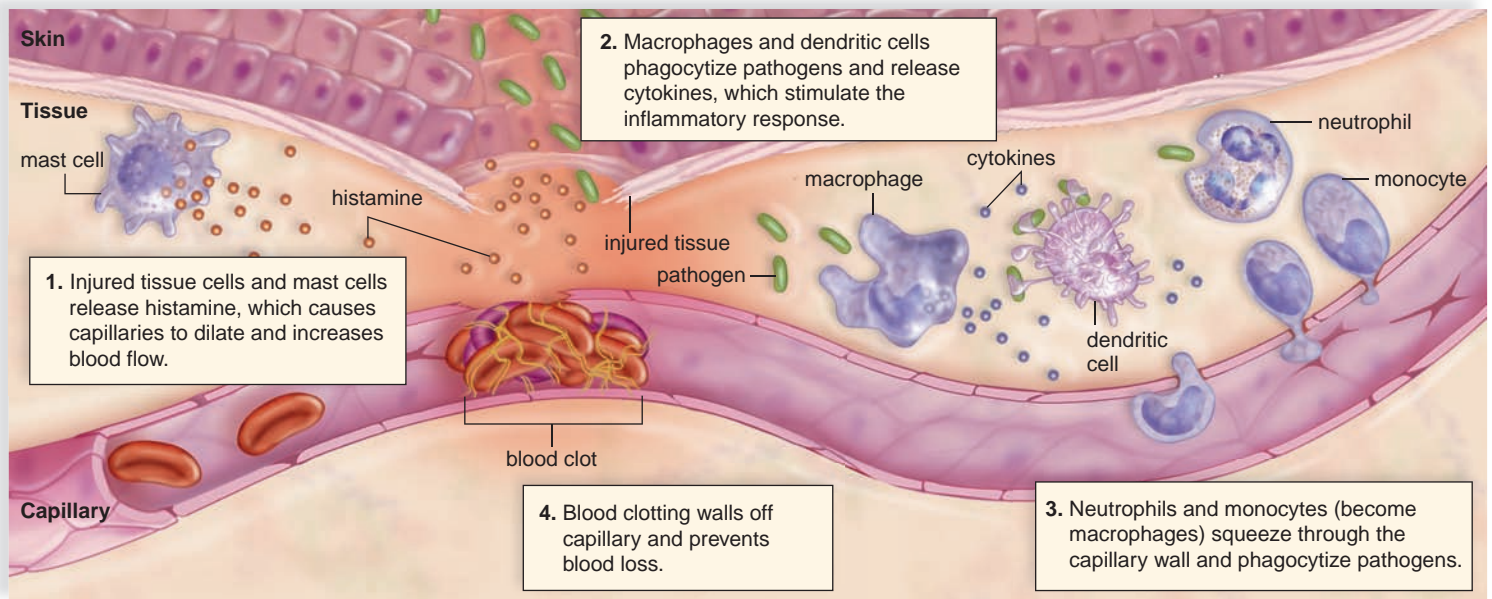


FIGURE 33.4 Inflammatory response.

Due to capillary changes in a damaged area and the release of chemical mediators, such as histamine by mast cells, an inflamed area exhibits redness, heat, swelling, and pain. The inflammatory response can be accompanied by other reactions to the injury. Macrophages and dendritic cells, present in the tissues, phagocytize pathogens, as do neutrophils, which squeeze through capillary walls from the blood. Macrophages and dendritic cells release cytokines, which stimulate the inflammatory and other immune responses. A blood clot can form to seal a break in a blood vessel.

overcome, some phagocytes die. These—along with dead tissue cells, dead bacteria, and living white blood cells—form pus, a whitish material. The presence of pus indicates that the body is trying to overcome an infection.

The inflammatory response can be accompanied by other responses to the injury. A blood clot can form to seal a

break in a blood vessel. Antigens, chemical mediators, dendritic cells, and macrophages move through the tissue fluid and lymph to the lymph nodes. There, B cells and T cells are activated to mount a specific defense to the infection.

Sometimes an inflammation persists, and the result is chronic inflammation that is often treated by administering anti-inflammatory agents such as aspirin, ibuprofen, or cortisone. These medications act against the chemical mediators released by the white blood cells in the damaged area.

