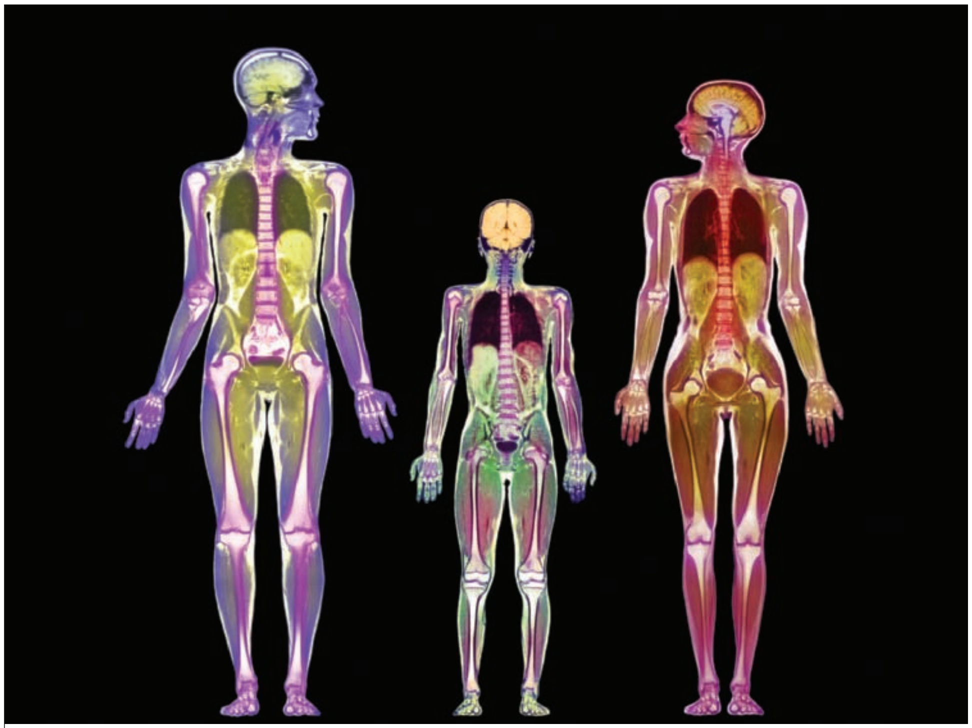
Magnetic resonance imaging (MRI) whole body scans of a man (left), a 9-year-old boy (middle), and a woman. Various organs can be seen in the scans: the whitish skeleton throughout the bodies, the brains within the skulls, lungs (dark) in the chests, lobes of the liver (green and brown ovals) in the abdomens, and bladders (dark ovals) in the lower abdomens.



Simon Fraser/SPL/Photo Researchers, Inc.

36 Introduction to Animal Organization and Physiology

Study Plan

Why It Matters

After a cold night in Africa's Kalahari Desert, gray meerkats *(Surricata suricatta),* a type of mongoose, awaken in their burrows. Although, like all mammals, meerkats regulate their body temperature, their internal temperature falls during cold nights. If the sun is shining in the morning and warms their burrows, the meerkats emerge and stand on their hind legs facing east, warming their bodies in the rays of the sun **(Figure 36.1).** This sunning behavior helps raise their body temperature.

Once the meerkats warm up, they fan out from their burrows looking for food, mainly insects and an occasional lizard. Their highly integrated body systems allow them to move about, sense the presence of prey, react with speed and precision to capture those prey, and consume them. Within their bodies, the food is broken down into glucose and other nutrient molecules, which are transported throughout the body to provide energy for living. At the same time, balancing mechanisms are constantly at work to maintain the animals' internal environment at a level that keeps body cells functioning. The maintenance of the internal environment in a stable state is called **homeostasis** (*homeo* = the same; *stasis* = standing or stopping). The processes and activi-

David Macdonald

Figure 36.1
Meerkats lining up to warm themselves in sunlight.

ties responsible for homeostasis are called **homeostatic mechanisms.** These mechanisms compensate both for the external environmental changes that the meerkats encounter as they explore places with differences in temperature, humidity, and other physical conditions, and for changes in their own body systems.

All animals have body systems for acquiring and digesting nutrients to provide energy for life, growth, reproduction, and movement. Biologists are interested in the structures and functions of these systems. **Anatomy** is the study of the structures of organisms, and **physiology** is the study of their functions—the physico-chemical processes of organisms.

In this chapter we begin with the organization of individual cells into tissues, organs, and organ systems, the major body structures that carry out animal activities. Our discussion continues with a look at how the processes and activities of organ systems coordinate to accomplish homeostasis. The other chapters in this unit discuss the individual organ systems that carry out major body functions such as digestion, movement, and reproduction. Although we emphasize vertebrates throughout the unit, with particular reference to human physiology, we also make comparisons with invertebrates, to keep the structural and functional diversity of the animal kingdom in perspective and to understand the evolution of the structures and processes involved.

36.1 Organization of the Animal Body

In Animals, Specialized Cells Are Organized into Tissues, Tissues into Organs, and Organs into Organ Systems

The individual cells of animals have the same requirements as cells of any kind. They must be surrounded by an aqueous solution that contains ions and molecules required by the cells, including complex organic molecules that can be used as an energy source. The concentrations of these molecules and ions must be balanced to keep cells from shrinking or swelling excessively due to osmotic water movement. Most animal cells also require oxygen to serve as the final acceptor for electrons removed in oxidative reactions. Animal cells must be able to release waste molecules and other by-products of their activities, such as carbon dioxide, to their environment. The physical conditions of the cellular environment, such as temperature, must also remain within tolerable limits.

The evolution of multicellularity (see Section 24.3) made it possible for organisms to create an *internal fluid environment* that supplies all the needs of individual cells, including nutrient supply, waste removal, and osmotic balance. This internal environment allows multicellular organisms to occupy diverse habitats, including dry terrestrial habitats that would be lethal to single cells. Multicellular organisms can also become relatively large because their individual cells remain small enough to exchange ions and molecules with the internal fluid. The fluid occupying the spaces between cells in multicellular animals is called **interstitial fluid**, or **extracellular fluid.**

The evolution of multicellularity also allowed major life functions to be subdivided among specialized groups of cells, with each group concentrating on a single activity. In animals, some groups of cells became specialized for movement, others for food capture, digestion, internal circulation of nutrients, excretion of wastes, reproduction, and other functions. Specialization greatly increases the efficiency by which animals carry out these functions.

In most animals, these specialized groups of cells are organized into tissues, the tissues into organs, and the organs into organ systems **(Figure 36.2).** A **tissue** is a group of cells with the same structure and function, working together as a unit to carry out one or more activities. The tissue lining the inner surface of the intestine, for example, is specialized to absorb nutrients released by digestion of food in the intestinal cavity.

An **organ** integrates two or more different tissues into a structure that carries out a specific function. The eye, liver, and stomach are examples of organs. Thus, the stomach integrates several different tissues into an organ specialized for processing food.

An **organ system** coordinates the activities of two or more organs to carry out a major body function such as movement, digestion, or reproduction. The organ system carrying out digestion, for example, coordinates the activities of organs including the mouth, stomach, pancreas, liver, and small and large intestines. Some organs contribute functions to more than one organ system. For instance, the pancreas forms part of the endocrine system as well as the digestive system.

Study Break

1. What are some advantages for an organism being multicellular?
2. What is the difference between a tissue, an organ, and an organ system?

