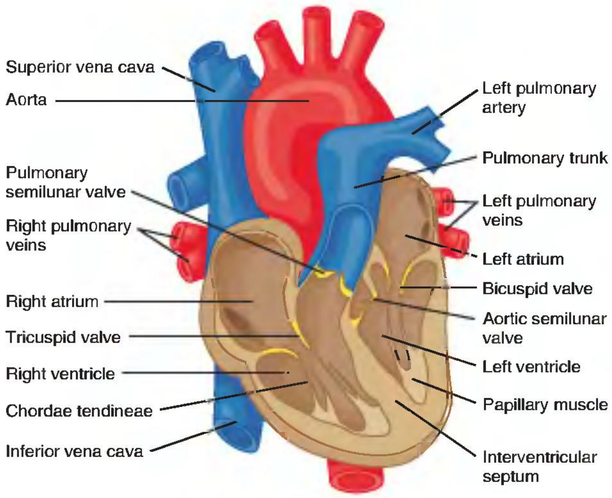

FIGURE 26.9

Structures of the Human Heart. Less oxygenated blood from the tissues of the body returns to the right atrium and flows through the tricuspid valve into the right ventricle. The right ventricle pumps the blood through the pulmonary semilunar valve into the pulmonary circuit, from which it returns to the left atrium and flows through the bicuspid valve into the left ventricle. The left ventricle then pumps blood through the aortic semilunar valve into the aorta. The various heart valves are shown in yellow.

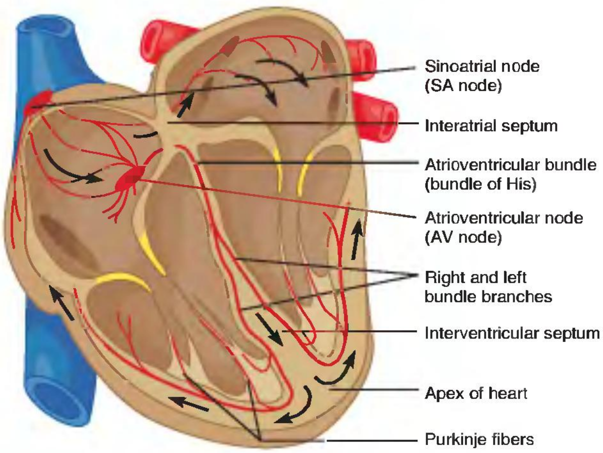

FIGURE 26.10

Electrical Conduction System of the Human Heart. The SA node initiates the depolarization wave, which passes successively through the atrial myocardium to the AV node, the atrioventricular bundle, the right and left bundle branches, and the Purkinje fibers in the ventricular myocardium. Black arrows indicate the direction of the electrical current flow.

tricuspid valve is between the right atrium and right ventricle, and the bicuspid valve is between the left atrium and left ventricle. (Collectively, these are referred to as the AV valves—atrioventricular valves.) The pulmonary semilunar valve is at the exit of the right ventricle, and the aortic semilunar valve is at the exit of the left ventricle. (Collectively, these are referred to as the semilunar valves.) All of these valves open and close due to blood pressure changes when the heart contracts during each heartbeat. Like the valves in veins, heart valves keep blood moving in one direction, preventing backflow.

The heartbeat is a sequence of muscle contractions and relaxations called the cardiac cycle. A "pacemaker," a small mass of tissue called the sinoatrial node (SA node) at the entrance to the right atrium, initiates each heartbeat (figure 26.10). (Because the pacemaker is in the heart, nervous innervation is not necessary, which is why a heart transplant without connection to nerves is possible.) The SA node initiates the cardiac cycle by producing an action potential that spreads over both atria, causing them to contract simultaneously. The action potential then passes to the atrioventricular node (AV node), near the interatrial septum. From here, the action potential continues through the atrioventricular bundle (bundle of His), at the tip of the interventricular septum. The atrioventricular bundle divides into right and left branches, which are continuous with the Purkinje fibers in the ventricular walls. Stimulation of these fibers causes the ventricles to contract almost simultaneously and eject blood into the pulmonary and systemic circulations.

The action potential moving over the surface of the heart causes current flow, which can be recorded at the surface of the body as an electrocardiogram (ECG or EKG).