Fever

An illness may result in a fever, an elevated body temperature. To treat or not to treat a fever is controversial within the medical field for, in some instances, a fever may be beneficial. Perhaps a fever is the body's way of informing us that something is wrong. Alternatively, a fever could be part of our first line of defense. At times, a fever may directly participate in overcoming an illness. For example, a fever can contribute to the host's defense by providing an unfavorable environment for the invader. Some pathogens have very strict temperature requirements, and turning up the heat on them can slow their ability to multiply and thrive. In fact, supporting this hypothesis is the observation that increasing the body temperature in mice has been shown to decrease death rates and shorten the recovery time linked to many infectious agents.

Other medical experts believe that the main function of a fever is to stimulate immunity. In support of this hypothesis, a fever has been shown to limit the growth of tumor

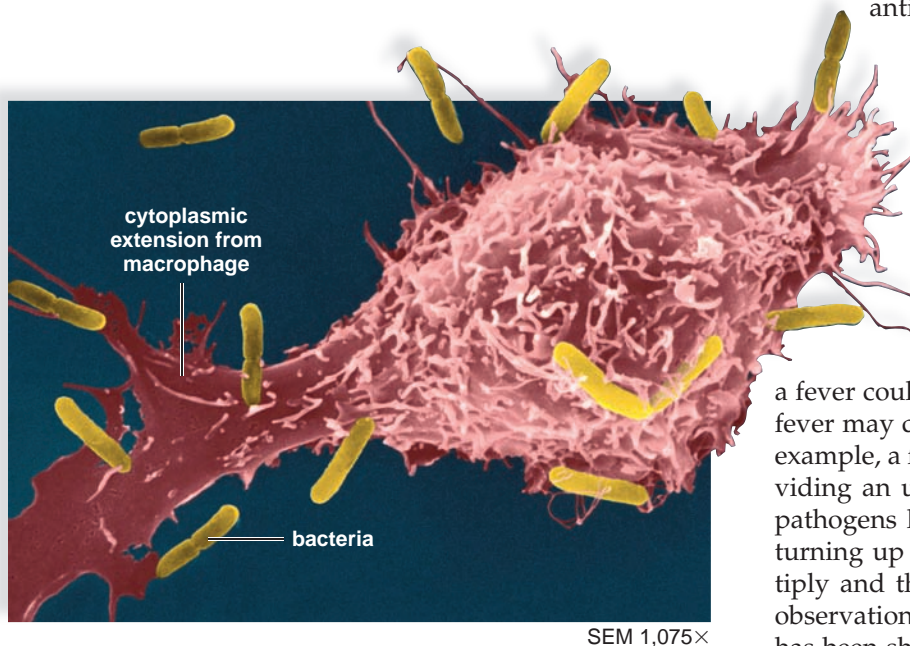


FIGURE 33.5 Macrophage engulfing bacteria.

Monocyte-derived macrophages are the body's scavengers. They engulf microbes and debris in the body's fluids and tissues, as illustrated in this colorized scanning electron micrograph.

cells more severely than that of normal body cells. This suggests either that tumor cells are directly sensitive to higher temperatures or that a fever stimulates immunity. Heat is a part of the inflammatory response, and perhaps its main function is to jump-start the response of the body.

While data concerning the benefits of fever are inconclusive, the general consensus is that an extreme fever should be treated but milder cases may be best left alone.

Phagocytes and Natural Killer Cells

Several types of white blood cells are phagocytic. **Neutrophils** are cells that are able to leave the bloodstream and phagocytize (engulf) bacteria in connective tissues. They have various other ways of killing bacteria also. For example, their granules release antimicrobial peptides called defensins. **Eosinophils** are phagocytic, but they are better known for mounting an attack against animal parasites such as tapeworms that are too large to be phagocytized. The two most powerful of the phagocytic white blood cells are **macrophages** (see Fig. 33.5) and macrophage-derived **dendritic cells**. They engulf pathogens, which are then destroyed by enzymes when their endocytic vesicles combine with lysosomes. Dendritic cells are found in the skin; once they devour pathogens, they travel to lymph nodes, where they stimulate natural killer cells or lymphocytes. Macrophages are found in all sorts of tissues, where they voraciously devour pathogens and then stimulate lymphocytes to carry on specific immunity.