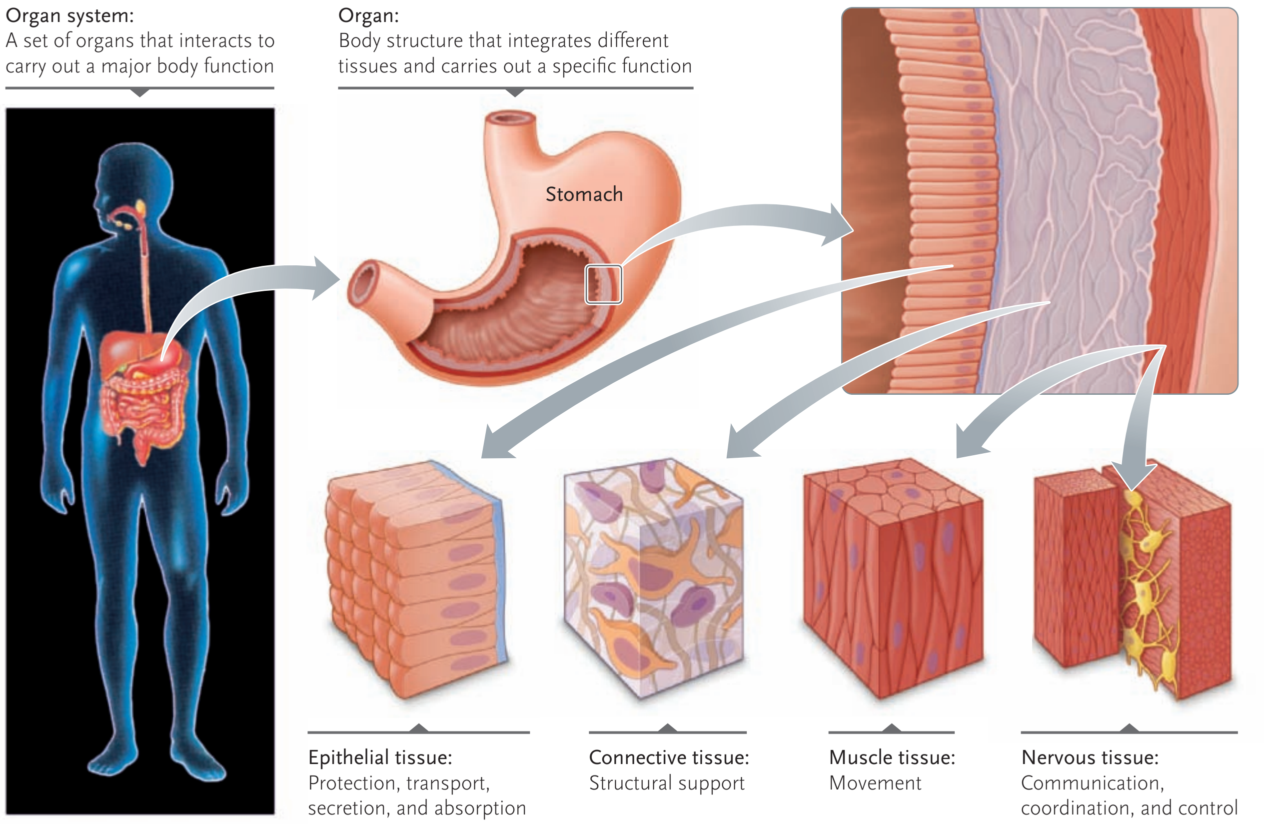


Figure 36.2 Organization of animal cells into tissues, organs, and organ systems.

36.2 Animal Tissues

Although the most complex animals may contain hundreds of distinct cell types, all can be classified into one of four basic tissue groups: *epithelial, connective, muscle,* and *nervous* (see Figure 36.2). Each tissue type is assembled from individual cells. The properties of those cells determine the structure and, therefore, the function of the tissue. More specifically, the structure and integrity of a tissue depend on the structure and organization of the cytoskeleton within the cell, the type and organization of the extracellular matrix (ECM) surrounding the cell, and the junctions holding cells together (see Section 5.5).

Junctions of various kinds link cells into tissues (see Figure 5.27). *Anchoring junctions* form buttonlike spots or belts that weld cells together. They are most abundant in tissues subject to stretching, such as skin and heart muscle. *Tight junctions* seal the spaces between cells, keeping molecules and even ions from leaking between cells. For example, tight junctions in the tissue lining the urinary bladder prevent waste molecules and ions from leaking out of the bladder into other body tissues. *Gap junctions* open channels between cells in the same tissue, allowing ions and small molecules to flow freely from one to another. For example, gap junctions between muscle cells help muscle tissue to function as a unit.

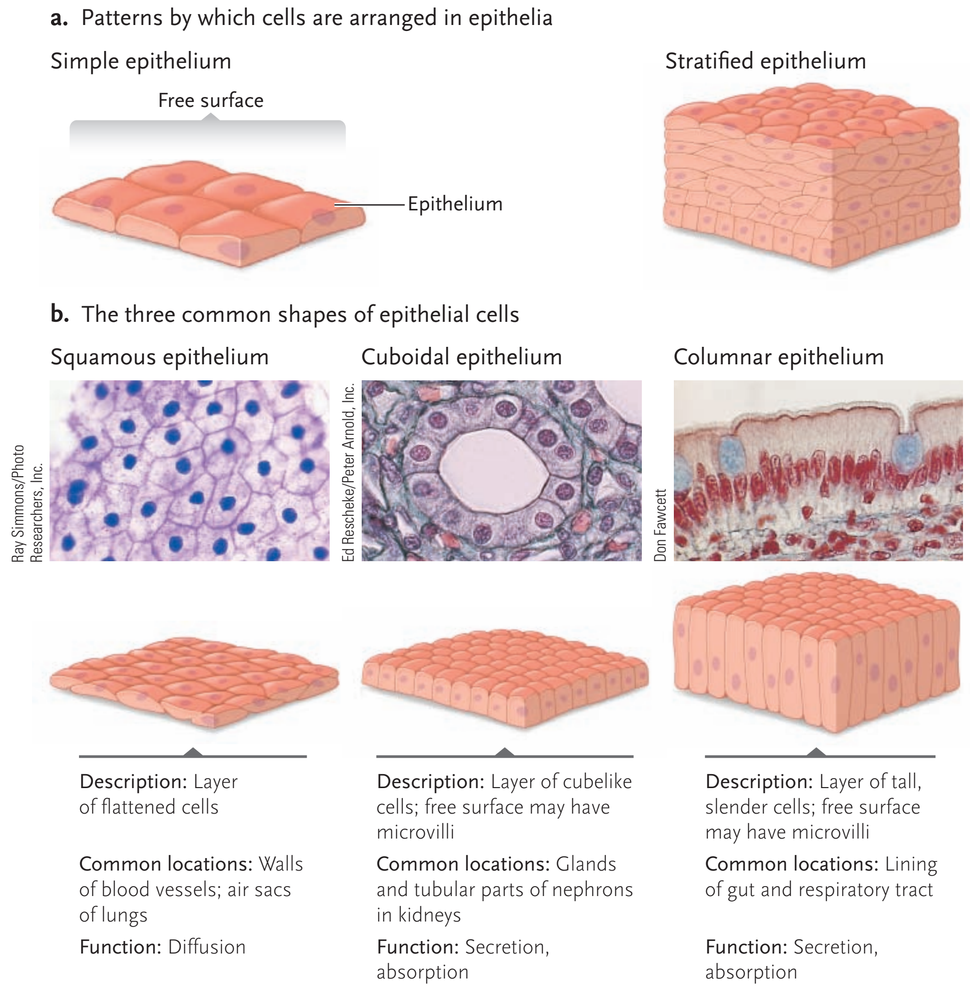
Let us now consider the structural and functional features that distinguish the four types of tissues, with primary emphasis on the forms they take in vertebrates.

Epithelial Tissue Forms Protective, Secretory, and Absorptive Coverings and Linings of Body Structures

Epithelial tissue (*epi* = over; *thele* = covering) consists of sheetlike layers of cells that are usually joined tightly together, with little ECM material between them **(Figure 36.3).** Also called *epithelia* (singular, *epithelium*), these tissues cover body surfaces and the surfaces of internal organs, as well as line cavities and ducts within the body. They protect body surfaces from invasion by bacteria and viruses, and secrete or absorb substances. For example, the epithelium covering a fish's gill structures serves as a barrier to bacteria and viruses and exchanges oxygen, carbon dioxide, and ions with the aqueous environment. Some epithelia, such as those lining the capillaries of the circulatory system, act as filters, allowing ions and small molecules to leak from the blood into surrounding tissues while barring the passage of blood cells and large molecules such as proteins.

Because epithelia form coverings and linings, they have one free (or outer) surface, which may be exposed to water, air, or fluids within the body. In internal cavities and ducts, the free surface is often covered with *cilia,* which beat like oars to move fluids through the cavity or duct. The epithelium lining the oviducts in mammals, for example, is covered with

Figure 36.3
Structure of epithelial tissues.



cilia that generate fluid currents to move eggs from the ovaries to the uterus. In some epithelia, including the lining of the small intestine, the free surface is crowded with *microvilli,* fingerlike extensions of the plasma membrane that increase the area available for secretion or absorption.

The inner surface of an epithelium adheres to a layer of glycoproteins secreted by the epithelial cells called the **basal lamina,** which fixes the epithelium to underlying tissues. The basal lamina is secreted by connective tissue cells immediately under the epithelium.

Epithelial Cell Structure. Epithelia are classified as *simple*—formed by a single layer of cells—or *stratified*—formed by multiple cell layers (see Figure 36.3a). The shapes of cells within an epithelium may be *squamous* (mosaic, flattened, and spread out), *cuboidal* (shaped roughly like dice or cubes), or *columnar* (elongated, with the long axis perpendicular to the epithelial layer; see Figure 36.3b). For example, the outer epithelium of mammalian skin is stratified and contains columnar, cuboidal, and squamous cells; the epithelium lining blood vessels is simple and squamous; and the intestinal epithelium is simple and columnar.

The cells of some epithelia, such as those forming the skin and the lining of the intestine, divide constantly to replace worn and dying cells. New cells are produced through division of stem cells in the basal (lowest) layer of the skin. *Stem cells* are undifferentiated (unspecialized) cells in the tissue that divide to produce more stem cells as well as cells that differentiate (that is, become specialized into one of the many cell types of the body). Stem cells are found both in adult organisms and in embryos. Besides the skin, adult stem cells are found in tissues of the brain, bone marrow, blood vessels, skeletal muscle, and liver. (*Insights from the Molecular Revolution* describes an effort to culture embryonic stem cells as a source of replacements for damaged tissues and organs.)

Glands Formed by Epithelia. Epithelia typically contain or give rise to cells that are specialized for secretion. Some of these secretory cells are scattered among nonsecretory cells within the epithelium. Others form structures called **glands,** which are derived from pockets of epithelium during embryonic development.

Some glands, called **exocrine glands** (*exo* = external; *crine* = secretion), remain connected to the epithelium by a duct, which empties their secretion at

Insights from the Molecular Revolution

Cultured Stem Cells

Stem cells derived from human embryos or fetal tissue have the potential to develop into any tissue, but until recently biomedical researchers had no method for maintaining human stem cells indefinitely in cultures. A reliable supply of cultured stem cells is essential to the growth of tissues for research or for possible use in replacing damaged tissues and organs.

