13.3 The Vascular Pathways

The cardiovascular system, which is represented in Figure 13.7, includes two circuits: the **pulmonary circuit,** which circulates blood through the lungs, and the **systemic circuit,** which serves the needs of body tissues.

The Pulmonary Circuit

The path of blood through the lungs can be traced as follows. Blood from all regions of the body first 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 branch as they approach the lungs. The arterioles take blood to the pulmonary capillaries, where carbon dioxide is given off and oxygen is picked up. Blood then passes through the pulmonary venules, which lead to the four **pulmonary veins** that enter the left atrium. Since blood in the pulmonary arteries is relatively low in oxygen but blood in the pulmonary veins is relatively high in oxygen, it is not correct to say that all arteries carry oxygenated blood and all veins carry deoxygenated blood. It is just the reverse in the pulmonary circuit.

> The pulmonary arteries take blood that is low in oxygen to the lungs, and the pulmonary veins return blood that is high in oxygen to the heart.

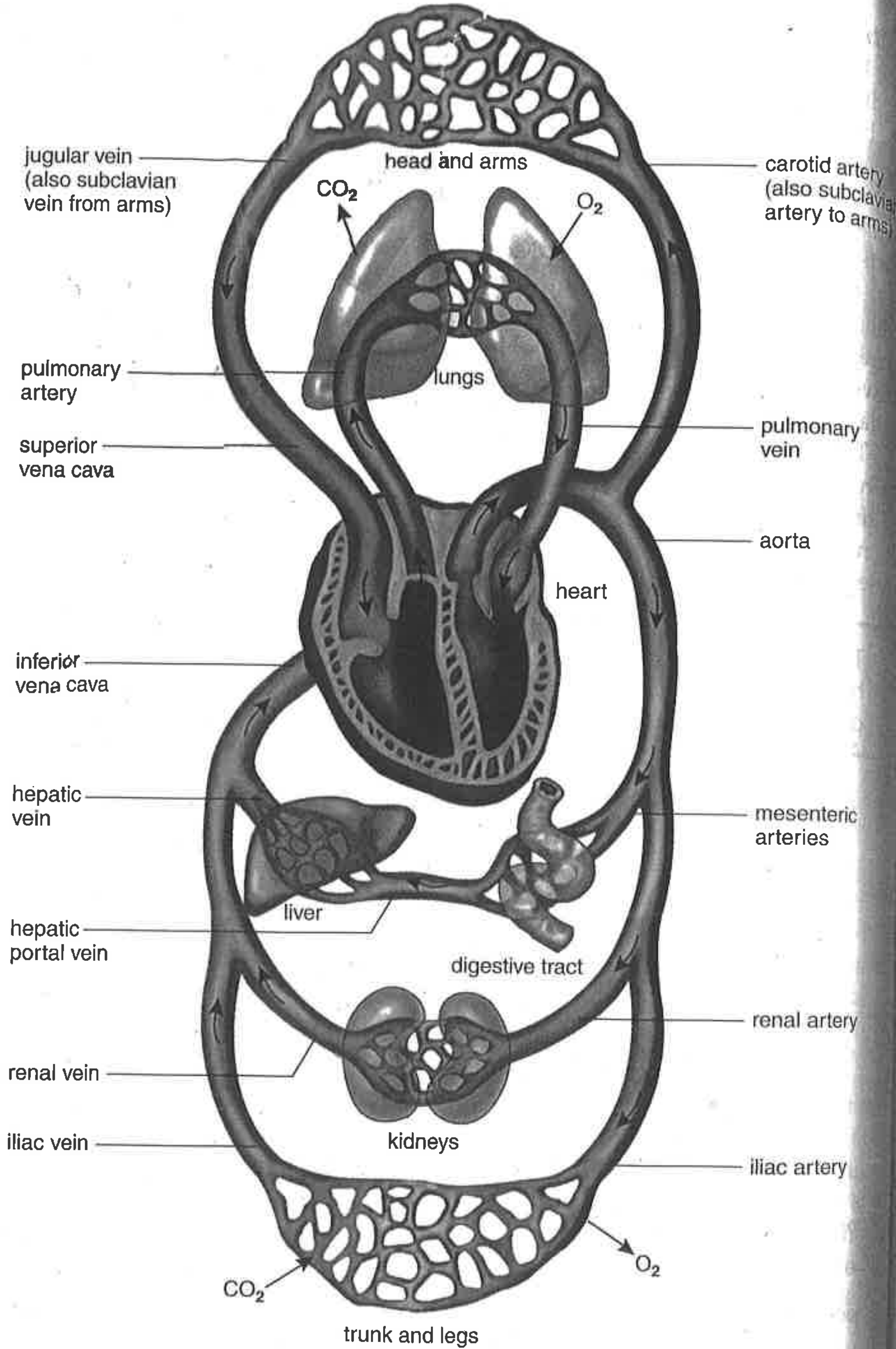


Figure 13.7 Cardiovascular system diagram.
The blue-colored vessels carry blood that is relatively low in oxygen, and the red-colored vessels carry blood that is relatively high in oxygen. The arrows indicate the flow of blood. Compare this diagram, useful for learning to trace the path of blood, to Figure 13.8 to realize that both arteries and veins go to all parts of the body. Also, there are capillaries in all parts of the body. No cell is located far from a capillary.

The Systemic Circuit

The systemic circuit includes all of the arteries and veins shown in Figure 13.8. The largest artery in the systemic circuit is the **aorta,** and the largest veins are the **superior** and **inferior venae cavae.** The superior vena cava collects blood from the head, the chest, and the arms, and the inferior vena cava collects blood from the lower body regions. Both enter the right atrium. The aorta and the venae cavae serve as the major pathways for blood in the systemic circuit.

Jane stretched out her arm and watched as the nurse slipped a needle into a vein at the crook of her arm. She was thinking about her friend who needed the blood that was now coursing through a plastic tube into a bag. Jane had the same blood type as her friend who had been in an automobile accident. Blood, a vital fluid, carries oxygen from the lungs and nutrients from the intestines to the cells. Kept in motion by the pumping of the heart, it helps fight infection, helps regulate body temperature, coordinates body tissues, and carries wastes to the kidneys. A severe loss of blood must be replaced by transfusion if life is to continue.

This chapter discusses the cardiovascular system, which includes blood but also the heart and blood vessels. Humans have a closed system in that the blood never runs free and is conducted to and from the tissues by blood vessels. Only the capillaries have walls thin enough to allow exchange of molecules with the tissues. The heart is the organ that keeps the blood moving through the vessels to the capillaries. If the heart fails to pump the blood for even a few minutes, the individual's life is in danger. The body has various mechanisms for ensuring that blood remains in the vessels and under a pressure that will maintain the transport function of blood.

13.1 The Blood Vessels

The cardiovascular system has three types of blood vess the **arteries** (and arterioles), which carry blood away fr the heart to the capillaries; the **capillaries,** which permit change of material with the tissues; and the **veins** (a venules), which return blood from the capillaries to t heart.

The Arteries

The *arterial wall has three layers* (Fig. 13.1*a*). The inner layer a simple squamous epithelium called endothelium with connective tissue basement membrane that contains elas fibers. The middle layer is the thickest layer and consists smooth muscle that can contract to regulate blood flow a blood pressure. The outer layer is fibrous connective tiss near the middle layer, but it becomes loose connective tiss at its periphery. Some arteries are so large that they requi their own blood vessels.

Arterioles are small arteries just visible to the nak eye. The middle layer of arterioles has some elastic tiss

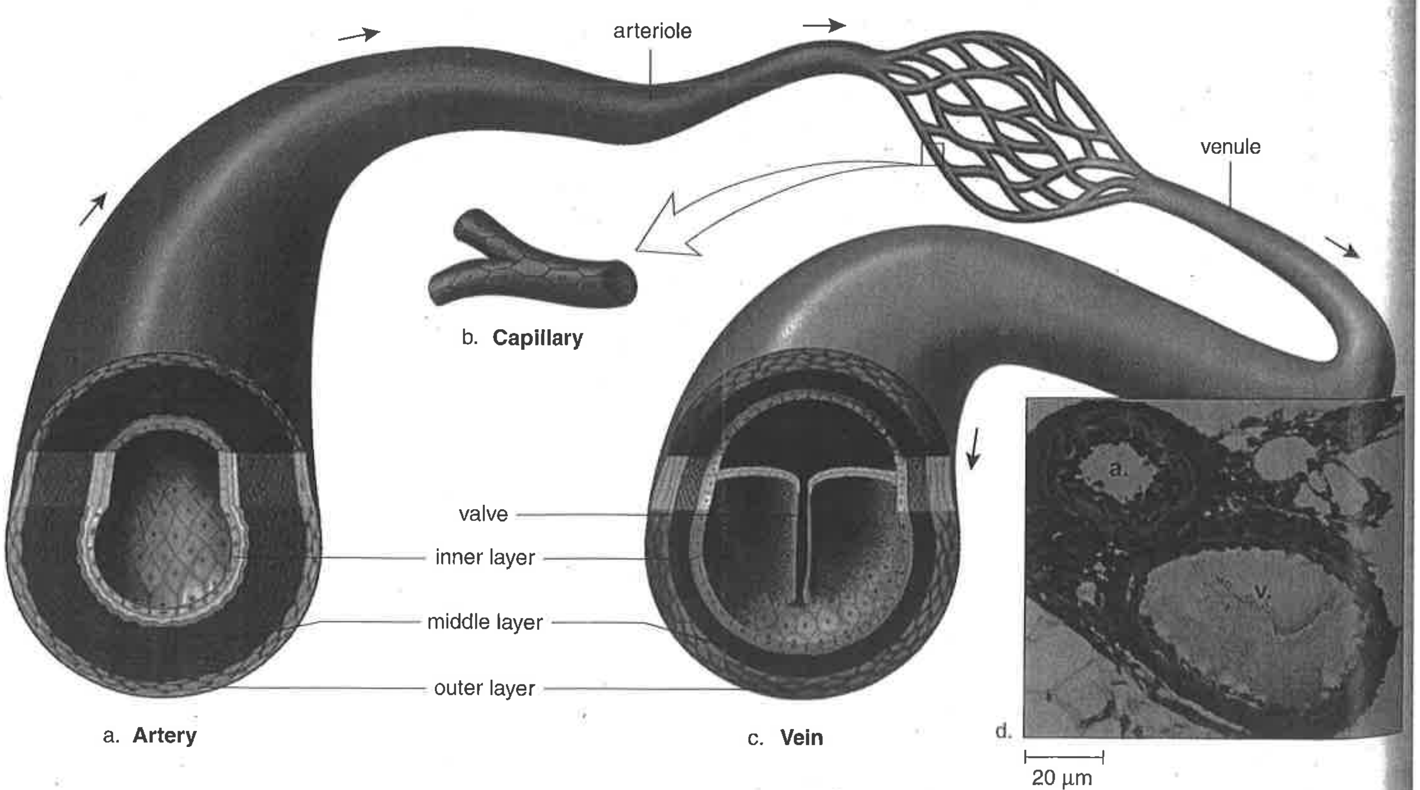


Figure 13.1 **Blood vessels.**
The walls of arteries and veins have three layers. The inner layer is composed largely of endothelium with a basement membrane that has elast fibers; the middle layer is smooth muscle tissue; the inner layer is connective tissue (largely collagen fibers). **a.** Arteries have a thicker wall than veins because they have a larger middle layer than veins. **b.** Capillary walls are one-cell-thick endothelium. **c.** Veins are larger in diameter than arteries, so that collectively veins have a larger holding capacity than arteries. **d.** Scanning electron micrograph of an artery and vein.

but is composed mostly of smooth muscle whose fibers encircle the arteriole. When these muscle fibers are contracted, the vessel has a smaller diameter (is constricted); and when these muscle fibers relax, the vessel has a larger diameter (is dilated). Whether arterioles are constricted or dilated affects blood pressure. The greater the number of vessels dilated, the lower the blood pressure.