Natural killer (NK) cells are large, granular lymphocytes that kill virus-infected cells and cancer cells by cell-to-cell contact. NK cells do their work while specific defenses are still mobilizing, and they produce cytokines that promote specific defenses.

What makes NK cells attack and kill a cell? First, they normally congregate in the tonsils, lymph nodes, and spleen, where they are stimulated by dendritic cells before they travel forth. Then, NK cells look for a self-protein on the body's cells. As may happen, if a virus-infected cell or a cancer cell has lost its self-proteins, the NK cell kills it in the same manner used by cytotoxic T cells. Unlike cytotoxic T cells, NK cells are not specific; they have no memory; and their numbers do not increase after stimulation.

Protective Proteins

Complement is composed of a number of blood plasma proteins that “complement” certain immune responses, which accounts for their name. These proteins are continually present in the blood plasma but must be activated by pathogens to exert their effects. Complement helps destroy pathogens in three ways:

1. Enhanced inflammation. Complement proteins are involved in and amplify the inflammatory response because certain ones can bind to **mast cells** (type of white blood cell in tissues) and trigger histamine release, and others can attract phagocytes to the scene.
2. Some complement proteins bind to the surface of pathogens already coated with antibodies, which

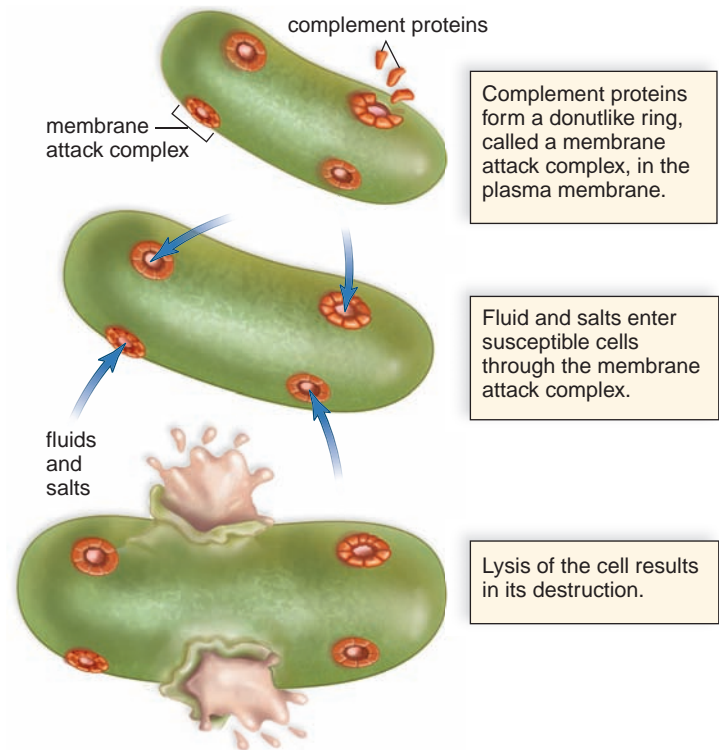


FIGURE 33.6 Action of the complement system against a bacterium.

When complement proteins in the blood plasma are activated by an immune response, they form a membrane attack complex that makes holes in bacterial cell walls and plasma membranes, allowing fluids and salts to enter until the cell eventually bursts.

ensures that the pathogens will be phagocytized by a neutrophil or macrophage.

3. Certain other complement proteins join to form a membrane attack complex that produces holes in the surface of some bacteria and viruses. Fluids and salts then enter the bacterial cell or virus to the point that it bursts (Fig. 33.6).

Interferons are **cytokines**, soluble proteins that affect the behavior of other cells. Interferons are made by virus-infected cells. They bind to the receptors of noninfected cells, causing them to produce substances that interfere with viral replication. Interferons, now available as a biotechnology product, are used to treat certain viral infections, such as hepatitis C.

Check Your Progress

33.2

1. What are some examples of the body's nonspecific defenses?
2. Which blood cells, in particular, should you associate with nonspecific defenses, and how do they function?
3. Why are the complement proteins so named?