Just a few years ago, James A. Thompson and his coworkers at the University of Wisconsin developed a successful method for culturing stem cells. Their starting point was very early human embryos produced by fertilization of eggs in the test tube. After the embryos had grown for several days, 14 samples of cells were removed and cultured. The challenge was to maintain the cultured cells in the embryonic state and keep them from differentiating into specialized forms.

The researchers' strategy was to place the cells in culture dishes over a bed of mouse fibroblasts. Earlier work had shown that this technique allows mouse and nonhuman primate embryonic cells to survive outside the body, but it had failed to work with some mammalian species. Would it work with human cells?

In 5 of the 14 cultures, the human cells multiplied on the fibroblasts without differentiating as long as the cell masses never contained more than 50 to 100 cells. Larger masses had to be separated and placed in small numbers on a fresh layer of mouse fibroblasts. Using this technique, the five cell cultures were maintained for as long as 8 months in the laboratory with no signs of differentiation or deterioration. They could be frozen, stored, and returned to active cultures at will.

But did they still have full stem-cell function? The investigators ran several tests to answer this question. One experiment tested molecules on the surface of the cultured cells. Stem cells have characteristic surface molecules that change when the cells begin to differentiate into adult tissues. Antibodies against typical stem cell surface molecules all reacted with the cultured cells, indicating that the cells still had the characteristic molecules.

Another experiment tested for telomerase, an enzyme that helps maintain chromosomes at their normal length during rapid cycles of DNA replication and cell division. The enzyme becomes inactive in most cells as they differentiate into adult form. A standard test for the enzyme showed that it was present and remained fully active in the cultured cells.

In the final experiment, the researchers injected samples of the cells into mice to test whether the cultured cells could differentiate into a wide range of tissues. Within these mice, the cells grew into balls of tissue that included skin cells, gut epithelium, cartilage, bone, smooth and striated muscle, and nerve cells. The cultured cells seemed to be able to differentiate into adult tissues when stimulated to do so, and thus to have all the characteristics of stem cells.

The ability to culture stem cells opens many opportunities for future biological and medical discoveries. Observing the differentiation of stem cells into adult types should fill gaps in our knowledge of human development, which until now could be studied only in embryos. These studies may also give clues to the processes that produce birth defects and spontaneous abortion and could indicate means to correct these problems.

Further, if stem cells can be stimulated to differentiate into desired tissues and organs, they may provide an essentially unlimited supply of material for transplants. Many conditions, such as Parkinson disease and juvenile-onset diabetes, result from the death or malfunction of only one or a few cell types. Replacing defective cells from banks of cultured stem cells may be the key to curing the diseases.

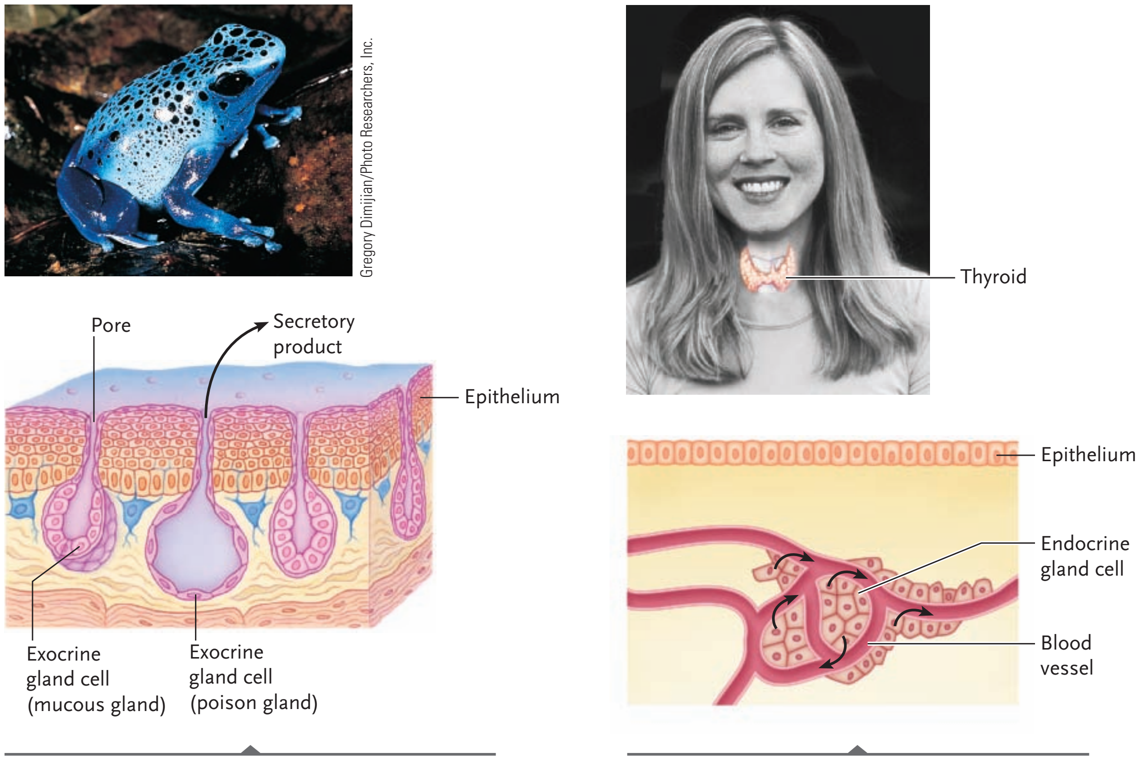
These scientific and medical prospects do not provide answers to ethical questions about culturing stem cells derived from embryos. Such questions are the subject of intense scrutiny and debate in the U.S. Congress and among scientists, religious authorities, and the general public. Hopefully, a balance will be found between concerns about the use of human embryonic cells in research and the prospects for significant improvements in human health and scientific knowledge.

the epithelial surface. Exocrine secretions include mucus, saliva, digestive enzymes, sweat, earwax, oils, milk, and venom (**Figure 36.4a** shows an exocrine gland in the skin of a poisonous tree frog). Other glands, called **endocrine glands** (*endo* = inside), become suspended in connective tissue underlying the epithelium, with no ducts leading to the epithelial surface. These ductless glands, such as the pituitary gland, adrenal gland, and thyroid gland **(Figure 36.4b),** release their products—called hormones—directly into the interstitial fluid, to be picked up and distributed by the circulatory system.

Some glands act as both exocrine glands and endocrine glands. The pancreas, for instance, has an exocrine function of secreting pancreatic juice through a duct into the small intestine where it plays an important role in food digestion, and an endocrine function of secreting the hormones insulin and glucagon into the bloodstream to help regulate glucose levels in the blood.

Connective Tissue Supports Other Body Tissues

Most animal body structures contain one or more types of **connective tissue.** Connective tissues support other body tissues, transmit mechanical and other forces, and in some cases act as filters. They consist of cells



a. Examples of exocrine glands: The mucus- and poison-secreting glands in the skin of a blue poison frog

b. Example of an endocrine gland: The thyroid gland, which secretes hormones that regulate the rate of metabolism and other body functions

Figure 36.4 Exocrine and endocrine glands. The poison secreted by the blue poison frog *(Dendrobates azureus)* is one of the most lethal glandular secretions known.

that form networks or layers in and around body structures and that are separated by nonliving material, specifically the ECM secreted by the cells of the tissue (see Section 5.5). Many forms of connective tissue have more ECM material (both by weight and by volume) than cellular material.

The mechanical properties of a connective tissue depend on the type and quantity of its ECM. The consistency of the ECM ranges from fluid (as in blood and lymph), through soft and firm gels (as in tendons), to the hard and crystalline (as in bone). In most connective tissues, the ECM consists primarily of the fibrous glycoprotein **collagen** embedded in a network of proteoglycans—glycoproteins that are very rich in carbohydrates. In bone, the glycoprotein network surrounding the collagen is impregnated with mineral deposits that produce a hard, yet still somewhat elastic, structure. Another class of glycoproteins, **fibronectin,** aids in the attachment of cells to the ECM and helps hold the cells in position.

In some connective tissues another rubbery protein, **elastin,** adds elasticity to the ECM—it is able to return to its original shape after being stretched, bent, or compressed. Elastin fibers, for example, help the skin return to its original shape when pulled or stretched, and give the lungs the elasticity required for their alternating inflation and deflation.

Vertebrates have six major types of connective tissue: *loose connective tissue, fibrous connective tissue, cartilage, bone, adipose tissue,* and *blood.* Each type has a characteristic function correlated with its structure **(Figure 36.5).**

Loose Connective Tissue. **Loose connective tissue** consists of sparsely distributed cells surrounded by a more or less open network of collagen and other glycoprotein fibers (see Figure 36.5a). The cells, called **fibroblasts,** secrete most of the collagen and other proteins in this connective tissue.

Loose connective tissues support epithelia and form a corsetlike band around blood vessels, nerves, and some internal organs; they also reinforce deeper layers of the skin. Sheets of loose connective tissue, covered on both surfaces with epithelial cells, form the **mesenteries,** which hold the abdominal organs in place and provide lubricated, smooth surfaces that prevent chafing or abrasion between adjacent structures as the body moves.