The Capillaries

Arterioles branch into capillaries (Fig. 13.1*b*). Each capillary is an extremely narrow, microscopic tube with one-cell-thick walls composed only of endothelium with a basement membrane. *Capillary beds* (networks of many capillaries) are present in all regions of the body; consequently, a cut to any body tissue draws blood. Capillaries are a very important part of the human cardiovascular system because an exchange of substances takes place across their thin walls. Oxygen and nutrients, such as glucose, diffuse out of a capillary into the tissue fluid that surrounds cells. Wastes, such as carbon dioxide, diffuse into the capillary.

Since the capillaries serve the cells, the heart and the other vessels of the cardiovascular system can be thought of as the means by which blood is conducted to and from the capillaries. Only certain capillaries are open at any given time. For example, after eating, the capillaries that serve the digestive system are open and those that serve the muscles are closed. When a capillary bed is closed, the precapillary sphincters contract, and the blood moves from arteriole to venule by way of an arteriovenous shunt (Fig. 13.2).

The Veins

Venules are small veins that drain blood from the capillaries and then join to form a vein. The walls of venules (and veins) have the same three layers as arteries, but there is less smooth muscle and connective tissue (Fig. 13.1*c*). Veins often have **valves**, which allow blood to flow only toward the heart when open and prevent the backward flow of blood when closed.

Since walls of veins are thinner, they can expand to a greater extent (Fig. 13.1*d*). At any one time about 70% of the blood is in the veins. In this way, the veins act as a blood reservoir.

Arteries and arterioles carry blood away from the heart toward the capillaries; capillaries join arterioles to venules; veins and venules return blood from the capillaries to the heart.

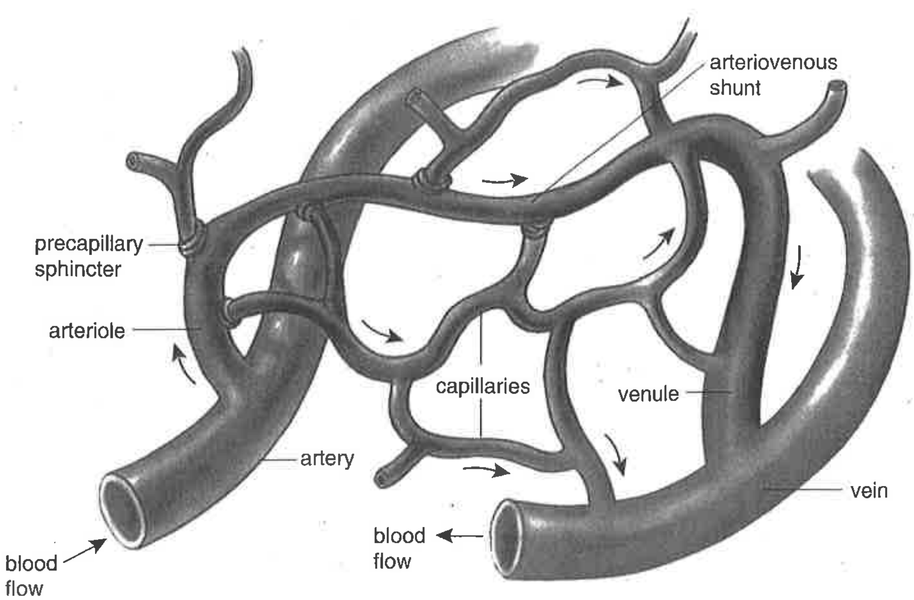


Figure 13.2 Anatomy of a capillary bed.
A capillary bed forms a maze of capillary vessels that lies between an arteriole and a venule. When sphincter muscles are relaxed, the capillary bed is open, and blood flows through the capillaries. When sphincter muscles are contracted, blood flows through a shunt that carries blood directly from an arteriole to a venule. As blood passes through a capillary in the tissues, it gives up its oxygen (O_2). Therefore, blood goes from carrying more oxygen in the arteriole (red color) to carrying less oxygen (blue color) in the vein.

Blood Flow

Blood flow differs with regard to pressure and velocity in the different vessels of the cardiovascular system (Fig. 13.9).

Blood Flow in Arteries

Blood pressure created by the pumping of the heart accounts for the velocity of blood in the arteries. **Blood pressure,** which is simply the pressure of blood against the wall of a blood vessel, fluctuates in the arteries. **Systolic pressure,** which occurs when the ventricles contract, is higher than **diastolic pressure** when the ventricles relax. Normal resting blood pressure for a young adult is said to be 120 mm Hg (mercury) over 80 mm Hg, or simply 120/80. The higher number is the systolic pressure, and the lower number is the diastolic pressure. Actually, 120/80 is the expected blood pressure in the brachial artery of the arm.

Both systolic and diastolic blood pressure decrease with distance from the left ventricle because the total cross-sectional area of the blood vessels increase—there are more arterioles than arteries. The decrease in blood pressure causes the blood velocity to gradually decrease as it flows toward the capillaries.

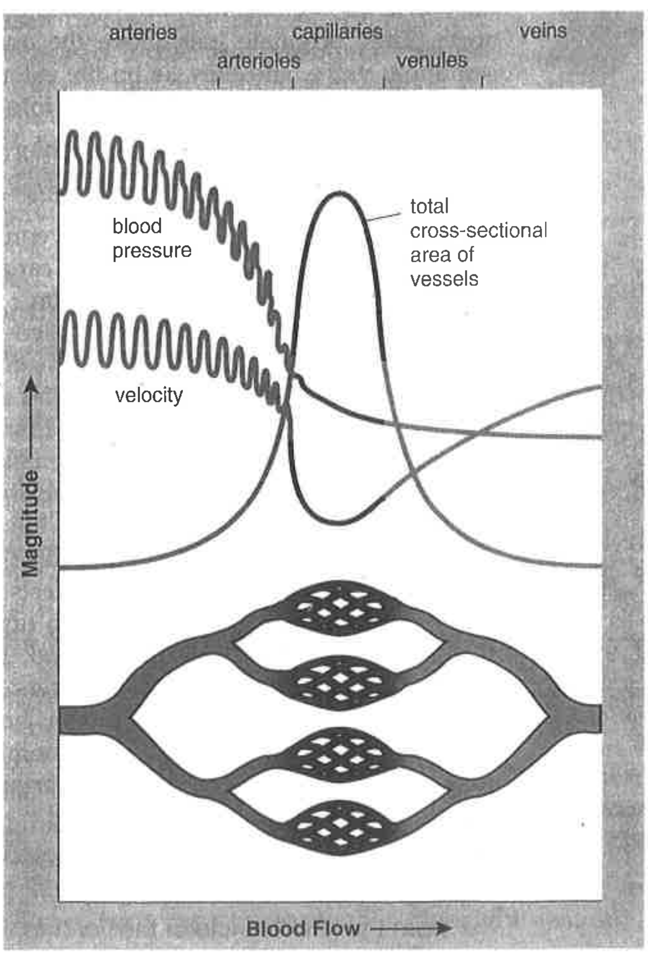


Figure 13.9 Cross-sectional area as it relates to blood pressure and blood velocity.
Blood pressure and blood velocity drop off in capillaries because capillaries have a greater cross-sectional area than arterioles.

Blood Flow in Capillaries

There are many more capillaries than arterioles, and bl moves slowly through the capillaries (Fig. 13.9). This is im portant because the slow progress allows time for the ex change of substances between blood in the capillaries an the surrounding tissues.

Blood Flow in Veins

Blood pressure is minimal in venules and veins (20–0 mm Hg). Instead of blood pressure, venous return is depen dent upon three factors: skeletal muscle contraction, pres ence of valves in veins, and respiratory movements. Whe the skeletal muscles contract, they compress the wea walls of the veins. This causes blood to move past the ne valve. Once past the valve, blood cannot flow backwar (Fig. 13.1*c*). The importance of muscle contraction in mo ing blood in the venous vessels can be demonstrated b forcing a person to stand rigidly still for an hour or so. Fre quently, fainting occurs because blood collects in th limbs, depriving the brain of needed blood flow an oxygen. In this case, fainting is beneficial because the re sulting horizontal position aids in getting blood to th head.

When inspiration occurs, the thoracic pressure falls an abdominal pressure rises as the chest expands. This also aid the flow of venous blood back to the heart because blo flows in the direction of reduced pressure. Blood velocity in creases slightly in the venous vessels due to a progressive re duction in the cross-sectional area as small venules join t form veins

> Blood pressure accounts for the flow of blood in the arteries and the arterioles. Skeletal muscle contraction, valves in veins, and respiratory movements account for the flow of blood in the venules and the veins.

Dilated and Inflamed Veins

Varicose veins develop when the valves of veins becom weak and ineffective due to the backward pressure of blo Abnormal and irregular dilations are particularly appar in the superficial (near the surface) veins of the lower le Crossing the legs or sitting in a chair so that its edge pres against the back of the knees can contribute to the develo ment of varicose veins. Varicose veins also occur in the re tum, where they are called piles, or more properly, **hem rhoids.**

Phlebitis, or inflammation of a vein, is a more serio condition, particularly when a deep vein is involved. Blo in an unbroken but inflamed vessel may clot, and the cl may be carried in the bloodstream until it lodges in a sm vessel. If a blood clot blocks a pulmonary vessel, death c result.