33.3 Specific Defense Against Disease

When nonspecific defenses have been inadequate to stop an infection, specific defense comes into play. Immunity is complete when a pathogen such as a bacteria or virus is unable to cause an infection now or in the future, or when people are able to avoid cancer. These steps accomplish a specific defense and from them you can see why the term *acquired immunity* is preferred by some. During the first step, *recognition* of a particular molecule, called an **antigen**, occurs. Some antigens are termed **foreign antigens** because the body does not produce them. Pathogens, cancer cells, and transplanted tissues and

organs bear antigens the immune system usually recognizes as foreign. Other antigens are termed **self-antigens** because the body itself produces them. (The self-proteins mentioned on the previous page are self-antigens.) It is unfortunate when the immune system reacts to the body's own pancreatic cells (causing diabetes mellitus) or to nerve fiber sheaths (causing multiple sclerosis), but fortunate when the immune system can destroy the cancerous cells of a tumor. Second, a *response* occurs. Unlike the nonspecific defenses, which occur immediately, it usually takes five to seven days to mount a specific defense. Third, the immune system can *remember* antigens it has met before. This is the reason, for example, that once we recover from the measles, we usually do not get the disease a second time. The reaction time for a nonspecific defense is always about the same, but if the body is immune, the reaction time for a specific defense is quite short the next time it encounters the same antigen.

Specific defenses primarily depend on the two types of lymphocytes, called B cells and T cells (Fig. 33.7). Both B cells and T cells are manufactured in the red bone marrow. B cells mature there, but T cells mature in the thymus. These cells are capable of recognizing antigens because they have specific **antigen receptors** that combine with antigens. B cells have **B-cell receptors (BCRs)**, and T cells have **T-cell receptors (TCRs)**. Each lymphocyte has receptors that will combine with only one type of antigen. If a particular B cell could respond to an antigen—a molecule projecting from the bacterium *Streptococcus pyogenes* for example—it would not react to any other antigen. It is often said that the receptor and the antigen fit together like a lock and a key. Remarkably, diversification occurs to such an extent during maturation that there are specific B cells and/or T cells for any possible antigen we are likely to encounter during a lifetime.

B cells are responsible for **antibody-mediated immunity** (Fig. 33.7, left). When B cells encounter an antigen, a BCR recognizes it directly and combines with it right away. Then, the B cell gives rise to **plasma cells**, which produce specific antibodies. These antibodies can react to the same antigen as the original B cell. Therefore, an antibody has the same specificity as the BCR. Some progeny of the activated B cells become **memory B cells**, so called because these cells always “remember” a particular antigen and make us immune to a particular illness, but not to any other illness.

In contrast to B cells, T cells are responsible for **cell-mediated immunity** (Fig. 33.7, right). T cells do not recognize an antigen directly and instead the antigen must be presented to them by an **antigen-presenting cell (APC)**. Macrophages and dendritic cells are APCs. T cells exist primarily as **helper T cells**, which regulate specific immunity, and **cytotoxic T cells**, which attack and kill virus-infected cells and cancer cells. Some cytotoxic T cells become **memory T cells**, ever ready to defend against the same virus or kill the same type of cancer cell again.

Because B and T cells defend us from disease by specifically reacting to antigens, they can be likened to special forces that can attack selected targets without harming nearby residents (cells).