Fibrous Connective Tissue. In **fibrous connective tissue,** fibroblasts are sparsely distributed among dense masses of collagen and elastin fibers that are lined up in highly ordered, parallel bundles (see Figure 36.5b). The parallel arrangement produces maximum tensile strength and elasticity. Examples include **tendons,** which attach muscles to bones, and **ligaments,** which connect bones to each other at a joint. The cornea of the eye is a transparent fibrous connective tissue formed from highly ordered collagen molecules.

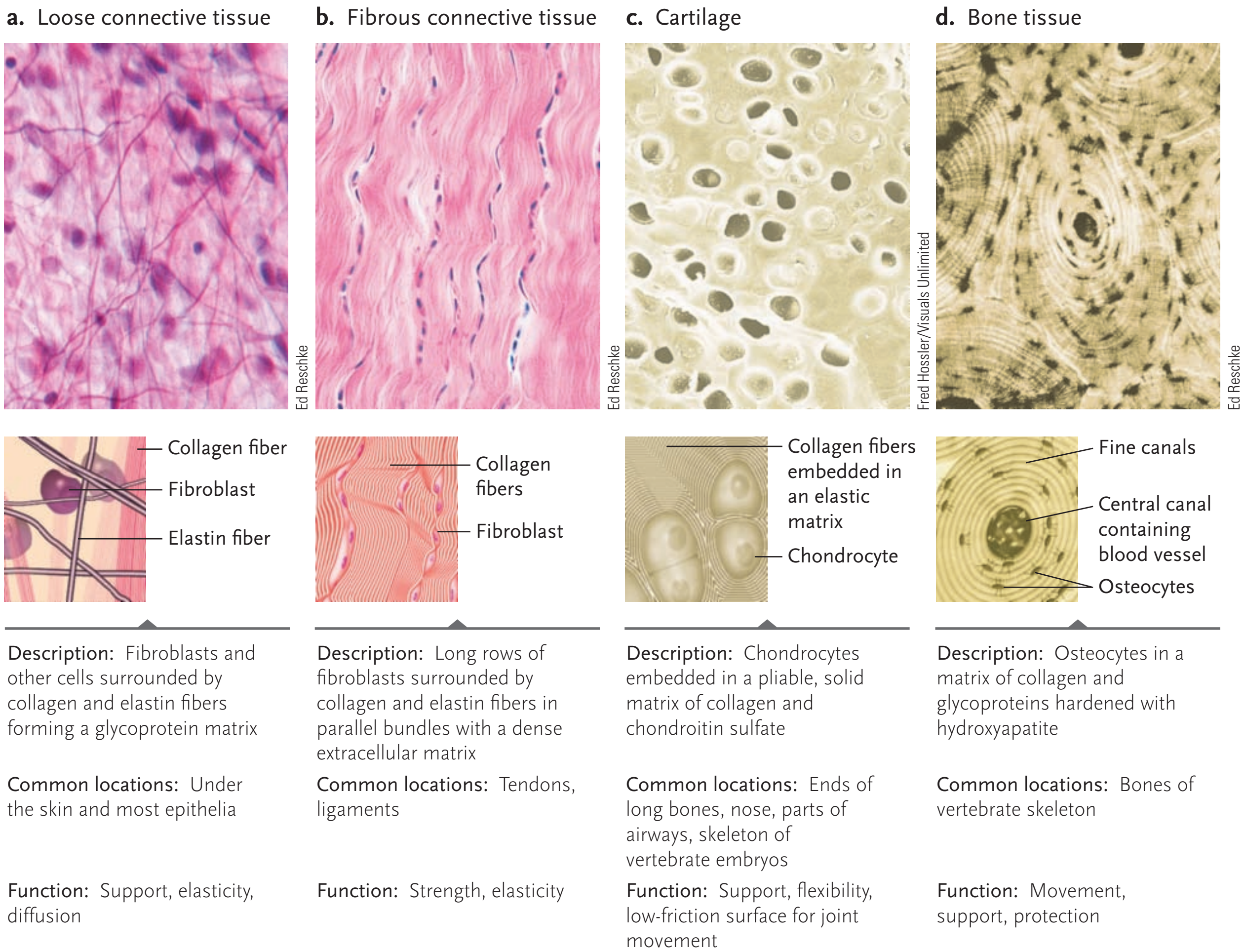
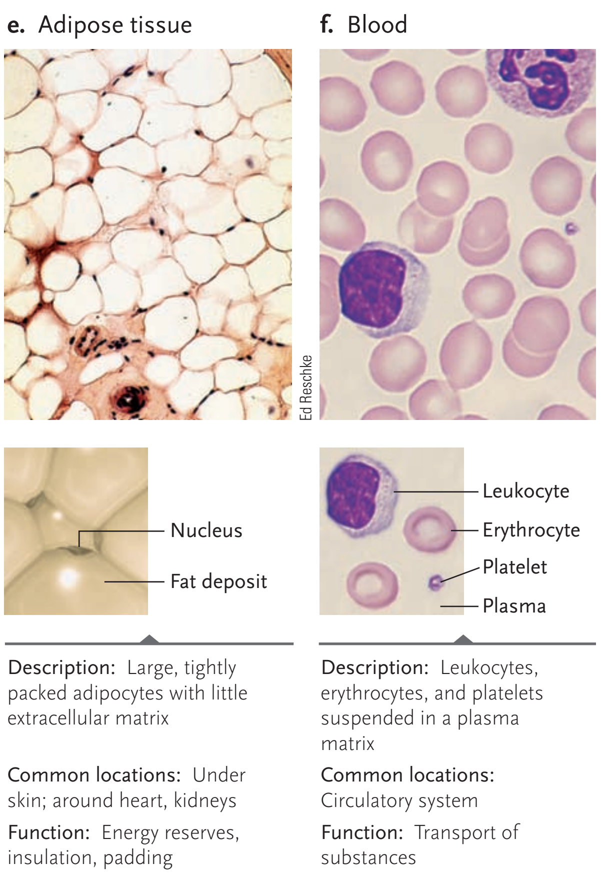


Figure 36.5 The six major types of connective tissues.



Cartilage. **Cartilage** consists of sparsely distributed cells called **chondrocytes**, surrounded by networks of collagen fibers embedded in a tough but elastic matrix of the glycoprotein *chondroitin sulfate* (see Figure 36.5c). Elastin is also present in some forms of cartilage.

The elasticity of cartilage allows it to resist compression and stay resilient, like a piece of rubber. Bending your ear or pushing the tip of your nose, which are supported by a core of cartilage, gives a good idea of the flexible nature of this tissue. In humans, cartilage also supports the larynx, trachea, and smaller air passages in the lungs. It forms the disks cushioning the vertebrae in the spinal column and the smooth, slippery capsules around the ends of bones in joints such as the hip and knee. Cartilage also serves as a precursor to bone during embryonic development; in sharks and rays and their relatives, almost the entire skeleton remains as cartilage in adults.

Bone. The densest form of connective tissue, **bone** forms the skeleton, which supports the body, protects softer body structures such as the brain, and contributes to body movements.

Mature bone consists primarily of cells called **osteocytes** (*osteon* = bone) embedded in an ECM containing collagen fibers and glycoproteins impregnated with *hydroxyapatite,* a calcium-phosphate mineral (see Figure 36.5d). The collagen fibers give bone tensile strength and elasticity; the hydroxyapatite resists compression and allows bones to support body weight. Cells called **osteoblasts** (*blast* = bud or sprout) produce the collagen and mineral of bone—as much as 85% of the weight of bone is mineral deposits. Osteocytes, in fact, are osteoblasts that have become trapped and surrounded by the bone materials they themselves produce. **Osteoclasts** (*clast* = break) remove the minerals and recycle them through the bloodstream. Bone is not a stable tissue; it is reshaped continuously by the bone-building osteoblasts and the bone-degrading osteoclasts.

Although bones appear superficially to be solid, they are actually porous structures, consisting of a system of microscopic spaces and canals. The structural unit of bone is the **osteon.** It consists of a minute central canal surrounded by osteocytes embedded in concentric layers of mineral matter (see Figure 36.5d). A blood vessel and extensions of nerve cells run through the central canal, which is connected to the spaces containing cells by very fine, radiating canals filled with interstitial fluid. The blood vessels supply nutrients to the cells with which the bone is built, and the nerve cells hook up the bone cells to the body's nervous system.

Adipose Tissue. The connective tissue called **adipose tissue** mostly contains large, densely clustered cells called *adipocytes* that are specialized for fat storage (see Figure 36.5e). It has little ECM. Adipose tissue also cushions the body and, in mammals, forms an especially important insulating layer under the skin.

The animal body stores limited amounts of carbohydrates, primarily in muscle and liver cells. Excess carbohydrates are converted into the fats stored in adipocytes. The storage of chemical energy as fats offers animals a weight advantage. For example, the average human would weigh about 45 kg (100 pounds) more if the same amount of chemical energy was stored as carbohydrates instead of fats. Adipose tissue is richly supplied with blood vessels, which move fats or their components to and from adipocytes.

Blood. **Blood** (see Figure 36.5f) is considered a connective tissue because its cells are suspended in a fluid ECM, plasma. The straw-colored **plasma** is a solution of proteins, nutrient molecules, ions, and gases.