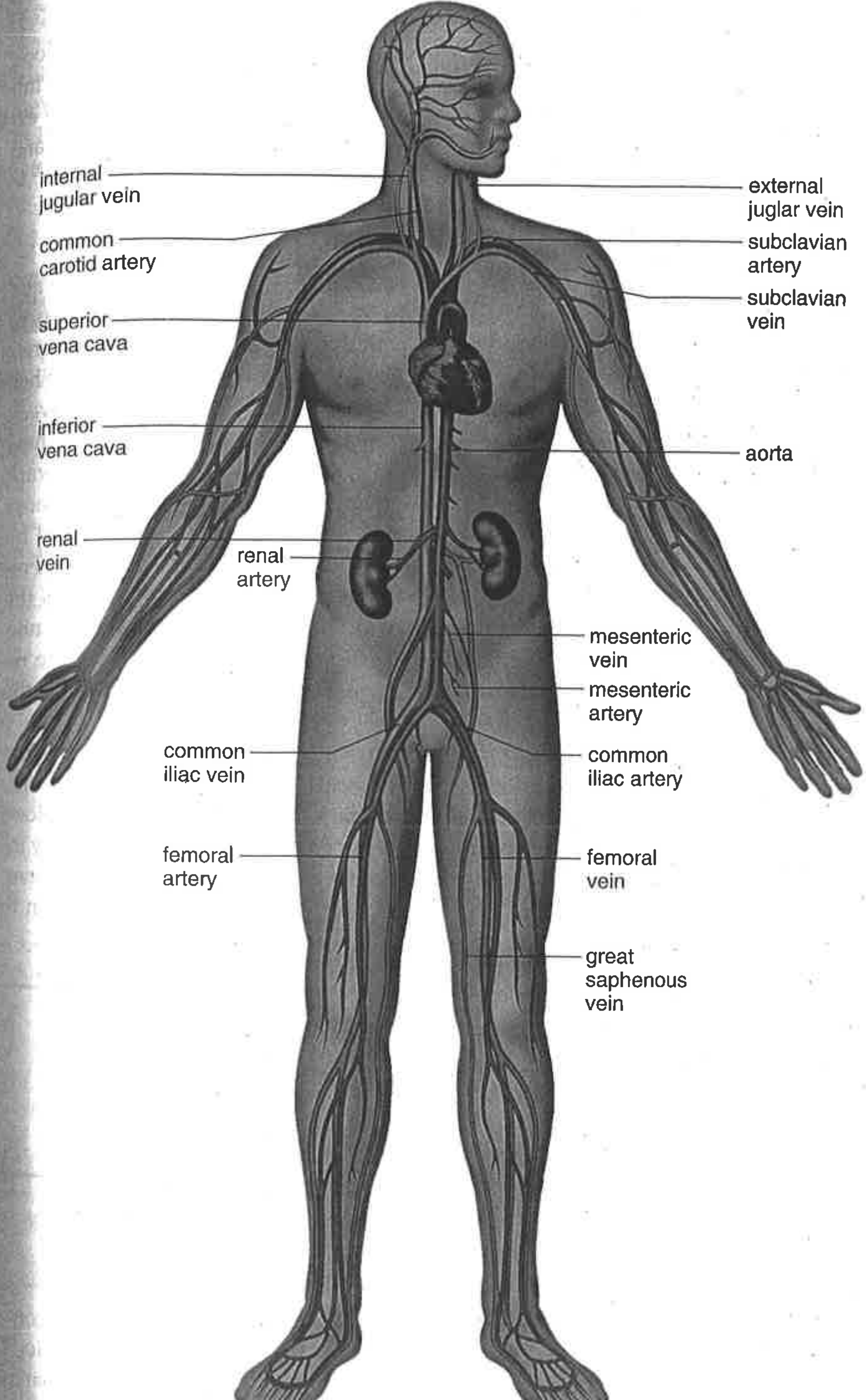


Figure 13.8 Major arteries and veins of the systemic circuit. A more realistic representation of major blood vessels of the systemic circuit shows how the systemic arteries and veins are actually arranged in the body. The superior and inferior venae cavae take their names from their relationship to which organ?

The path of systemic blood to any organ in the body begins in the left ventricle, which pumps blood into the aorta. Branches from the aorta go to the organs and major body regions. For example, this is the path of blood to and from the legs:

left ventricle—aorta—
common iliac artery—
legs—common iliac vein—
inferior vena cava—
right atrium

Notice when tracing blood, you need only mention the aorta, the proper branch of the aorta, the region, and the vein returning blood to the vena cava. In most instances, the artery and the vein that serve the same region are given the same name (Fig. 13.8). In the systemic circuit, arteries contain oxygenated blood and have a bright red color, but veins contain deoxygenated blood and appear a dark purplish color.

The **coronary arteries** (see Fig. 13.3) serve the heart muscle itself. (The heart is not nourished by the blood in its chambers.) The coronary arteries are the first branches off the aorta. They originate just above the aortic semilunar valve, and they lie on the exterior surface of the heart, where they divide into diverse arterioles. Because they have a very small diameter, the coronary arteries may become clogged, as discussed on page 258. The coronary capillary beds join to form venules. The venules converge to form the cardiac veins, which empty into the right atrium.

The body has a portal system called the **hepatic portal system,** which is associated with the liver. A portal system begins and ends in capillaries; in this instance, the first set of capillaries occurs at the villi of the small intestine and the second occurs in the liver. Blood passes from the capillaries of the intestinal villi into venules that join to form the **hepatic portal vein,** a vessel that connects the villi of the intestine with the liver, an organ that monitors the makeup of the blood. The **hepatic vein** leaves the liver and enters the inferior vena cava. While Figure 13.7 is helpful in tracing the path of blood, remember that all parts of the body receive both arteries and veins, as illustrated in Figure 13.8.

The systemic circuit takes blood from the left ventricle of the heart to the right atrium of the heart. It serves the body proper.

13.4 Blood

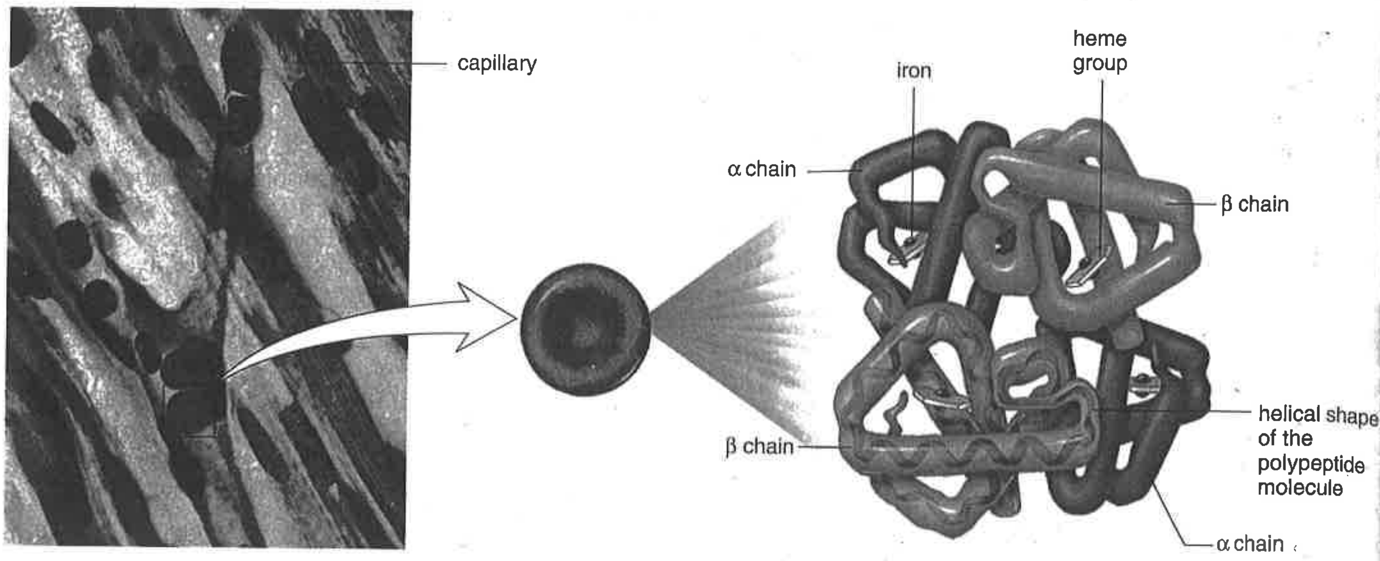
If blood is transferred from a person's vein to a test tube and is prevented from clotting, it separates into two layers (Fig. 13.10). The lower layer consists of red blood cells (erythrocytes), white blood cells (leukocytes), and blood platelets (thrombocytes). Collectively, these are called the **formed elements.** Formed elements make up about 45% of the total volume of whole blood. The upper layer, called **plasma,** is the liquid portion of blood. Plasma, which accounts for about 55% of the total volume of whole blood, contains a variety of inorganic and organic substances dissolved or suspended in water.