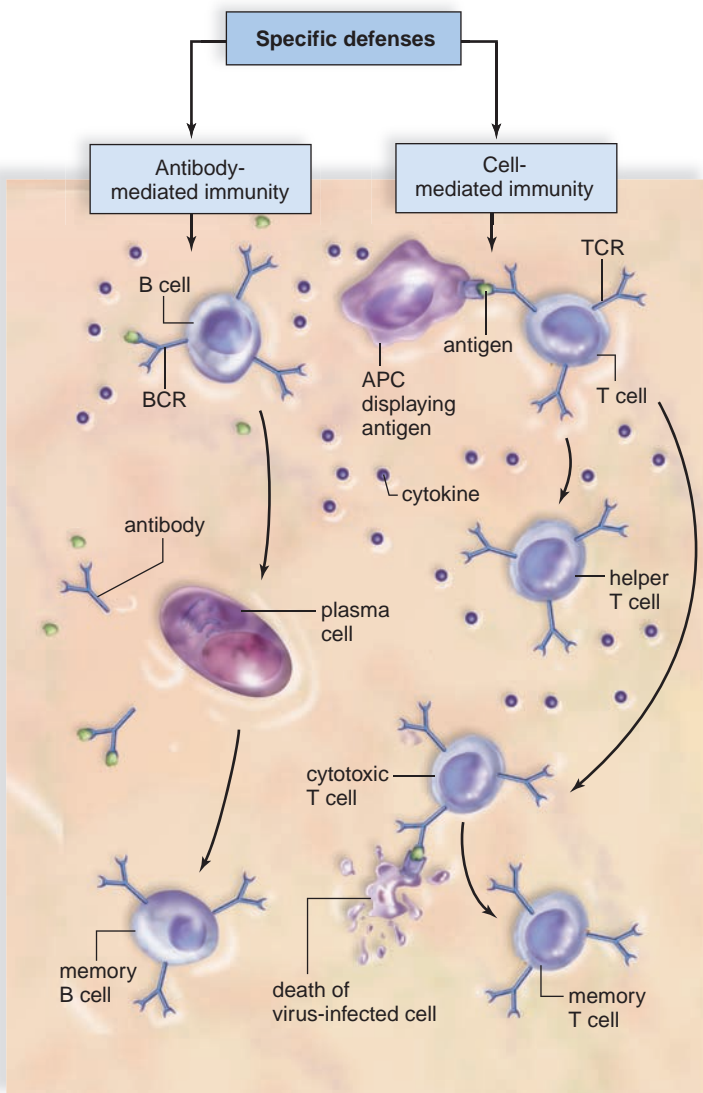


FIGURE 33.7 Overview of specific defenses.

If nonspecific defenses are inadequate, specific defenses come into play, and attack is then directed against a particular antigen (colored green). The antigen is a part of a pathogen or cancer cell. On the left, B cells are responsible for antibody-mediated immunity, which involves the production of antibodies by plasma cells and the production of memory B cells. On the right, T cells are responsible for cell-mediated immunity. They recognize an antigen only after it is presented to them by an APC. Then, T cells kill virus-infected or cancer cells on contact.

B Cells and Antibody-Mediated Immunity

The **clonal selection model** describes what happens when a *B-cell receptor (BCR)* combines with an antigen (Fig. 33.8).

① Many B cells are present, but only the one that has BCRs that can combine with the specific antigen clone goes on to divide and produce many new cells. Therefore, the antigen is said to “select” the B cell that will clone. Also, at this time, cytokines secreted by helper T cells stimulate B cells to clone. ② Defense by B cells is called *antibody-*

mediated immunity because most members of the clone become plasma cells that produce specific antibodies. It is also called humoral immunity because these antibodies are present in blood and lymph. (A *humor* is any fluid normally occurring in the body.) ③ Some progeny of activated B cells become **memory B cells**, which are the means by which long-term immunity is possible. Once the threat of an infection has passed, the development of new plasma cells ceases, and those present undergo apoptosis.

Active Versus Passive Immunity

Active immunity occurs when an individual produces a supply of antibodies. For example, when you catch the measles, you recover because your body produces the antibodies that combine with the measles-causing viruses and bring about their destruction. Another way to become actively immune is to undergo immunization. **Immunization** involves the use of vaccines to bring about clonal expansion, not only of B cells, but also of T cells. Traditionally, vaccines are the pathogens themselves, or their products, that have been treated so they are no longer virulent (able to cause disease). Vaccines against smallpox, polio, and tetanus have been successfully used worldwide. Today, it is possible to genetically engineer bacteria to mass-produce a protein from pathogens, and this protein can be used as a vaccine. This method was used to produce a vaccine against hepatitis B, a viral disease, and is being used to prepare a potential vaccine against malaria.