Blood contains two primary cell types, **erythrocytes** (red blood cells; *erythros* = red) and **leukocytes** (white blood cells; *leukos* = white). Erythrocytes are packed with hemoglobin, a protein that can bind and transport oxygen. There are several types of leukocytes—all help to protect the body against invading viruses, bacteria, and other disease-causing agents. The blood plasma also contains **platelets,** membrane-bound fragments of specialized blood cells, which take part in the reactions that seal wounds with blood clots.

Blood is the major transport vehicle of the body. It carries oxygen and nutrients to body cells, removes wastes and by-products such as carbon dioxide, and maintains the internal fluid environment, including the osmotic balance between cells and the interstitial fluid. Blood also transports hormones and other signal molecules that coordinate body responses. (The components and roles of blood are described in Chapter 42.)

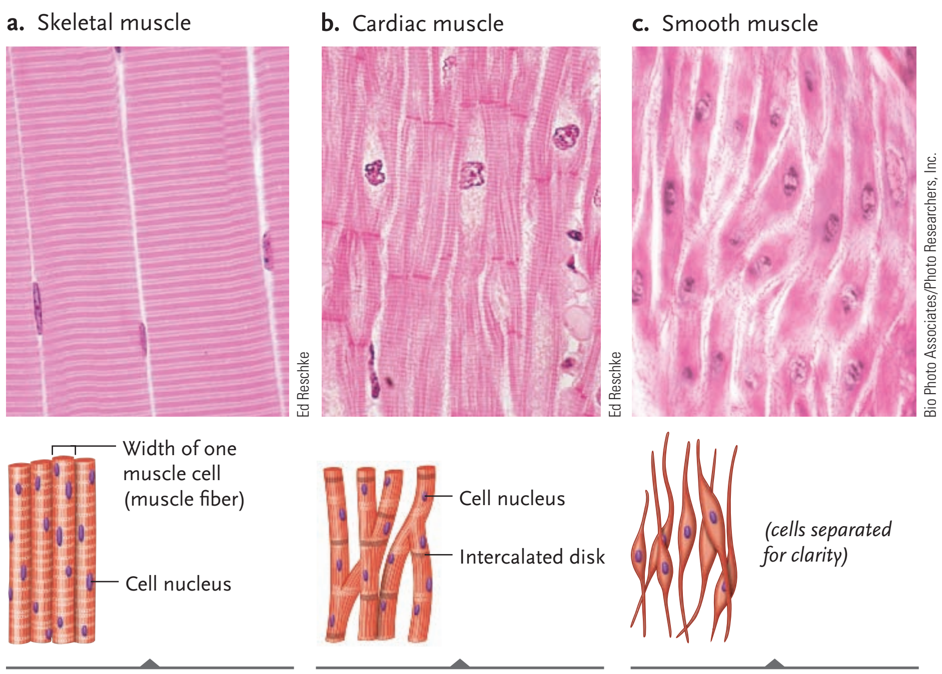
Muscle Tissue Produces the Force for Body Movements

Muscle tissue consists of cells that have the ability to contract (shorten). The contractions, which depend on the interaction of two proteins—*actin* and *myosin*—move body limbs and other structures, pump the blood, and produce a squeezing pressure in organs such as the intestine and uterus. Three types of muscle tissue, *skeletal, cardiac,* and *smooth,* produce body movements in vertebrates **(Figure 36.6).** In all types of muscle tissue, the cells are densely packed, leaving little room for ECM.

Skeletal Muscle. **Skeletal muscle** is so called because most muscles of this type are attached by tendons to the skeleton. Skeletal muscle cells are also called **muscle fibers** because each is an elongated cylinder (see Figure 36.6a). These cells contain many nuclei and are packed with actin and myosin molecules arranged in highly ordered, parallel units that give the tissue a banded or striated appearance when viewed under a microscope. Muscle fibers packed side by side into parallel bundles surrounded by sheaths of connective tissue form many body muscles, such as the biceps.

Skeletal muscle contracts in response to signals carried by the nervous system. The contractions of skeletal muscles, which are characteristically rapid and powerful, move body parts and maintain posture. The contractions also release heat as a by-product of cellular metabolism. This heat helps mammals, birds, and some other vertebrates maintain their body temperatures when environmental temperatures fall. (Skeletal muscle is discussed further in Chapter 41.)

Cardiac Muscle. **Cardiac muscle** is the contractile tissue of the heart (see Figure 36.6b). Cardiac muscle has a striated appearance because it contains actin and myosin molecules arranged like those in skeletal muscle. However, cardiac muscle cells are short and branched, with each cell connecting to several neighboring cells; the joining point between two such cells is called an *intercalated disk*. Cardiac muscle cells thus form an interlinked network, which is stabilized by anchoring junctions and gap junctions. This network makes heart muscle contract in all directions, producing a squeezing or pumping action rather than the



a. Skeletal muscle
Description: Bundles of long, cylindrical, striated, contractile cells called muscle fibers
Typical location: Attached to bones of skeleton
Function: Locomotion, movement of body parts

b. Cardiac muscle
Description: Cylindrical, striated cells that have specialized end junctions
Location: Wall of heart
Function: Pumping of blood within circulatory system

c. Smooth muscle
Description: Contractile cells with tapered ends
Typical location: Wall of internal organs, such as stomach
Function: Movement of internal organs

Figure 36.6
Structure of skeletal, cardiac, and smooth muscle.

lengthwise, unidirectional contraction characteristic of skeletal muscle.

Smooth Muscle. **Smooth muscle** is found in the walls of tubes and cavities in the body, including blood vessels, the stomach and intestine, the bladder, and the uterus. Smooth muscle cells are relatively small and spindle-shaped (pointed at both ends), and their actin and myosin molecules are arranged in a loose network rather than in bundles (see Figure 36.6c). This loose network makes the cells appear smooth rather than striated when viewed under a microscope. Smooth muscle cells are connected by gap junctions and enclosed in a mesh of connective tissue. The gap junctions transmit ions that make smooth muscles contract as a unit, typically producing a squeezing motion. Although smooth muscle contracts more slowly than skeletal and cardiac muscle do, its contractions can be maintained at steady levels for a much longer time. These contractions move and mix the stomach and intestinal contents, constrict blood vessels, and push the infant out of the uterus during childbirth.

Nervous Tissue Receives, Integrates, and Transmits Information

Nervous tissue contains cells called **neurons** (also called *nerve cells*) that serve as lines of communication and control between body parts. Billions of neurons are packed into the human brain; others extend throughout the body. Nervous tissue also contains **glial cells** (*glia* = glue), which physically support and provide nutrients to neurons, provide electrical insulation between them, and scavenge cellular debris and foreign matter.

A neuron consists of a *cell body,* which houses the nucleus and organelles, and two types of cell extensions, dendrites and axons **(Figure 36.7).** *Dendrites* receive chemical signals from other neurons or from body cells of other types, and convert them into an electrical signal that is transmitted to the cell body of the receiving neuron. Dendrites are usually highly branched. *Axons* conduct electrical signals away from the cell body to the axon terminals, or endings. At their terminals, axons convert the electrical signal to a chemical signal that stimulates a response in nearby muscle cells, gland cells, or other neurons. Axons are usually unbranched except at their terminals. Depending on the type of neuron and its location in the body, its axon may extend from a few micrometers or millimeters to more than a meter. (Neurons and their organization in body structures are discussed further in Chapters 37, 38, and 39.)

All four major tissue types—epithelial, connective, muscle, and nervous—combine to form the organs and organ systems of animals. The next section depicts the major organs and organ systems of vertebrates, and outlines their main tasks.

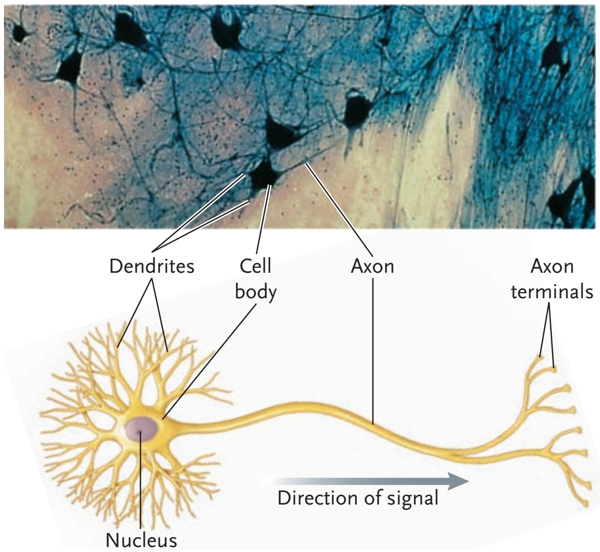


Figure 36.7
Neurons and their structure. The micrograph shows a network of motor neurons, which relay signals from the brain or spinal cord to muscles and glands. (Micrograph: Lennart Nilsson from Behold Man, © 1974 Albert Bonniers Forlag and Little, Brown and Company, Boston.)