FORMED ELEMENTS	Function and Description	Source
Red Blood Cells (erythrocytes)  4 million–6 million per mm^3 blood	Transport O_2 and help transport CO_2 7–8 μm in diameter Bright-red to dark-purple biconcave disks without nuclei	Red bone marrow
White Blood Cells (leukocytes) 4,000–11,000 per mm^3 blood	Fight infection	Red bone marrow
Granular leukocytes		
• Basophil  20–50 per mm^3 blood	10–12 μm in diameter Spherical cells with lobed nuclei; large, irregularly shaped, deep-blue granules in cytoplasm	
• Eosinophil  100–400 per mm^3 blood	10–14 μm in diameter Spherical cells with bilobed nuclei; coarse, deep-red, uniformly sized granules in cytoplasm	
• Neutrophil  3,000–7,000 per mm^3 blood	10–14 μm in diameter Spherical cells with multilobed nuclei; fine, pink granules in cytoplasm	
Agranular leukocytes		
• Lymphocyte  1,500–3,000 per mm^3 blood	5–17 μm in diameter (average 9–10 μm) Spherical cells with large round nuclei	
• Monocyte  100–700 per mm^3 blood	10–24 μm in diameter Large spherical cells with kidney-shaped, round, or lobed nuclei	
• **Platelets** (thrombocytes)  150,000–300,000 per mm^3 blood	Aid clotting 2–4 μm in diameter Disk-shaped cell fragments with no nuclei; purple granules in cytoplasm	Red bone marrow

PLASMA	Function	Source
Water (90–92% of plasma)	Maintains blood volume; transports molecules	Absorbed from intestine
Plasma proteins (7–8% of plasma)	Maintain blood osmotic pressure and pH	Liver
Albumin	Maintain blood volume and pressure	
Globulins	Transport; fight infection	
Fibrinogen	Clotting	
Salts (less than 1% of plasma	Maintain blood osmotic pressure and pH; aid metabolism	Absorbed from intestine
Gases		
Oxygen Carbon dioxide	Cellular respiration End product of metabolism	Lungs Tissues
Nutrients	Food for cells	Absorbed from intestine
Fats Glucose Amino acids		
Nitrogenous waste	Excretion by kidneys	Liver
Urea Uric acid		
Other		
Hormones, vitamins, etc.	Aid metabolism	Varied

• with Wright's stain

Figure 13.10 Composition of blood.
When blood is transferred to a test tube and is prevented from clotting, it forms two layers. The transparent, yellow, top layer is plasma, the liquid portion of blood. The formed elements are in the bottom layer. The tables describe these components in detail.



a. Blood capillary b. Red blood cell c. Hemoglobin molecule

Figure 13.11 **Physiology of red blood cells.**
a. Red blood cells move single file through the capillaries. **b.** Each red blood cell is a biconcave disk containing many molecules of hemoglobin, the respiratory pigment. **c.** Hemoglobin contains four polypeptide chains (color coded blue), two of which are alpha (α) chains and two of which are beta (β) chains. The plane in the center of each chain represents an iron-containing heme group. Oxygen combines loosely with iron when hemoglobin is oxygenated. Oxygenated hemoglobin is bright red, and deoxygenated hemoglobin is a darker red color.

Plasma proteins, which make up 7–8% of plasma, assist in transporting large organic molecules in blood. For example, **albumin** transports bilirubin, a breakdown product of hemoglobin. The lipoproteins that transport cholesterol contain a type of protein called globulins. Plasma proteins also maintain blood volume because their size prevents them from readily passing through a capillary wall. Therefore, capillaries are always areas of lower water concentration compared to tissue fluid, and water automatically diffuses into capillaries. Certain plasma proteins have specific functions. As discussed later in the chapter, fibrinogen is necessary to blood clotting, and immunoglobulins are antibodies, which help fight infection.

We shall see that blood has numerous functions that help maintain homeostasis. Blood transports substances to and from the capillaries, where exchanges with tissue fluid take place. It helps guard the body against invasion by **pathogens** (microscopic infectious agents, such as bacteria and viruses), and it clots, preventing a potentially life-threatening loss of blood. It also regulates pH by the presence of buffers in blood.

The Red Blood Cells

Red blood cells (erythrocytes) are continuously manufactured in the red bone marrow of the skull, the ribs, the vertebrae, and the ends of the long bones. Normally, there are 4 to 6 million red blood cells per mm^3 of whole blood.

Red blood cells carry oxygen because they contain **hemoglobin,** the respiratory pigment. Since hemoglobin is a red pigment, the cells appear red, and their color also makes blood red. A hemoglobin molecule (Fig. 13.11) contains four polypeptide chains, making up the protein globin. Each chain is associated with heme, a complex iron-containing group. The iron portion of hemoglobin acquires oxygen in the lungs and gives it up in the tissues. Plasma carries only about 0.3 ml of oxygen per 100 ml of blood, but whole blood carries 20 ml of oxygen per 100 ml of blood. This shows that hemoglobin increases the oxygen-carrying capacity of blood more than 60 times. Unfortunately, as discussed in the reading on page 253, carbon monoxide combines with hemoglobin more readily than does oxygen, and it stays combined for several hours, making hemoglobin unavailable for oxygen transport.

The number of red blood cells increases whenever arterial blood carries a reduced amount of oxygen, as happens when an individual first takes up residence at a high altitude. Under these circumstances, the kidneys increase their production of a hormone called **erythropoietin,** which speeds the maturation of red blood cells. A **stem cell** is a cell that is ever capable of dividing and producing new cells that differentiate. The stem cell called an erythroblast produces red blood cells in red bone marrow (Fig. 13.12). Before they are released from the bone marrow into blood, red blood cells lose their nuclei and acquire hemoglobin.

Visual Focus

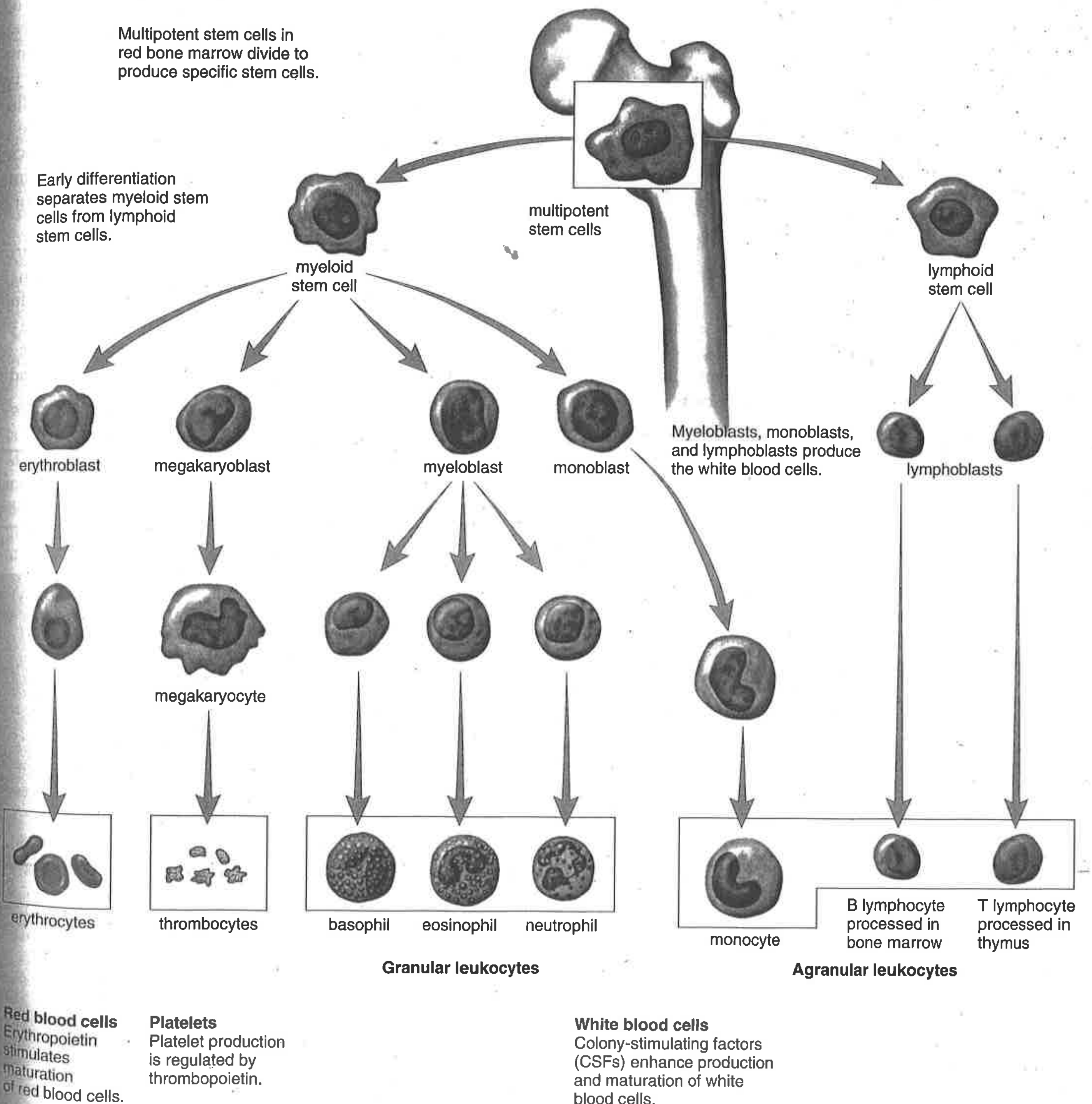


Figure 13.12 Blood cell formation in red bone marrow.
Multipotent stem cells give rise to specialized stem cells. The myeloid stem cell gives rise to still other cells, which become red blood cells, platelets, and all the white blood cells except lymphocytes. The lymphoid stem cell gives rise to lymphoblasts, which become lymphocytes.

Table 14.2 The ABO System

Blood Type	Antigen on Red Blood Cells	Antibody in Plasma	% U.S. African American	% U.S. Caucasian	% U.S. Asian	% North American Indians	% Americans of Chinese Descent
A	A	Anti-B	27	41	28	8	25
B	B	Anti-A	20	9	27	1	35
AB	A,B	None	4	3	5	0	10
O	None	Anti-A and anti-B	49	47	40	91	30

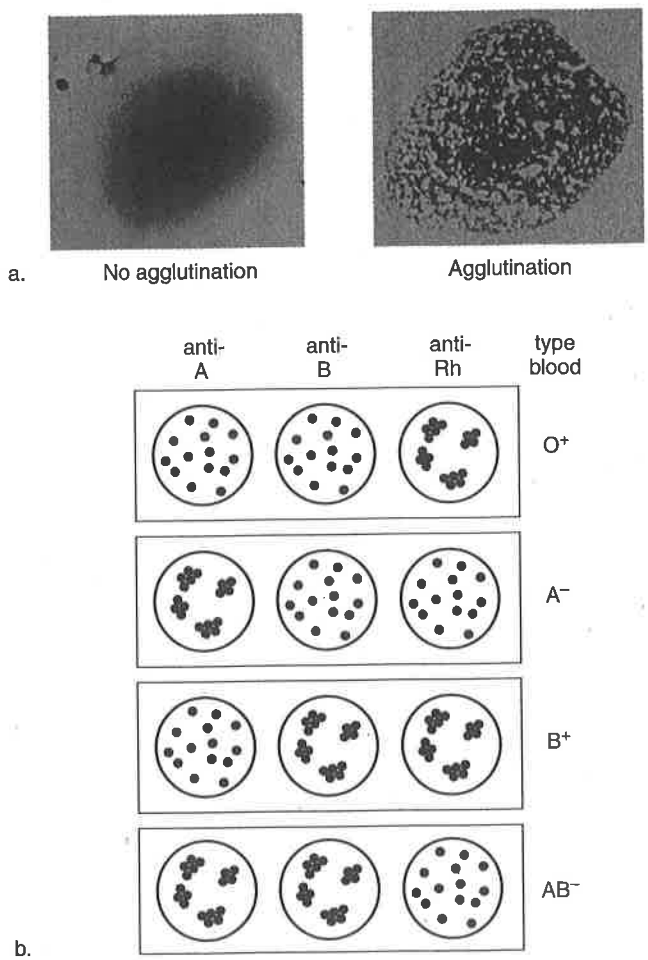


Figure 14.12 Blood typing.
The standard test to determine ABO and Rh blood type consists of putting a drop of anti-A antibodies, anti-B antibodies, and anti-Rh antibodies on a slide. To each of these, a drop of the person's blood is added. **a.** If agglutination occurs, as seen in the photo on the right, the person has this antigen on red blood cells. **b.** Several possible results.