After a vaccine is given, it is possible to determine the antibody titer (the amount of antibody present in a sample of plasma). After the first exposure to a vaccine, a primary response occurs. For a period of several days, no antibodies are present; then the titer rises slowly, followed by first a plateau and then a gradual decline as the antibodies bind to the antigen or simply break down (Fig. 33.9). After a second exposure, the titer rises rapidly to a plateau level much greater than before. The second exposure is called a “booster” because it boosts the antibody titer to a high level. The high antibody titer is expected to prevent disease symptoms when the individual is exposed to the antigen. Even years later, if the antigen enters the body, memory B cells quickly give rise to more plasma cells capable of producing the correct type of antibody.

Passive immunity occurs when an individual is given prepared antibodies (immunoglobulins) to combat a disease. Since these antibodies are not produced by the individual's plasma cells, passive immunity is short-lived. For example, newborn infants are passively immune to some diseases because antibodies have crossed the placenta from the mother's blood (Fig. 33.10). These antibodies soon disappear, however, so that within a few months, infants become more susceptible to infections. Breast-feeding prolongs the natural passive immunity an infant receives from its mother because antibodies are present in the mother's milk.

Even though passive immunity does not last, it is sometimes used to prevent illness in a patient who has been

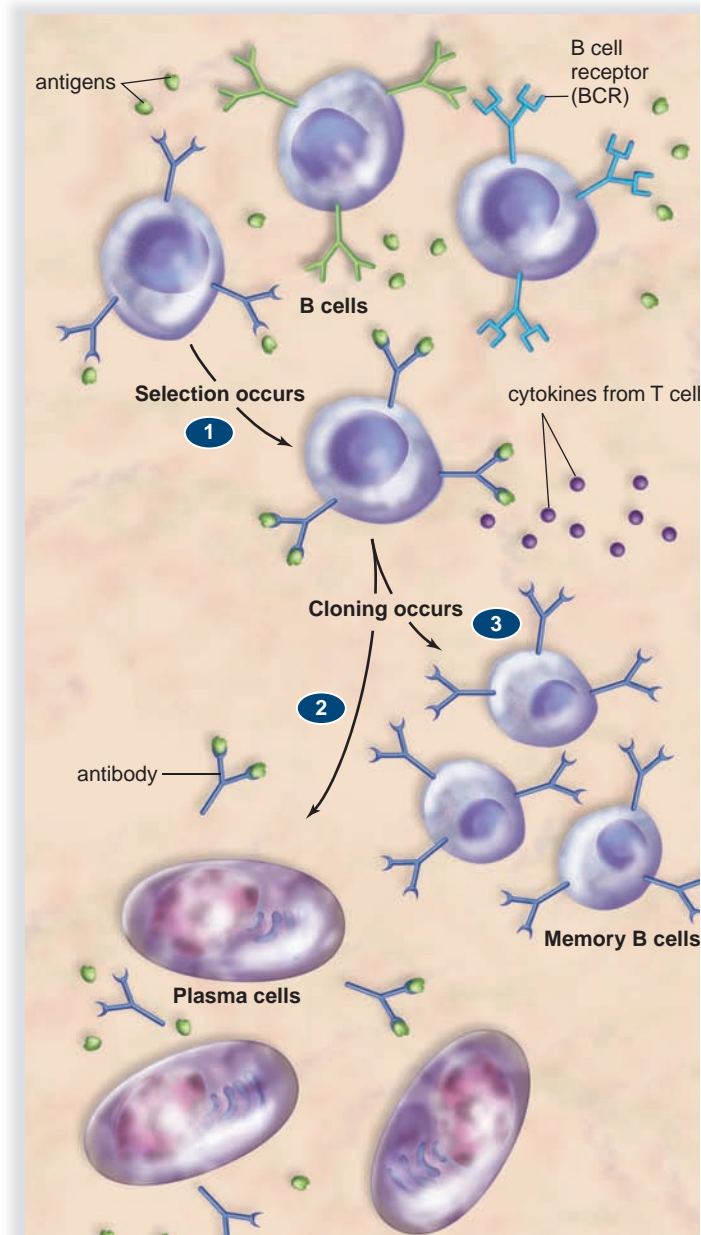
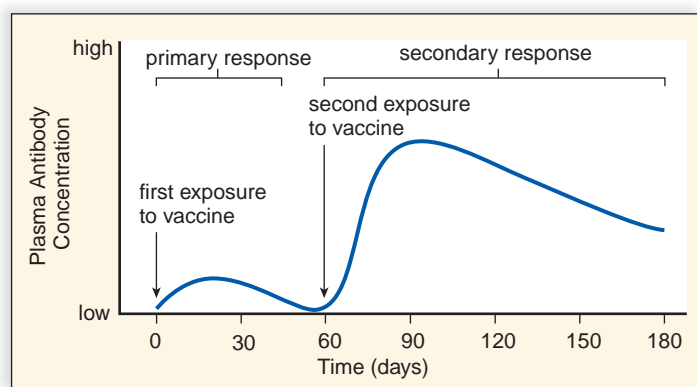