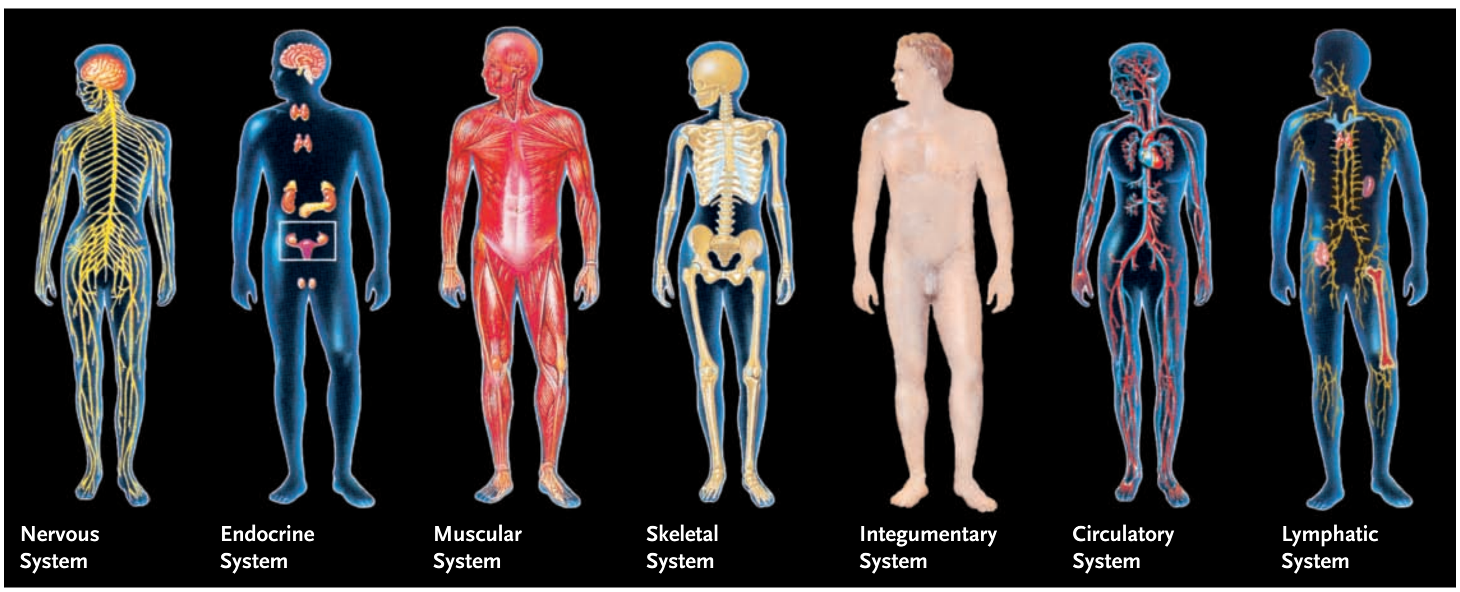
Study Break

1. Distinguish between exocrine and endocrine glands. What is the tissue type of each of these glands?
2. What are the six major types of connective tissue in vertebrates?
3. What three types of muscle tissue produce body movements?

36.3 Coordination of Tissues in Organs and Organ Systems

Organs and Organ Systems Function Together to Enable an Animal to Survive

In the tissues, organs, and organ systems of an animal, each cell engages in the basic metabolic activities that ensure its own survival, and performs one or more functions of the system to which it belongs. All verte-



Nervous System
Main organs: Brain, spinal cord, peripheral nerves, sensory organs
Main functions: Principal regulatory system; monitors changes in internal and external environments and formulates compensatory responses; coordinates body activities

Endocrine System
Main organs: Pituitary, thyroid, adrenal, pancreas, and other hormone-secreting glands
Main functions: Regulates and coordinates body activities through secretion of hormones

Muscular System
Main organs: Skeletal, cardiac, and smooth muscle
Main functions: Moves body parts; helps run bodily functions; generates heat

Skeletal System
Main organs: Bones, tendons, ligaments, cartilage
Main functions: Supports and protects body parts; provides leverage for body movements

Integumentary System
Main organs: Skin, sweat glands, hair, nails
Main functions: Covers external body surfaces and protects against injury and infection; helps regulate water content and body temperature

Circulatory System
Main organs: Heart, blood vessels, blood
Main functions: Distributes water, nutrients, oxygen, hormones, and other substances throughout body and carries away carbon dioxide and other metabolic wastes; helps stabilize internal temperature and pH

Lymphatic System
Main organs: Lymph nodes, lymph ducts, spleen, thymus
Main functions: Returns excess fluid to the blood; defends body against invading viruses, bacteria, fungi, and other pathogens as part of immune system

brates (and most invertebrates) have eleven major organ systems, which are summarized in **Figure 36.8,** and discussed in the rest of this unit of the book.

The functions of all these organ systems are coordinated and integrated to accomplish collectively a series of tasks that are vital to all animals, whether a flatworm, a salmon, a meerkat, or a human. These functions include:

1. Acquiring nutrients and other required substances such as oxygen, coordinating their processing, distributing them throughout the body, and disposing of wastes.
2. Synthesizing the protein, carbohydrate, lipid, and nucleic acid molecules required for body structure and function.
3. Sensing and responding to changes in the environment, such as temperature, pH, and ion concentrations.
4. Protecting the body against injury or attack from other animals, and from viruses, bacteria, and other disease-causing agents.
5. Reproducing and, in many instances, nourishing and protecting offspring through their early growth and development.

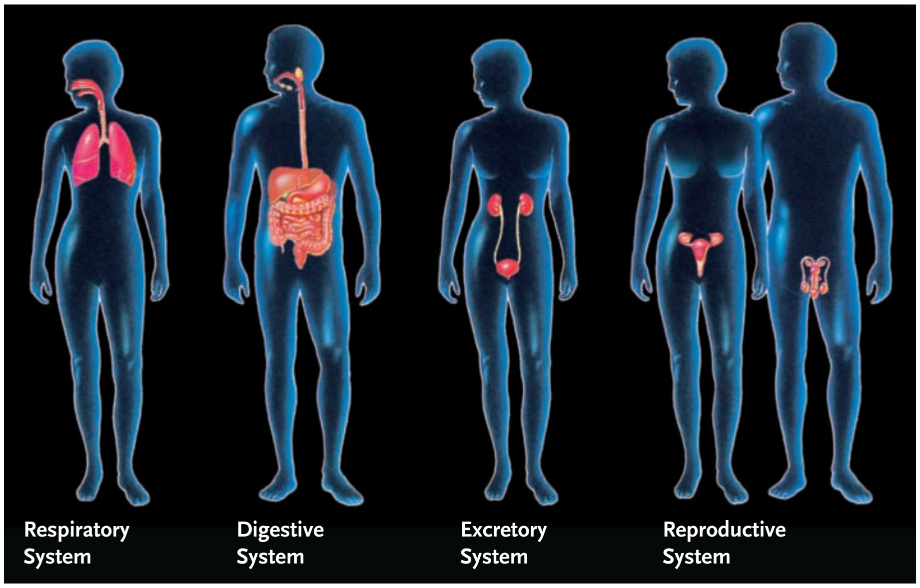
Together these tasks maintain homeostasis, preserving the internal environment required for survival of the body. Homeostasis is the topic of the next section.

Study Break

What are the major functions of each of the eleven organ systems of the vertebrate body?

36.4 Homeostasis

Homeostasis is the process by which animals maintain their internal environment in a steady state (constant level) or between narrow limits. Homeostasis depends on a number of the body's organ systems, with the



Respiratory System	Digestive System	Excretory System	Reproductive System
Main organs: Lungs, diaphragm, trachea, and other airways	Main organs: Pharynx, esophagus, stomach, intestines, liver, pancreas, rectum, anus	Main organs: Kidneys, bladder, ureter, urethra	Main organs: *Female*: ovaries, oviducts, uterus, vagina, mammary glands *Male*: testes, sperm ducts, accessory glands, penis
Main functions: Exchanges gases with the environment, including uptake of oxygen and release of carbon dioxide	Main functions: Converts ingested matter into molecules and ions that can be absorbed into body; eliminates undigested matter; helps regulate water content	Main functions: Removes and eliminates excess water, ions, and metabolic wastes from body; helps regulate internal osmotic balance and pH	Main functions: Maintains the sexual characteristics and passes on genes to the next generation

Figure 36.8
Organ systems of the human body. The immune system, which is primarily a cellular system, is not shown.

nervous system and endocrine system being the most important. For example, blood pH is controlled by both the nervous and endocrine systems, blood glucose by the endocrine system, internal temperature by the nervous and endocrine systems, and oxygen and carbon dioxide concentrations by the nervous system.

Although the *stasis* part of homeostasis might suggest a static, unchanging process, homeostasis is actually a dynamic process, in which internal adjustments are made continuously to compensate for environmental changes. For example, internal adjustments are needed for homeostasis during exercise or hibernation. The factors controlled by homeostatic mechanisms all require energy that must be constantly acquired from the external environment.

Homeostasis Is Accomplished by Negative Feedback Mechanisms

The primary mechanism of homeostasis is **negative feedback**, in which a stimulus—a change in the external or internal environment—triggers a response that compensates for the environmental change **(Figure 36.9).** Homeostatic mechanisms typically include three elements: a sensor, an integrator, and an effector. The **sensor** consists of tissues or organs that detect a change in external or internal factors such as pH, temperature, or the concentration of a molecule such as glucose. The **integrator** is a control center that compares the detected environmental change with a **set point**, the level at which the condition controlled by the pathway is to be maintained. The **effector** is a system, activated by the integrator, that returns the condition to the set point if it has strayed away. In most animals, the integrator is part of the central nervous system or endocrine system, while effectors may include parts of essentially any body tissue or organ.