Blood Types

When blood transfusions were first attempted, illness and even death sometimes resulted. Eventually, it was discovered that only certain types of blood are compatible because red blood cell membranes carry proteins or sugar residues that are antigens to blood recipients. The ABO system of typing blood is based on this principle.

ABO System

Blood typing in the ABO system is based on two antigens known as antigen A and antigen B. There are four blood types: O, A, B, and AB. Type O has neither the A antigen nor the B antigen on red blood cells; the other types of blood have antigen A, B, or both A and B, respectively (Table 14.2).

Within plasma, there are naturally occurring antibodies to the antigens not present on the person's red blood cells. This is reasonable, because if the same antigen and antibody are present in blood, **agglutination,** or clumping of red blood cells, occurs. Agglutination causes blood to stop circulating and red blood cells to burst.

Figure 14.12 shows a way to use the antibodies derived from plasma to determine the blood type. If agglutination occurs after a sample of blood is mixed with a particular antibody, the person has that type of blood.

Rh System

Another important antigen in matching blood types is the Rh factor. Persons with the Rh factor on their red blood cells are Rh positive (Rh^+); those without it are Rh negative (Rh^-). Rh-negative individuals normally do not have antibodies to the Rh factor, but they may make them when exposed to the Rh factor during pregnancy or blood transfusion.

If a mother is Rh negative and a father is Rh positive, a child may be Rh positive (Fig. 14.13). The Rh-positive red blood cells of the child may begin leaking across the placenta into the mother's circulatory system, as placental tissues normally break down before and at birth. This sometimes causes the mother to produce anti-Rh antibodies. In this or a subsequent pregnancy with another Rh-positive child, anti-Rh antibodies may cross the placenta and destroy the child's red blood cells. This condition is called hemolytic disease of the newborn (HDN).

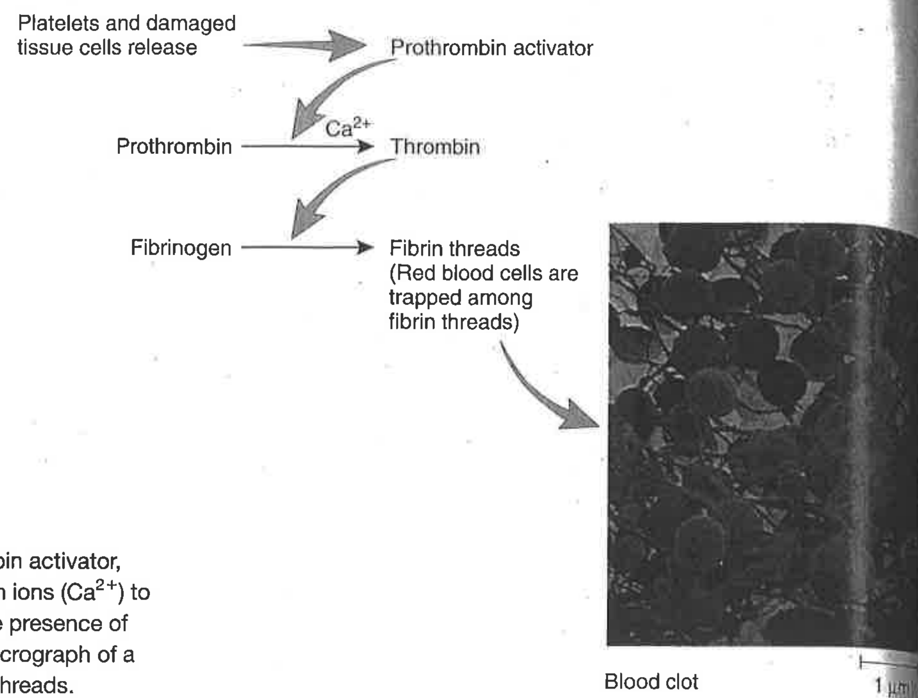


Figure 13.14 **Blood clotting.**
Platelets and damaged tissue cells release prothrombin activator, which acts on prothrombin in the presence of calcium ions (Ca^{2+}) to produce thrombin. Thrombin acts on fibrinogen in the presence of Ca^{2+} to form fibrin threads. The scanning electron micrograph of a blood clot shows red blood cells caught in the fibrin threads.

The Platelets and Blood Clotting

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 the process of blood **clotting,** or coagulation.

There are at least 12 clotting factors in the blood that participate in the formation of a blood clot. We will discuss the roles played by platelets, prothrombin, and fibrinogen. **Fibrinogen** and **prothrombin** are proteins manufactured and deposited in blood by the liver. Vitamin K, found in green vegetables and also formed by intestinal bacteria, is necessary for the production of prothrombin, and if by chance this vitamin is missing from the diet, hemorrhagic disorders develop.

Blood Clotting

When a blood vessel in the body is damaged, platelets clump at the site of the puncture and partially seal the leak. They 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. 13.14). 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.

Table 13.1 **Body Fluids**

Name	*Composition*
Blood	Formed elements and plasma
Plasma	Liquid portion of blood
Serum	Plasma minus fibrinogen
Tissue fluid	Plasma minus most proteins
Lymph	Tissue fluid within lymphatic vessels

If blood is allowed to clot in a test tube, a yellowish fluid develops above the clotted material. This fluid is called **serum,** and it contains all the components of plasma except fibrinogen. Table 13.1 reviews the many different terms we have used to refer to various body fluids related to blood.

Hemophilia

Hemophilia is an inherited clotting disorder due to a deficiency in a clotting factor. The slightest bump can cause the affected person to bleed into the joints. Cartilage degeneration in the joints and resorption of underlying bone can follow. Bleeding into muscles can lead to nerve damage and muscular atrophy. The most frequent cause of death is bleeding into the brain with accompanying neurological damage.

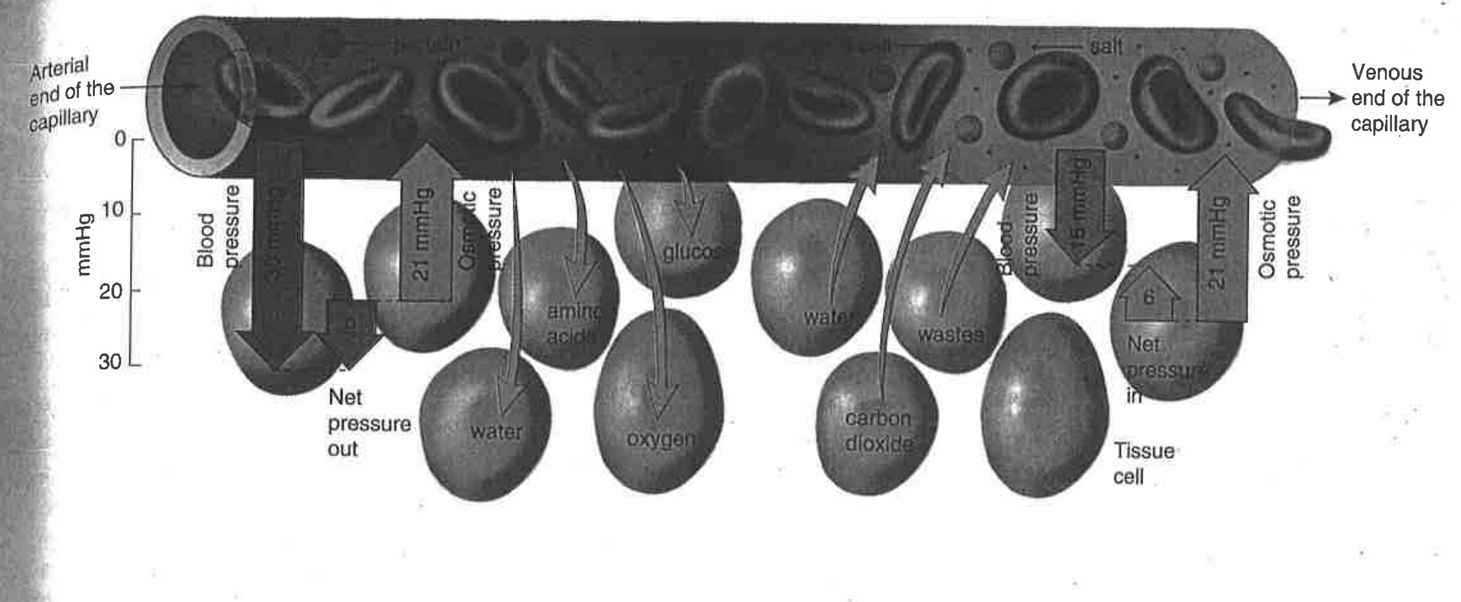


Figure 13.15 **Exchanges between blood and tissue fluid across a capillary wall.**

Capillary Exchange

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 is higher than the osmotic pressure of blood (Fig. 13.15). 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—nutrients (glucose and oxygen) diffuse out of the capillary, and wastes (carbon dioxide) diffuse into the capillary. Red blood cells and almost all plasma proteins remain in the capillaries, but small substances leave. 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 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 there is always some excess tissue fluid collected by the lymphatic capillaries (Fig. 13.16). Tissue fluid contained within lymphatic vessels is called **lymph.** Lymph is returned to the systemic venous blood when the major lymphatic vessels enter the subclavian veins in the shoulder region.