FIGURE 33.8 Clonal selection model as it applies to B cells.

Activation of a B cell occurs when its B-cell receptor (BCR) can combine with an antigen (colored green). In the presence of cytokines, this B cell undergoes clonal expansion, producing many plasma cells that secrete antibodies specific to the antigen.

FIGURE 33.9**Antibody titers.**

During immunization, the primary response after the first injection of a vaccine is minimal, but the secondary response, which may occur after the second injection, shows a dramatic rise in the amount of antibody present in plasma.

**FIGURE 33.10****Passive immunity.**

Breast-feeding is believed to prolong the passive immunity an infant receives from the mother during pregnancy because antibodies are present in the mother's milk.



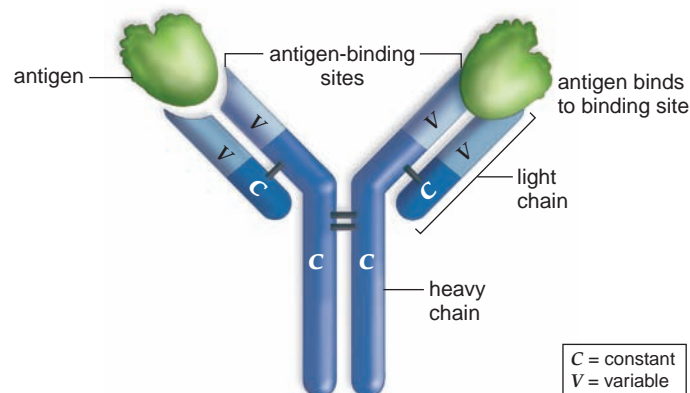
unexpectedly exposed to an infectious disease. Artificial passive immunity is used in the emergency treatment of rabies, measles, tetanus, diphtheria, botulism, hepatitis A, and snakebites. Usually, the patient receives a gamma globulin injection (serum that contains antibodies), extracted from a large, diverse adult population.

Structure of Antibodies

The basic unit that composes antibody structure is a Y-shaped protein molecule with two arms. Each arm has a “heavy” (long) polypeptide chain and a “light” (short) polypeptide chain (Fig. 33.11). These chains have constant regions, located at the trunk of the Y, where the sequence of amino acids is set. The class of antibody is determined by the structure of the antibody's constant region. The variable regions form an antigen-binding site, and their shape is specific to a particular antigen. The antigen combines with the antibody at the antigen-binding site in a lock-and-key manner.

Another name for an antibody is **immunoglobulin (Ig)**. The most typical antibody, called **IgG**, is one Y-shaped molecule (Fig. 33.11). IgG antibodies are the major type in blood, and lesser amounts are found in lymph and tissue fluid. IgG antibodies bind to pathogens and their toxins (poisons they secrete). IgG antibodies can cross the placenta from a mother to her fetus, so the newborn has a temporary, particular immune response. Other types of antibodies contain two or more Y-shaped molecules. Antibodies belonging to the M class are pentamers—that is, clusters of five Y-shaped molecules linked together. IgM antibodies are the first antibodies produced by a newborn's body.

The antigen-antibody reaction can take several forms. When antigens are a part of a pathogen, antibodies may coat them completely, a process called neutralization. Often, the reaction produces a clump of antigens combined with antibodies, termed an immune complex. The antibodies in an immune complex are like a beacon that attracts white blood cells that move in for the kill.

**FIGURE 33.11 Structure of antibodies.**

An antibody contains two heavy (long) polypeptide chains and two light (short) chains arranged so there are two variable regions, where a particular antigen is capable of binding with the antibody. The shape of the antigen fits the shape of the binding site.