The Thermostat as a Negative Feedback Mechanism. The concept of negative feedback may be most familiar in systems designed by human engineers. The thermostat maintaining temperature at a chosen level in a house provides an example. A sensor within the thermostat measures the temperature. If the room temperature changes more than a degree or so from the set point—the temperature that you set in the thermostat—an integrator circuit in the thermostat activates an effector that returns the room temperature to the set point. If the temperature has fallen below the set point, the effector is the furnace, which adds heat to the house until the temperature rises to the set point. If the temperature has risen above the set point, the effector is the air conditioner, which removes heat from the room until the temperature falls to the set point.

Negative Feedback Mechanisms in Animals. Mammals and birds—warm-blooded vertebrates—also have a homeostatic mechanism that maintains body temperature within a relatively narrow range around a set point. The integrator (thermostat) for this mechanism is located in a brain center called the *hypothalamus*. A group of neurons in the hypothalamus detects changes in the temperature of the brain and the rest of the body, and compares it with a set point. For humans, the set point has a relatively narrow range centered at about 37°C.

One or more effectors are activated in humans if the temperature varies beyond the limits of the set point. If the temperature falls below the lower limit, the hypothalamus activates effectors that constrict the blood vessels in the skin. The reduction in blood flow means that less heat is conducted from the blood through the skin to the environment; in short, heat loss from the skin is reduced. Other effectors may induce shivering, a physical mechanism to generate body heat. Also, integrating neurons in the brain, stimulated by signals from the hypothalamus, make us consciously sense a chill, which we may counteract behaviorally by putting on more clothes or moving to a warmer area.

Conversely, if blood temperature rises above the set point, the hypothalamus triggers effectors that dilate the blood vessels in the skin, increasing blood flow and heat loss from the skin. Other effectors induce sweating, which cools the skin and the blood flowing through it as the sweat evaporates. And again, through integrating neurons in the brain, we may consciously sense being overheated, which we may counteract by shedding clothes, moving to a cooler location, or taking a dip in a pool.

Sometimes the temperature set point changes, and the negative feedback mechanisms then operate to maintain body temperature at the new set point. For example, if you become infected by certain viruses and bacteria, the temperature set point increases to a higher level, producing a fever to help overcome the infection. Once the infection is combated, the set point is readjusted down again to its normal level.

All other mammals have similar homeostatic mechanisms that maintain or adjust body temperature. Dogs and birds pant to release heat from their bodies **(Figure 36.10)** and shiver to increase internal heat production. Many terrestrial animals

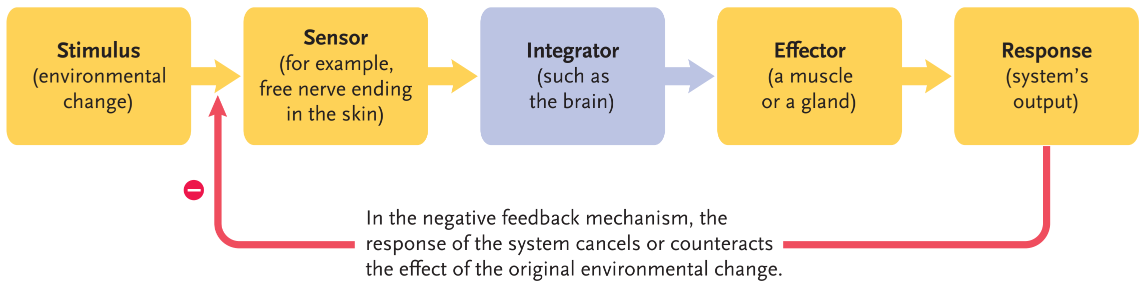
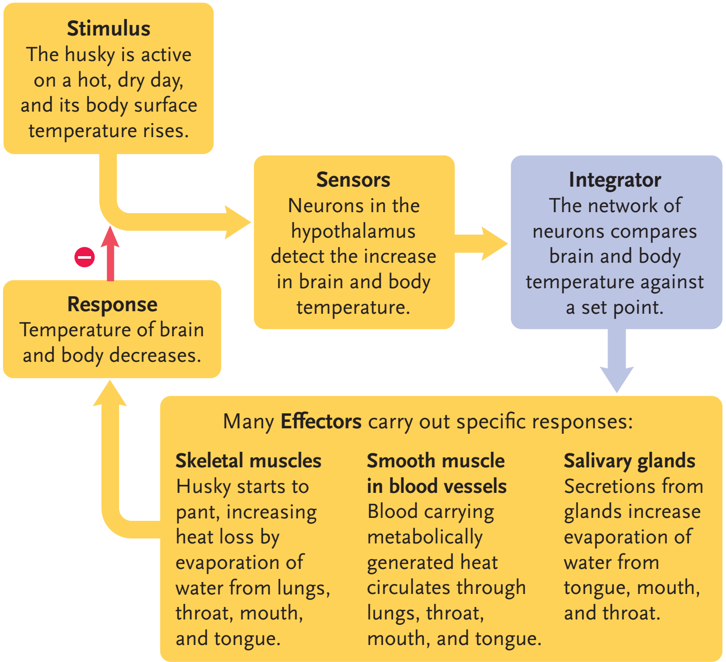


Figure 36.9 Components of a negative feedback mechanism maintaining homeostasis. The integrator coordinates a response by comparing the level of an environmental condition with a set point that indicates where the level should be.



Fred Bruemmer

Figure 36.10 Homeostatic mechanisms maintaining the body temperature of a husky when environmental temperatures are high.

enter or splash water over their bodies to cool off. Also, recall from the beginning of the chapter how meerkats use behavioral mechanisms to regulate their body temperature.

Whereas mammals regulate their internal body temperature within a narrow range around a set point, certain other vertebrates regulate over a broader range. These vertebrates use other, less precise negative feedback mechanisms for their temperature regulation. Snakes and lizards, for example, respond behaviorally to compensate for variations in environmental temperatures. They may absorb heat by basking on sunny rocks in the cool early morning and move to cooler, shaded spots in the heat of the afternoon. Some fishes, such as the tuna, generate enough heat by contraction of the swimming muscles to maintain body temperature well above the temperature of the surrounding water.

Some invertebrates, such as dragonflies, moths, and butterflies, use muscular contractions equivalent to shivering when their body temperature falls below the level required for flight. The shivering contractions warm the muscles to flying temperature. All of these physiological and behavioral responses depend on negative feedback mechanisms involving sensors, integrators, and effectors.

Animals Also Have Positive Feedback Mechanisms That Do Not Result in Homeostasis

Under certain circumstances, animals respond to a change in internal or external environmental condition by a **positive feedback** mechanism that intensifies or adds to the change. Such mechanisms, with some exceptions, do not result in homeostasis. They operate when the animal is responding to life-threatening conditions (an attack, for instance), or as part of reproductive processes.

The birth process in mammals is a prime example. During human childbirth, initial contractions of the uterus push the head of the fetus against the cervix, the opening of the uterus into the vagina. The pushing causes the cervix to stretch. Sensors that detect the stretching signal the hypothalamus to release a hormone, oxytocin, from the pituitary gland. Oxytocin increases the uterine contractions, intensifying the squeezing pressure on the fetus and further stretching the cervix. The stretching results in more oxytocin release and stronger uterine contraction, repeating the positive feedback circuit and increasing the squeezing pressure until the fetus is pushed entirely out of the uterus.

Because positive feedback mechanisms such as the one triggering childbirth do not result in homeostasis, they occur less commonly than negative feedback in animals. They also operate as part of larger, more inclusive negative feedback mechanisms that ultimately shut off the positive feedback pathway and return conditions to normal limits.

In conclusion, we learned in this chapter about the various tissues and organ systems of the body, and of the involvement of organ systems in homeostasis. Next, we begin a series of chapters describing the organ systems in detail, starting with the nervous system.

Study Break

What are the components of a negative feedback mechanism that results in homeostasis?

Unanswered Questions

Why do so many strokes and heart attacks occur in the morning?
Stroke and heart attack occur most frequently at a particular time of the day—in the morning—exhibiting a profound circadian variation. Circadian rhythms are generated through a discrete set of molecular interactions including the Bmal1, Clock, NPAS2, Cry, and Per proteins. We have recently shown that the biological clock is expressed and oscillating in blood vessels; however, it remains unknown if this "vascular clock" acts to modulate the function of blood vessels. Moreover, if the vascular clock does influence normal vascular function, might a broken clock contribute to the onset of heart attack and stroke? Current research in my laboratory and others is addressing these questions.

How could a vascular clock influence vascular function?
Circadian rhythms are seen in endothelial function, blood pressure, vascular resistance, and blood flow. Could the circadian clock play a role in the regulation of blood vessel homeostasis? What targets within vascular cells might the clock control? One possibility is that the vascular clock may act to regulate production of signaling molecules in endothelial cells, which comprise the inner lining of blood vessels. In addition, direct actions on vascular smooth muscle cells, which contain the nerve and muscle elements critical for constriction and relaxation of blood vessels, may also be under circadian control. To assess these questions, the use of mice with genetic disruption of the circadian clock (knockout or mutant mice) has been invaluable. Garret FitzGerald and colleagues at the University of Pennsylvania demonstrated that *Bmal1* knockout mice and *Clock* mutant mice lack circadian rhythms in blood pressure, in part due to a blunted sympathetic drive. However, the contribution of parasympathetic outflow remains unknown. Might the clock directly induce or inhibit transcription of genes important to vascular function? One approach is to introduce molecular clock components into cultured cells and to assess promoter regulation of a gene of interest. This has already proved useful in identifying the PAI-1 (plasminogen activator inhibitor-1) protein as a target of the molecular clock. PAI-1 inhibits plasminogen activator, an enzyme that breaks up clots. So PAI-1 promotes clot formation. Future studies implementing tissue-specific knockout mice of molecular clock components will determine more directly how and where these targets are regulated by the circadian clock.