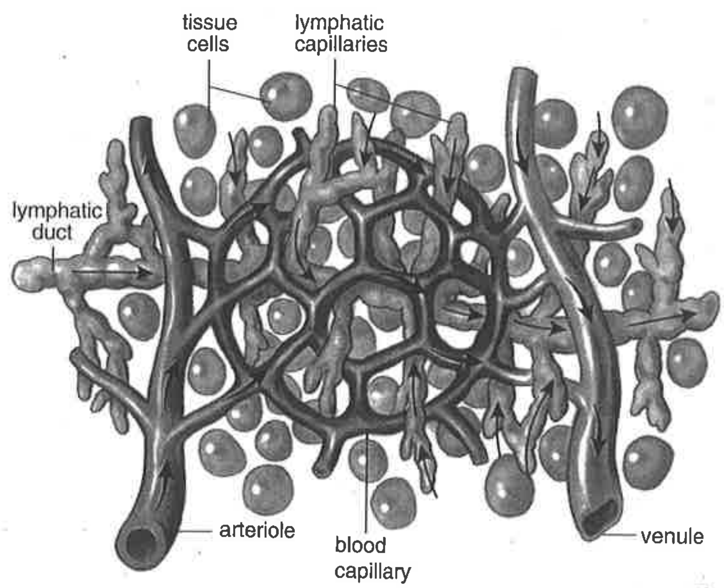


Figure 13.16 **Lymphatic vessels.**
Arrows indicate that lymph is formed when lymphatic capillaries take up excess tissue fluid. Lymphatic capillaries lie near blood capillaries.

Oxygen and nutrient substances exit a capillary near the arterial end; carbon dioxide and waste molecules enter a capillary near the venous end.

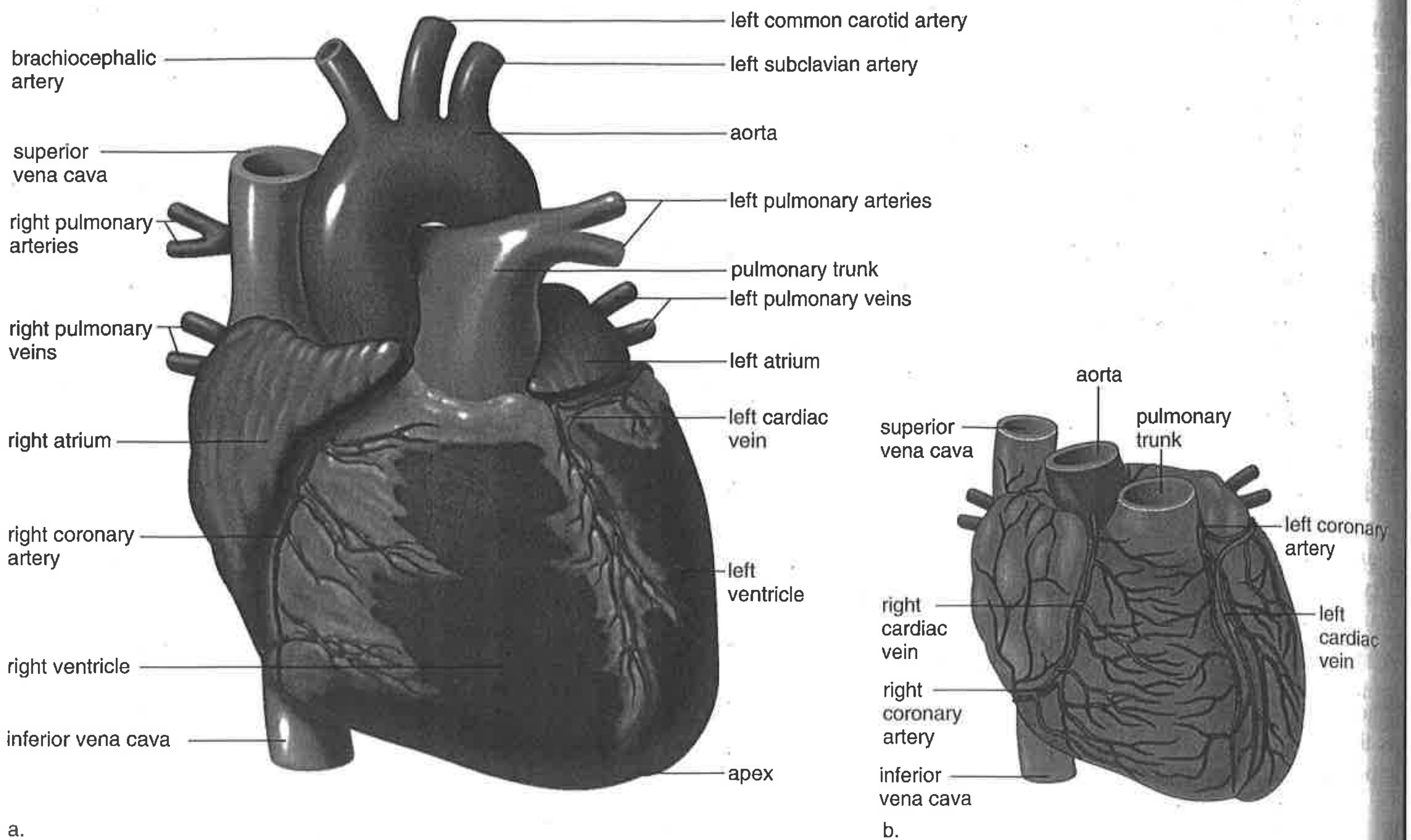


Figure 13.3 External heart anatomy.
a. The superior vena cava and the pulmonary arteries are attached to the right side of the heart. The aorta and left pulmonary veins are attached to the left side of the heart. The right ventricle forms most of the anterior surface of the heart, and the left ventricle forms most of the posterior. **b.** The coronary arteries and cardiac veins pervade cardiac muscle. They bring oxygen and nutrients to cardiac cells, and return blood to the right atrium.

13.2 The Heart

The **heart** is a cone-shaped, muscular organ about the size of a fist (Fig. 13.3). 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. The muscle fibers of the myocardium are branched and tightly joined to one another. 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, which consists of connective tissue and endothelial tissue.

Internally, a wall called the **septum** separates the heart into a right side and a left side (Fig. 13.4) 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.

Humans have a four-chambered heart (two atria and two ventricles). A septum separates the right side from the left side.

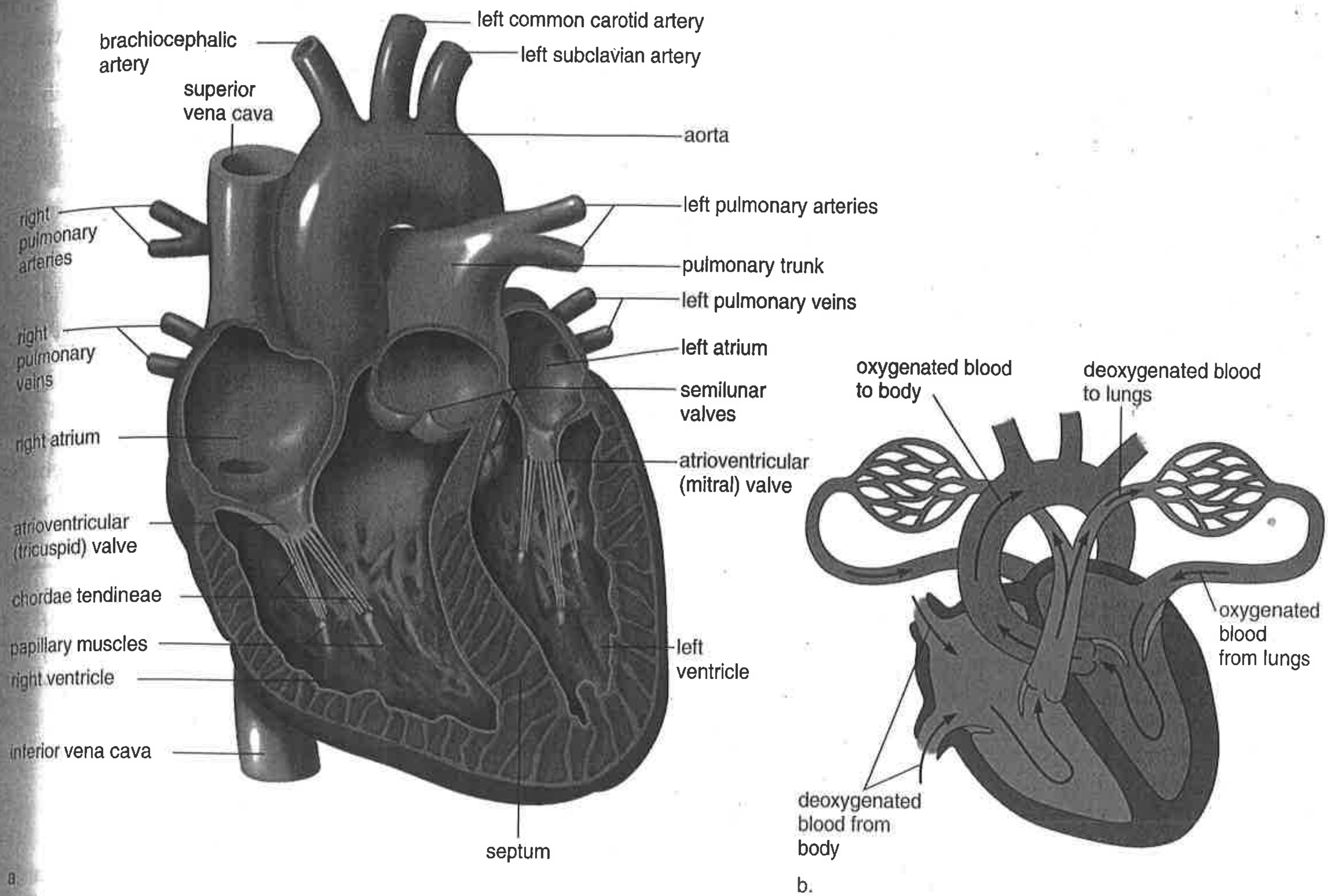


Figure 13.4 Internal view of the heart.
a. The heart has four valves. The atrioventricular valves allow blood to pass from the atria to the ventricles, and the semilunar valves allow blood to pass out of the heart. **b.** This diagrammatic representation of the heart allows you to trace the path of the blood.

Passage of Blood Through the Heart

We can trace the path of blood through the heart (Fig. 13.4) in the following manner:

- The superior vena cava and the inferior **vena cava,** which carry blood that is relatively low in oxygen and 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 blood that is relatively high in oxygen and relatively low in carbon dioxide, 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, you can see that deoxygenated blood never mixes with oxygenated 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 through the lungs, and the left ventricle sends blood throughout the body. 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.