During each cycle, the atria and ventricles go through a phase of contraction called **systole** and a phase of relaxation called **diastole.** Specifically, while the atria are relaxing and filling with blood, the ventricles are also relaxed. As more and more blood accumulates in the atria, blood pressure rises, and the atria contract, forcing the AV valves open and causing blood to rush into the ventricles. When the ventricles contract, the AV valves close, and the semilunar valves open, allowing blood to be pumped into the pulmonary arteries and aorta. After blood has been ejected from the ventricles, they relax and start the cycle anew.

BLOOD PRESSURE

Ventricular contraction generates the fluid pressure, called **blood pressure,** that forces blood through the pulmonary and systemic circuits. More specifically, blood pressure is the force the blood exerts against the inner walls of blood vessels. Although such a force occurs throughout the vascular system, the term blood pressure most commonly refers to systemic arterial blood pressure.

Arterial blood pressure rises and falls in a pattern corresponding to the phases of the cardiac cycle. When the ventricles contract (ventricular systole), their walls force the blood in them into the pulmonary arteries and the aorta. As a result, the pressure in these arteries rises sharply. The maximum pressure achieved during ventricular contraction is called the **systolic pressure.** When the ventricles relax (ventricular diastole), the arterial pressure drops, and the lowest pressure that remains in the arteries before the next ventricular contraction is called the **diastolic pressure.**

TABLE 26.1
MAJOR STRUCTURAL AND FUNCTIONAL COMPONENTS OF THE LYMPHATIC SYSTEM IN VERTEBRATES

STRUCTURE	FUNCTION
Lymphatic capillaries	Collect excess extracellular fluid in tissues
Lymphatics	Carry lymph from lymphatic capillaries to veins in the neck, where lymph returns to the bloodstream
Lymph nodes	House the WBCs that destroy foreign substances; play a role in antibody formation
Spleen	Filters foreign substances from blood; manufactures phagocytic lymphocytes; stores red blood cells; releases blood to the body when blood is lost
Thymus gland (in mammals)	Site of antibodies in the newborn; is involved in the initial development of the immune system; site of T-cell differentiation
Bursa of Fabricius (in birds)	A lymphoid organ at the lower end of the alimentary canal in birds; the site of B-cell maturation

In humans, normal systolic pressure for a young adult is about 120 mm Hg, which is the amount of pressure required to make a column of mercury (Hg) in a sphygmomanometer (sfig″mo-mah-nom′e-ter) rise 120 mm. Diastolic pressure is approximately 80 mm Hg. Conventionally, these readings are expressed as 120/80.

THE LYMPHATIC SYSTEM

The vertebrate **lymphatic system** begins with small vessels called lymphatic capillaries, which are in direct contact with the extracellular fluid surrounding tissues (*see figure* 26.8). The system has four major functions: (1) to collect and drain most of the fluid that seeps from the bloodstream and accumulates in the extracellular fluid; (2) to return small amounts of proteins that have left the cells; (3) to transport lipids that have been absorbed from the small intestine; and (4) to transport foreign particles and cellular debris to disposal centers called lymph nodes. The small lymphatic capillaries merge to form larger lymphatic vessels called lymphatics. Lymphatics are thin-walled vessels with valves that ensure the one-way flow of lymph. **Lymph** (L. *lympha*, clear water) is the extracellular fluid that accumulates in the lymph vessels. These vessels pass through the lymph nodes on their way back to the heart. Lymph nodes concentrate in several areas of the body and play an important role in the body's defense against disease.

In addition to the previously mentioned parts, the lymphatic system of birds and mammals consists of lymphoid organs—the spleen and either the bursa of Fabricius in birds or the thymus gland, tonsils, and adenoids in mammals. Table 26.1 summarizes the major components of the lymphatic system. The lymphatic system is also vital to an animal's defense against injury and attack.

GAS EXCHANGE

To take advantage of the rich source of energy that earth's organic matter represents, animals must solve two practical problems. First, they must break down and digest the organic matter so that it can enter the cells that are to metabolize it (chapter 27 describes this digestive process). Second, they must provide cells with both an adequate supply of oxygen required for aerobic respiration and a way of eliminating the carbon dioxide that aerobic respiration produces. This process of gas exchange with the environment, also called external respiration, is the subject of the rest of this chapter.

RESPIRATORY SURFACES

Protists and animals have five main types of respiratory systems (surfaces): (1) simple diffusion across plasma membranes, (2) tracheae, (3) cutaneous (integument or body surface) exchange, (4) gills, and (5) lungs. Each of these surfaces is now discussed.