Might a dysfunctional vascular clock contribute to chronic vascular disease?
Chronic impairments in blood pressure and blood flow rhythms are sensed by blood vessels, which causes them to respond by changing architecture through a process called vascular remodeling. Vascular remodeling is an extremely intensive and active area of vascular biology research that is important to understanding the progression to blood vessel disease. Using models of blood vessel ligation in mice with a disrupted molecular clock, we are currently assessing the impact of the biological clock on vascular remodeling.

Research to address the role of the vascular clock may ultimately change the way we understand and treat arteriosclerosis, hypertension, and heart attack.

R. Daniel Rudic is an assistant professor in the Department of Pharmacology and Toxicology at the Medical College of Georgia. To learn more about his research on circadian rhythms and vascular biology, go to http://www.mcg.edu/som/phmtox/RudicLab/index.asp.

Review

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36.1 Organization of the Animal Body

- In most animals, cells are specialized and organized into tissues, tissues into organs, and organs into organ systems. A tissue is a group of cells with the same structure and function, working as a unit to carry out one or more activities. An organ is an assembly of tissues integrated into a structure that carries out a specific function. An organ system is a group of organs that carry out related steps in a major physiological process.

36.2 Animal Tissues

- Animal tissues are classified as epithelial, connective, muscle, or nervous (Figure 36.2). The properties of the cells of these tissues determine the structures and functions of the tissues.
- Various kinds of junctions link cells in a tissue. Anchoring junctions "weld" cells together. Tight junctions seal the cells into a leak-proof layer. Gap junctions form direct avenues of communication between the cytoplasm of adjacent cells in the same tissue.
- Epithelial tissue consists of sheetlike layers of cells that cover body surfaces and the surfaces of internal organs, and line cavities and ducts within the body (Figure 36.3).
- Glands are secretory structures derived from epithelia. They may be exocrine (connected to an epithelium by a duct that empties on the epithelial surface) or endocrine (ductless, with no direct connection to an epithelium) (Figure 36.4).
- Connective tissue consists of cell networks or layers and an extracellular matrix (ECM). It supports other body tissues, transmits mechanical and other forces, and in some cases acts as a filter (Figure 36.5).
- Loose connective tissue consists of sparsely distributed fibroblasts surrounded by an open network of collagen and other glycoproteins. It supports epithelia and organs of the body and forms a covering around blood vessels, nerves, and some internal organs.
- Fibrous connective tissue contains sparsely distributed fibroblasts in a matrix of densely packed, parallel bundles of collagen

and elastin fibers. It forms high tensile-strength structures such as tendons and ligaments.

- Cartilage consists of sparsely distributed chondrocytes surrounded by a network of collagen fibers embedded in a tough but highly elastic matrix of branched glycoproteins. Cartilage provides support, flexibility, and a low-friction surface for joint movement.
- In bone, osteocytes are embedded in a collagen matrix hardened by mineral deposits. Osteoblasts secrete collagen and minerals for the ECM; osteoclasts remove the minerals and recycle them into the bloodstream.
- Adipose tissue consists of cells specialized for fat storage. It also cushions and rounds out the body and provides an insulating layer under the skin.
- Blood consists of a fluid matrix, the plasma, in which erythrocytes and leukocytes are suspended. The erythrocytes carry oxygen to body cells; the leukocytes produce antibodies and initiate the immune response against disease-causing agents.
- Muscle tissue contains cells that have the ability to contract forcibly (Figure 36.6). Skeletal muscle, containing long cells called muscle fibers, moves body parts and maintains posture.
- Cardiac muscle, which contains short contractile cells with a branched structure, forms the heart.
- Smooth muscle consists of spindle-shaped contractile cells that form layers surrounding body cavities and ducts.
- Nervous tissue contains neurons and glial cells. Neurons communicate information between body parts in the form of electrical and chemical signals (Figure 36.7). Glial cells support the neurons or provide electrical insulation between them.

Animation: Cell junctions

Animation: Structure of an epithelium

Animation: Types of simple epithelium

Animation: Soft connective tissues

Animation: Specialized connective tissues

Animation: Muscle tissues

Animation: Functional zones of a motor neuron

Animation: Structure of human skin

Practice: Differences between cell and tissue types

36.3 Coordination of Tissues in Organs and Organ Systems

- Organs and organ systems are coordinated to carry out vital tasks, including maintenance of internal body conditions; nutrient acquisition, processing, and distribution; waste disposal; molecular synthesis; environmental sensing and response; protection against injury and disease; and reproduction.
- In vertebrates and most invertebrates, the major organ systems that accomplish these tasks are the nervous, endocrine, muscular, skeletal, integumentary, circulatory, lymphatic, immune, respiratory, digestive, excretory, and reproductive systems (Figure 36.8).

Animation: Human organ systems

36.4 Homeostasis

- Homeostasis is the process by which animals maintain their internal fluid environment under conditions their cells can tolerate. It is a dynamic state, in which internal adjustments are made continuously to compensate for environmental changes.
- Homeostasis is accomplished by negative feedback mechanisms that include a sensor, which detects a change in an external or internal condition; an integrator, which compares the detected change with a set point; and an effector, which returns the condition to the set point if it has varied (Figure 36.9).
- Animals also have positive feedback mechanisms, in which a change in an internal or external condition triggers a response that intensifies the change, and typically does not result in homeostasis.

Questions

Self-Test Questions

1. Which organ or tissue is an early major defense against viruses and bacteria?
   a. kidneys
   b. skin
   c. stomach
   d. skeletal muscle
   e. heart
2. Which tissue is a constant source of adult stem cells in a mammal?
   a. bone marrow
   b. pancreas
   c. basal lamina
   d. heart muscle
   e. kidneys
3. A flexible, rubbery protein in connective tissue is called ___, whereas a more fibrous, less flexible glycoprotein is called ___.
   a. adipose; cartilage
   b. endocrine; exocrine
   c. sweat; hormones
   d. chondroitin sulfate; hydroxapatite
   e. elastin; collagen
4. Adipose tissue:
   a. gives elasticity under epithelium.
   b. gives strength to tendons.
   c. insulates and is an energy reserve.
   d. provides movement, support, and protection.
   e. supports the nose and airways.
5. The bones of an elderly woman break more easily than those of a younger person. You would surmise that with aging, the cell type that diminishes in activity is the:
   a. osteocyte.
   b. osteoblast.
   c. osteoclast.
   d. chondrocyte.
   e. fibroblast.
6. The enormous mass of weight lifters is due to an increase in the size of:
   a. skeletal muscle.
   b. smooth muscle.
   c. cardiac muscle.
   d. involuntary muscle.
   e. interlinked, branched muscle.
7. Which muscle types appear striated under a microscope?
   a. skeletal muscles only
   b. cardiac muscles only
   c. skeletal muscles and cardiac muscles
   d. smooth muscles only
   e. skeletal muscles and smooth muscles
8. Which of the following is *not* a homeostatic response?
   a. In a contest, a student eats an entire chocolate cake in 10 minutes. Due to hormonal secretions, his blood glucose level does not change dramatically.
   b. The basketball players are dripping sweat at half time.
   c. The pupils in the eyes constrict when looking at a light.

d. Slower breathing in sleep changes carbon dioxide and oxygen blood levels, which affect blood pH.
e. The brain is damaged when a fever rises above 105°F.

8. The pituitary gland secretes a hormone that in turn stimulates the thyroid to secrete hormones. When the thyroid hormones are no longer needed, the pituitary stops or reduces its stimulus. This is an example of:
   a. osmolarity.
   b. environmental sensing.
   c. integration.
   d. positive feedback.
   e. negative feedback.

10. The system that coordinates other organ systems is the:
   a. skeletal system.
   b. reproductive system.
   c. muscular system.
   d. nervous system.
   e. integumentary system.

Questions for Discussion

1. Blood is often described as an atypical connective tissue. If you had to argue that blood is a connective tissue, what reasons would you include? What reasons would you include if you had to argue that blood is not a connective tissue?
2. What effect do you think a program of lifting weights would have on the bones of the skeleton? How would you design an experiment to test your prediction?
3. Positive feedback mechanisms are rare in animals compared with negative feedback mechanisms. Why do you think this is so?
4. Near the time of childbirth, collagen fibers in the connective tissue of the cervix break down, and gap junctions between the smooth muscle cells of the uterus increase in number. What do you think is the significance of these tissue changes?
5. Explain how, when driving, you control the car's speed by a typical negative feedback mechanism.

Experimental Analysis

The regulation of temperature in mammals and birds is an example of homeostasis. Design an experiment to observe and measure processes involved in temperature homeostasis in sedentary versus athletic humans during exercise.

Evolution Link

Steroid hormones are similar in structure and function across a wide array of animal species. For example, estradiol, which plays a critical role in reproductive and sexual functioning, is chemically identical in turtles and humans. What do these observations suggest about the time when steroid hormones evolved?