The right side of the heart pumps blood to the lungs, and the left side of the heart pumps blood throughout the body.

The Heartbeat

Each heartbeat is called a **cardiac cycle** (Fig. 13.5). When the heart beats, first, the two atria contract at the same time; then the two ventricles contract at the same time. Then all chambers relax. The word **systole** refers to contraction of heart muscle, and the word **diastole** refers to relaxation of heart muscle. The heart contracts, or beats, about 70 times a minute, and each heartbeat lasts about 0.85 seconds.

Time	*Atria*	*Ventricles*
0.15 sec	Systole	Diastole
0.30 sec	Diastole	Systole
0.40 sec	Diastole	Diastole

A normal adult rate at rest can vary from 60 to 80 beats per minute.

When the heart beats, the familiar lub-dup sound occurs. The longer and lower-pitched lub is caused by vibrations occurring when the atrioventricular valves close due to ventricular contraction. The shorter and sharper dup is heard when the semilunar valves close due to back pressure of blood in the arteries. A heart murmur, or 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. Rheumatic fever resulting from a bacterial infection is one cause of a faulty valve, particularly the bicuspid valve. Faulty valves can be surgically corrected.

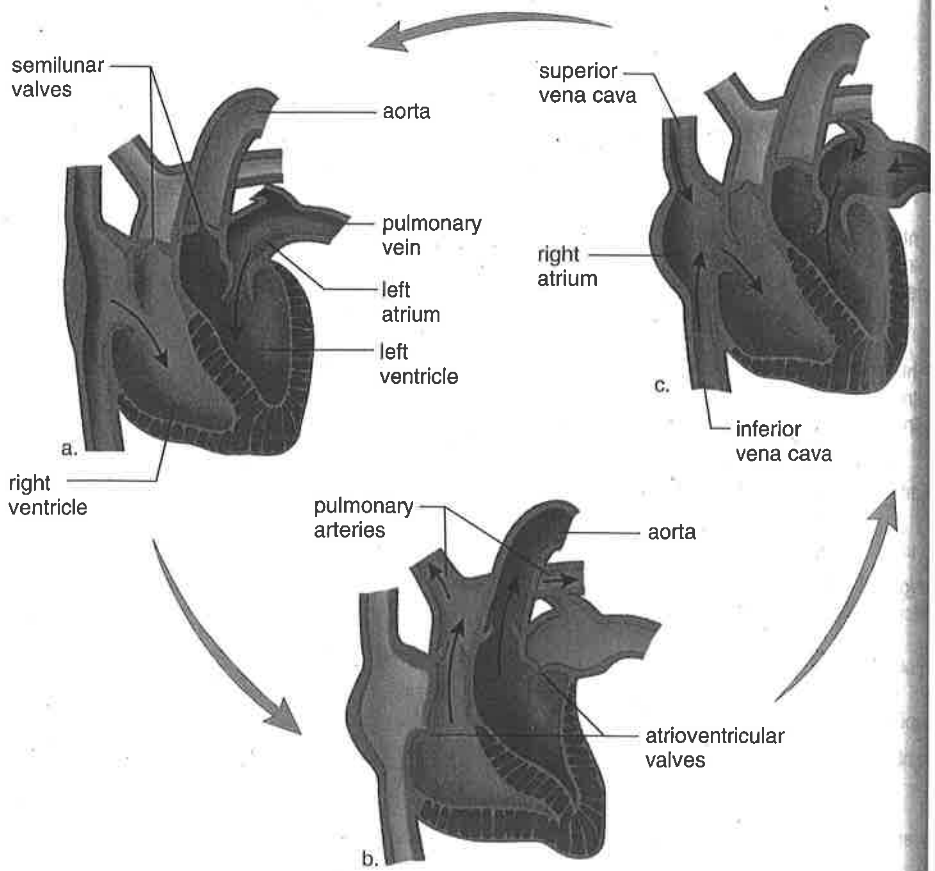


Figure 13.5 **Stages in the cardiac cycle.**
a. When the atria contract, the ventricles are relaxed and filling with blood. **b.** When the ventricles contract, the atrioventricular valves are closed, the semilunar valves are open, and the blood is pumped into the pulmonary trunk and aorta. **c.** When the heart is relaxed, both atria and ventricles are filling with blood.

The surge of blood entering the arteries causes their elastic walls to stretch, but then they almost immediately recoil. This alternating expansion and recoil of an arterial wall can be felt as a **pulse** in any artery that runs close to the body's surface. It is customary to feel the pulse by placing several fingers on a radial artery, which lies near the outer border of the palm side of the wrist. A carotid artery, on either side of the trachea in the neck, is another accessible location to feel the pulse. Normally, the pulse rate indicates the rate of the heartbeat because the arterial walls pulse whenever the left ventricle contracts.

Intrinsic Control of Heartbeat

The rhythmical contraction of the atria and ventricles is due to the instrinsic conduction system of the heart. Nodal tissue, which has both muscular and nervous characteristics, is a unique type of cardiac muscle located in two regions of the heart. The **SA (sinoatrial) node** is located in the upper wall of the right atrium; the other, the **AV (atrioventricular) node,** is located in the base of the right atrium very near the septum (Fig. 13.6*a*). The SA node initiates the heartbeat and automatically sends out an excitation impulse every 0.85 seconds; this causes the atria to contract. When impulses reach the AV node there is a slight delay that allows the atria to finish their contraction before the ventricles begin theirs. The signal for the ventricles to contract then travels through the two branches of the **atrioventricular bundle** before reaching the numerous and smaller **Purkinje fibers.** This ventricular portion of the conduction system consists of specialized cardiac muscle fibers that efficiently cause the ventricles to contract.

The SA node is called the **pacemaker** because it usually keeps the heartbeat regular. If the SA node fails to work properly, the heart still beats due to impulses generated by the AV node. But the beat is slower (40 to 60 beats per minute). To correct this condition, it is possible to implant an artificial pacemaker, which automatically gives an electric stimulus to the heart every 0.85 seconds.

The intrinsic conduction system of the heart consists of the SA node, the AV node, the atrioventricular bundle, and the Purkinje fibers.

Extrinsic Control of Heartbeat

The body has an extrinsic way to regulate the heartbeat. A cardiac control center in the medulla oblongata, a portion of the brain that controls internal organs, can alter the beat of the heart by way of the autonomic system, a division of the nervous system. This system has two divisions: the parasympathetic system, which promotes those functions we tend to associate with a restful state, and the sympathetic system, which brings about those responses we associate with increased activity and/or stress. The parasympathetic system decreases SA and AV nodal activity when we are inactive, and the sympathetic system increases SA and AV nodal activity when we are active or excited.

The hormones epinephrine and norepinephrine, which are released by the adrenal medulla, also stimulate the heart. During exercise, for example, the heart pumps faster and stronger due to sympathetic stimulation and due to the release of epinephrine and norepinephrine.

The body has an extrinsic way to regulate the heartbeat. The autonomic system and hormones can modify the heartbeat rate.

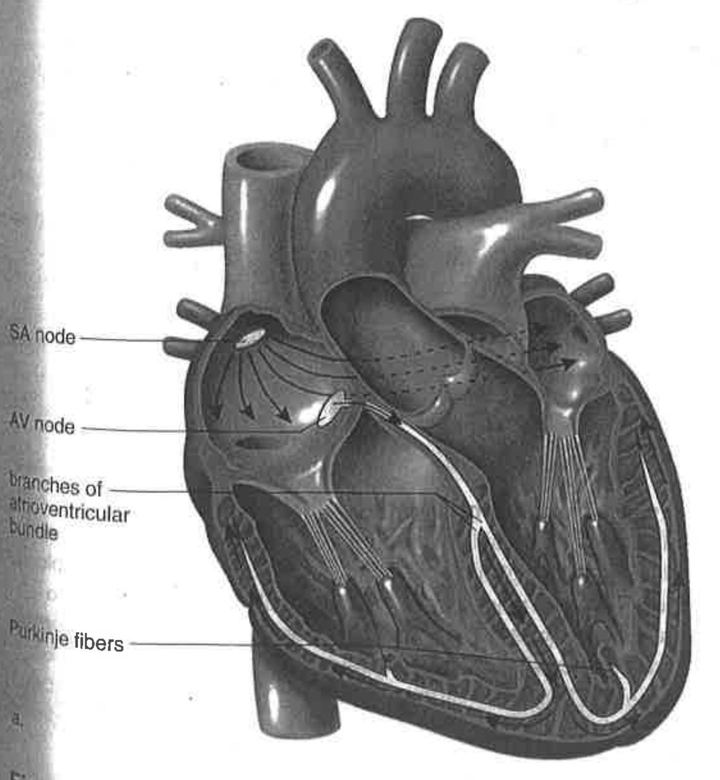
The Electrocardiogram

An **electrocardiogram (ECG)** is a recording of the electrical changes that occur in myocardium during a cardiac cycle. Body fluids contain ions that conduct electrical currents, and therefore the electrical changes in 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 pen rises or falls on a moving strip of paper. Figure 13.6*b* depicts the pen's movements during a normal cardiac cycle.

When the SA node triggers an impulse, the atrial fibers produce an electrical change that is 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. The electrical changes that occur as the ventricular muscle fibers recover produces 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. 13.6*c*) 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.

The electrocardiogram (ECG) is a recording of electrical changes occurring in the myocardium during a cardiac cycle.



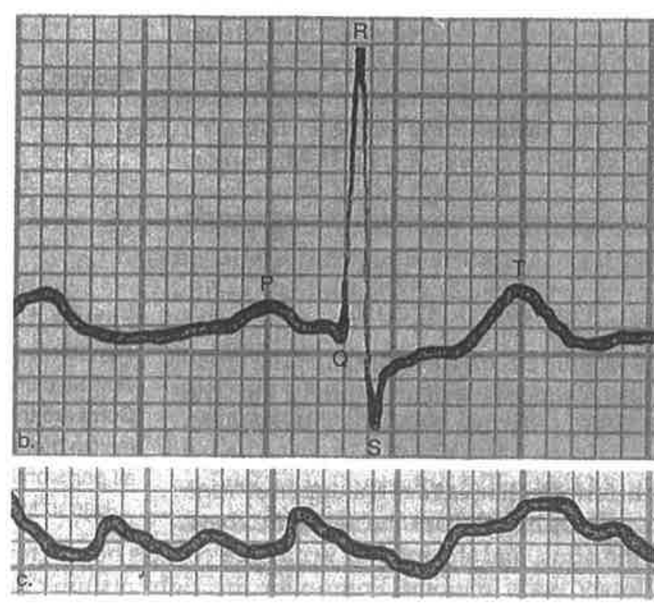


Figure 13.6 Conduction system of the heart.
a. The SA node sends out a stimulus, which causes the atria to contract. When this stimulus reaches the AV node, it signals the ventricles to contract. Impulses pass down the two branches of the atrioventricular bundle to the Purkinje fibers and thereafter the ventricles contract. b. A normal ECG 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.