INVERTEBRATE RESPIRATORY SYSTEMS

In single-celled protists, such as protozoa, **diffusion** across the plasma membrane moves gases into and out of the organism (figure 26.11*a*). Some multicellular invertebrates either have very flat bodies (e.g., flatworms) in which all body cells are relatively close to the body surface or are thin-walled and hollow (e.g., *Hydra*) (figure 26.11*b*,*c*). Again, gases diffuse into and out of the animal.

Invertebrates such as earthworms that live in moist environments use **integumentary exchange.** Earthworms have capillary networks just under their integument, and they exchange gases with the air spaces among soil particles (*see figure 13.14*).

Most aquatic invertebrates carry out gas exchange with **gills.** The simplest gills are small, scattered projections of the skin, such as the gills of sea stars. Other aquatic invertebrates have their gas exchange structures in more restricted areas. For example, marine and annelid worms have prominent lateral projections called parapodia that are richly supplied with blood vessels and function as gills.

Crustaceans and molluscs have gills that are compact and protected with hard covering devices (*see figure 12.11*). Such gills divide into highly branched structures to maximize the area for gas exchange.

Some terrestrial invertebrates (e.g., insects, centipedes, and some mites, ticks, and spiders) have **tracheal systems** consisting of highly branched chitin-lined tubes called tracheae (figure 26.12*a*). Tracheae open to the outside of the body through spiracles, which usually have some kind of closure device to prevent

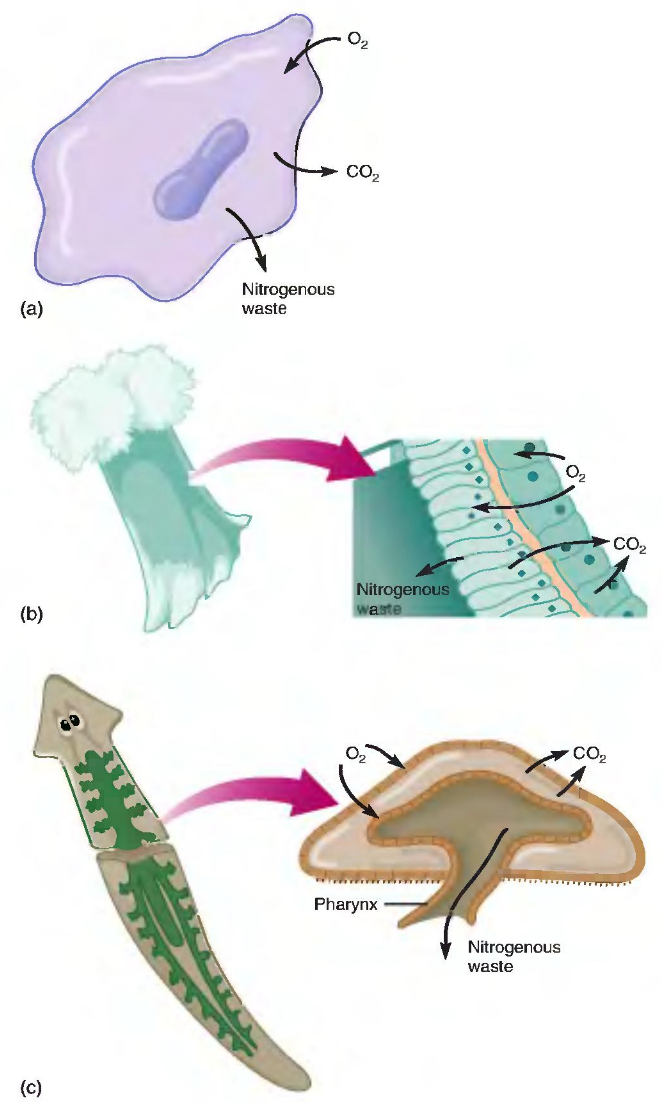

FIGURE 26.11

Invertebrate Respiration: Diffusion through Body Surfaces. The cells of small organisms, such as *(a)* protozoa, *(b)* cnidarians, and *(c)* flatworms, maintain close enough contact with the environment that they have no need for a respiratory system. Diffusion moves gases, as well as waste products, into and out of these organisms.

excessive water loss. Spiracles lead to branching tracheal trunks that eventually give rise to smaller branches called tracheoles, whose blind ends lie close to all cells of the body. Since no cells are more than 2 or 3 μm from a tracheole, gases move between the tracheole and the tissues of the body by diffusion (figure 26.12*b*). Most insects have ventilating mechanisms that move air into and out of the trachea. For example, contracting flight muscles of insects alternately compress and expand the large tracheal trunks and thereby ventilate the tracheae.

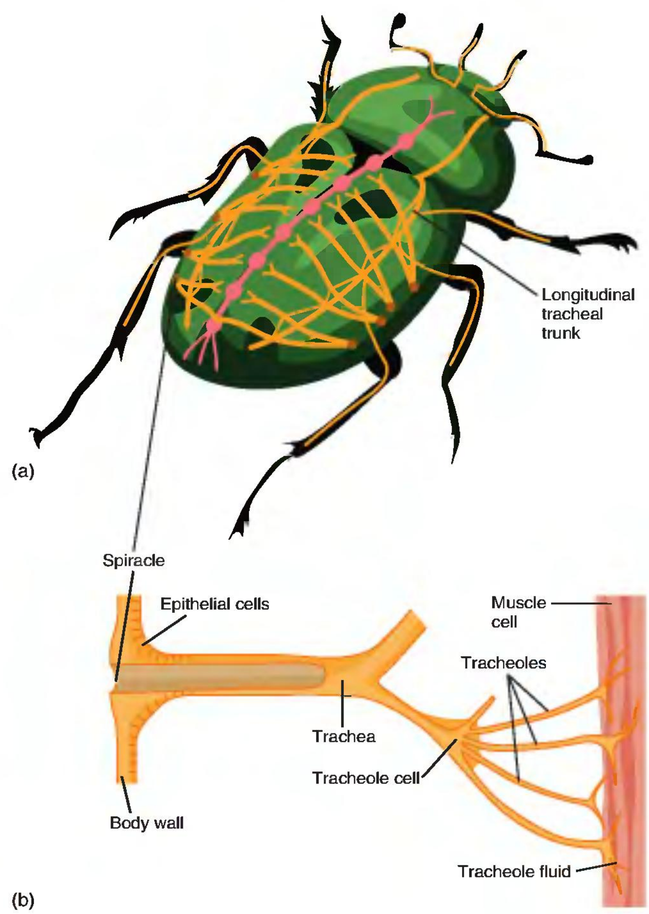

FIGURE 26.12

Invertebrate Respiration: A Tracheal System. *(a)* Tracheal system of an insect, showing the major tracheal trunks. *(b)* Tracheoles end at cells, and the terminal portions of tracheoles are fluid filled. The fluid acts as a solvent for gases.

Arachnids possess tracheae, book lungs, or both. **Book lungs** are paired invaginations of the ventral body wall that are folded into a series of leaflike lamellae (figure 26.13). Air enters the book lung through a slitlike opening called a spiracle and circulates between lamellae. Respiratory gases diffuse between the hemolymph moving along the lamellae and the air in the air chamber. Some ventilation also results from the contraction of a muscle attached to the dorsal side of the air chamber. This contraction dilates the chamber and opens the spiracle, but most gas movement is still by diffusion.

The only other major group of terrestrial invertebrates whose members have distinct air-breathing structures is the molluscan subclass Pulmonata—the land snails and slugs. The gas-exchange structure in these animals is a **pulmonate lung** that opens to the outside via a pore called a **pneumostome** (Gr. *pneumo*, breath + *stoma*, mouth) (figure 26.14). This lung is derived from a feature common to molluscs in general—the mantle

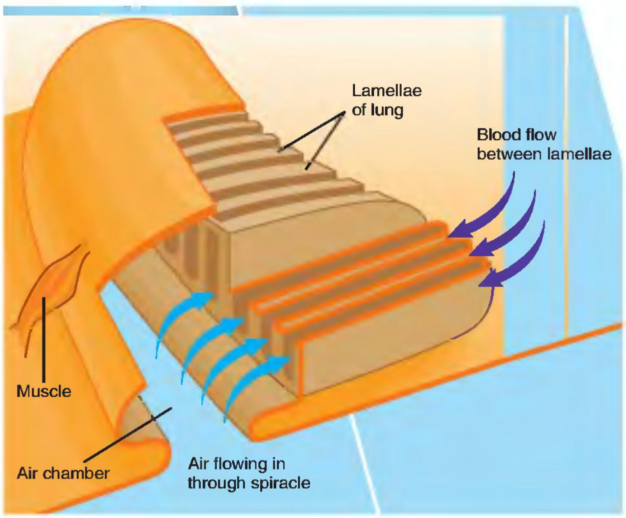

FIGURE 26.13

Invertebrate Respiration: A Book Lung. Structure of an arachnid (spider) book lung. Air enters through a spiracle into the air chamber by diffusion and by ventilation due to muscle contraction. Air diffuses from the air chamber into the lamellar spaces; hemolymph circulates through the blood lamellar spaces that alternate with air lamellar spaces. Small, peglike surface projections hold the lamellae apart. Due to this structural arrangement, air (blue arrows) and blood (purple arrows) move on opposite sides of a lamella in a countercurrent flow, allowing the exchange of respiratory gases by diffusion.

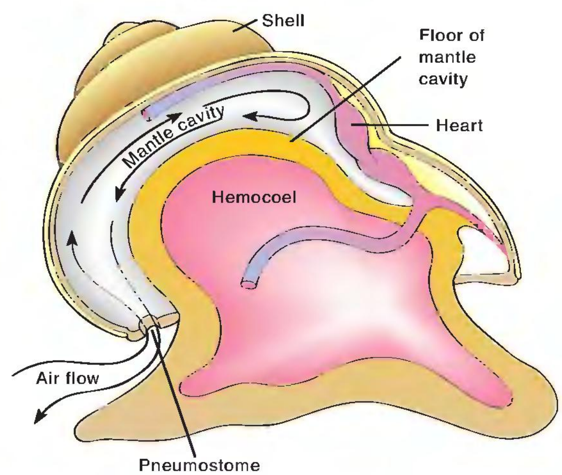

FIGURE 26.14

Invertebrate Respiration: The Pulmonate Lung. The mantle cavity of the pulmonate snail, *Lymnaea*, is highly vascularized and functions as a lung. Downward movement of the floor of the cavity increases the cavity's volume, so that air is drawn into the mantle cavity for respiration. Decreasing the volume of the mantle cavity expels the air. Air flows into and out of the lung through a single pore called the pneumostome. Black arrows indicate the direction of air flow.

cavity—which in other molluscs houses the gills and other organs. Some of the more primitive pulmonate snails are aquatic (freshwater) and close the pneumostome during submergence. When the snail surfaces to breathe air, the pneumostome opens. Most of the higher pulmonates are terrestrial and rely on their lungs for gas exchange. The lung may be ventilated by arching and then flattening the body, but most gas exchange occurs by diffusion through the pneumostome, which is open most of the time.

VERTEBRATE RESPIRATORY SYSTEMS

Aquatic vertebrates (fish, amphibians, and some reptiles) rely on one, or a combination of, the following surfaces for gas exchange: the cutaneous body surface, external filamentous gills, and internal lamellar gills. **Bimodal breathing** is the ability of an organism to exchange respiratory gases simultaneously with both air and water. A bimodal organism (e.g., some salamanders, crabs, barnacles, bivalve molluscs, and fishes [lungfishes]) uses gills for water breathing and lungs for air breathing. However, some gas exchange is always cutaneous, and some bimodal breathers are actually trimodal (skin, gills, and lungs). *Bimodal breathing was an important respiratory adaptation that made possible the evolutionary transition between aquatic and terrestrial habitats. Fundamental changes in the structure and function of the respiratory organs accompanied the transition from water to air breathing. In air-breathing terrestrial vertebrates (reptiles, birds, and mammals) lungs replaced gills.* These vertebrate surfaces and transitions are now discussed.

CUTANEOUS EXCHANGE

Some vertebrates that have lungs or gills, such as some aquatic turtles, salamanders with lungs, snakes, fishes, and mammals, use **cutaneous respiration** or integumentary exchange to supplement gas exchange. However, cutaneous exchange is most highly developed in frogs, toads, lungless salamanders, and newts.

Amphibian skin has the simplest structure of all the major vertebrate respiratory organs (*see figure 23.6*). In frogs, a uniform capillary network lies in a plane directly beneath the epidermis. This vascular arrangement facilitates gas exchange between the capillary bed and the environment by both diffusion and convection. A slimy mucous layer that keeps amphibian skin moist and protects against injury aids in this gas exchange. Some amphibians obtain about 25% or more of their oxygen by this exchange, and the lungless salamanders carry out all of their gas exchange through the skin and buccal-pharyngeal region.

GILLS

Gills are respiratory organs that have either a thin, moist, vascularized layer of epidermis to permit gas exchange across thin gill membranes, or a very thin layer of epidermis over highly vascularized dermis. Larval forms of a few fishes and amphibians have