Karlin casually rubs her nose, unaware she is infecting herself with a cold virus picked up by shaking hands with a coworker. The viral particles slip past the protective mucous barrier of her nasal cavities, enter cells, and begin to make copies of themselves. Just before the infected cells succumb, they secrete chemicals that alert her immune system to the invaders. As newly made viruses burst forth killing the cells, antibodies latch onto them and mark them for destruction. This is the job of amoebae-like immune cells that rush to the infection site and devour such complexes. Some other immune cells hereafter kill cells infected with the virus, and in this way prevent the production of more viruses. After a week of sniffles, Karlin's immune system wins its battle with the virus. This chapter explains how the immune system, working with the lymphatic system, fights off bacteria, viruses, even cancer, and how vaccines exploit these two systems to provide long-lasting protection from many diseases.

14.1 Lymphatic System

The **lymphatic system** consists of lymphatic vessels and the lymphoid organs. This system, which is closely associated with the cardiovascular system, has three main functions: (1) lymphatic capillaries take up excess tissue fluid and return it to the bloodstream; (2) lymphatic capillaries absorb fats at the intestinal villi and transport them to the bloodstream; and (3) the lymphatic system helps to defend the body against disease.

Lymphatic Vessels

Lymphatic vessels are quite extensive; most regions of the body are richly supplied with lymphatic capillaries (Fig.14.1). The construction of the larger lymphatic vessels is similar to that of cardiovascular veins, including the presence of valves. Also, the movement of lymph within these vessels is dependent upon skeletal muscle contraction. When the muscles contract, the lymph is squeezed past a valve that closes, preventing the lymph from flowing backwards.

The lymphatic system is a one-way system that begins with lymphatic capillaries. These capillaries take up fluid that has diffused from and has not been reabsorbed by the blood capillaries. **Edema** is localized swelling caused by the accumulation of tissue fluid. This can happen if too much tissue fluid is made and/or not enough of it is drained away. Once tissue fluid enters the lymphatic vessels, it is called **lymph.** 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 *thoracic duct* is much larger than the right lymphatic duct. It serves the lower extremities, the abdomen, the left arm, and the left side of both the head and the neck. The *right lymphatic duct* serves the right arm, the right side of both the head and the neck, and the right thoracic area. The lymphatic ducts enter the subclavian veins, which are cardiovascular veins in the thoracic region.

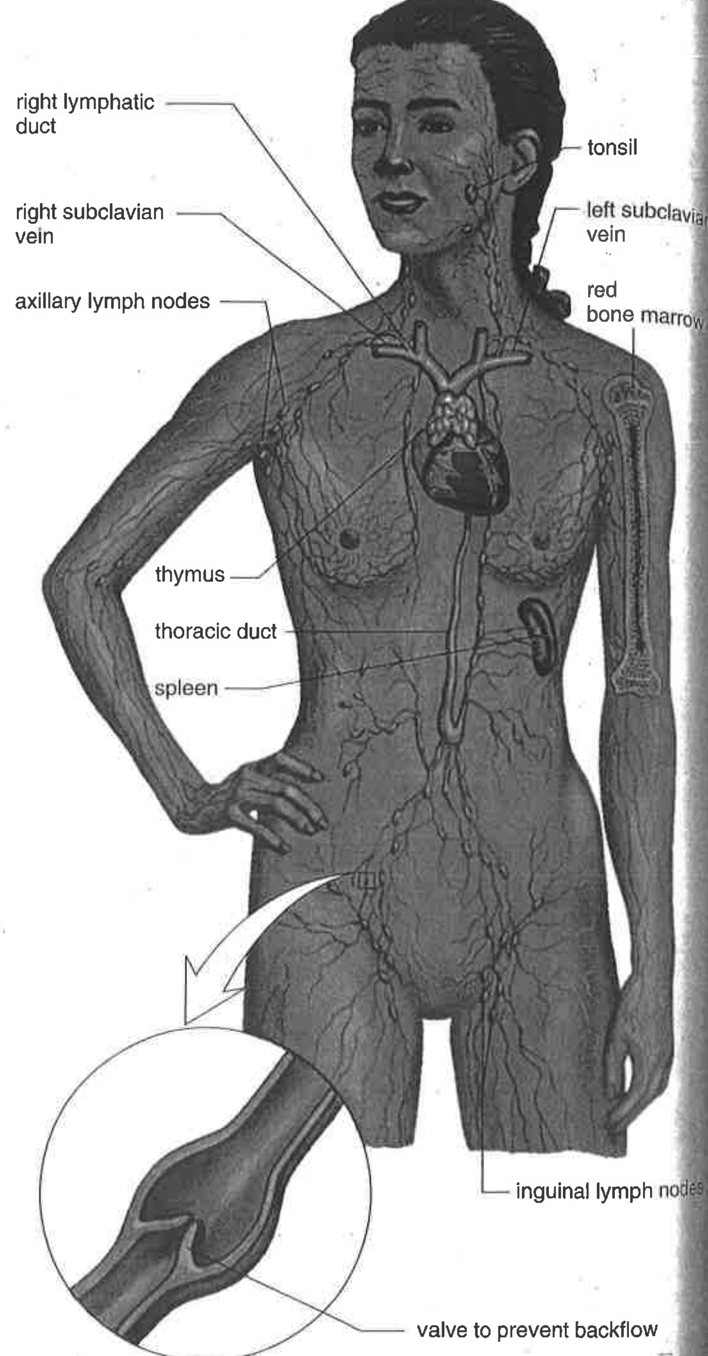


Figure 14.1 **Lymphatic system.**
The lymphatic vessels drain excess fluid from the tissues and return it to the cardiovascular system. The enlargement shows that lymphatic vessels have valves to prevent backward flow.

Lymph flows one way from a capillary to ever-larger lymphatic vessels and finally to a lymphatic duct, which enters a subclavian vein.

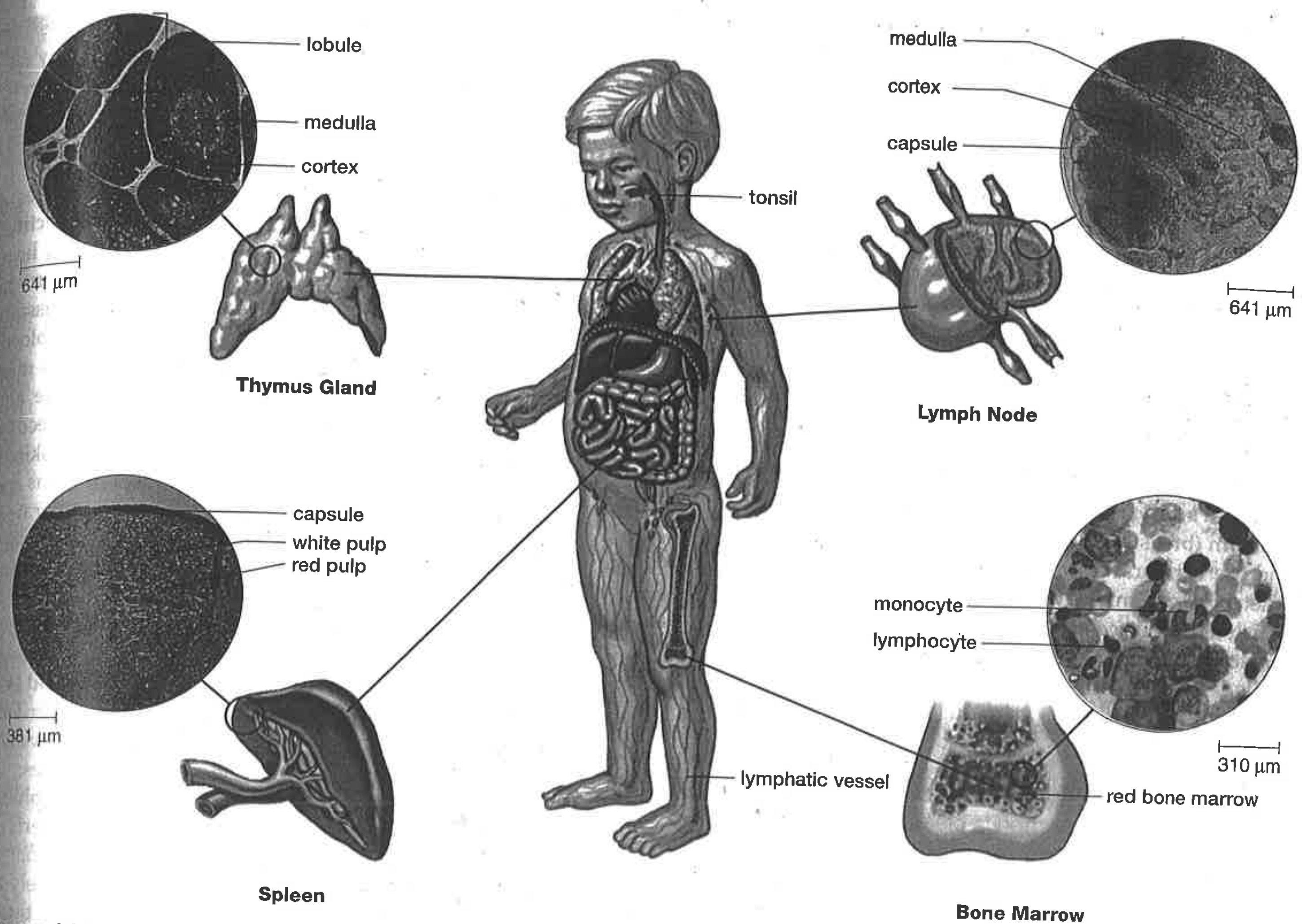


Figure 14.2 The lymphoid organs.
The lymphoid organs include the lymph nodes, the spleen, the thymus gland, and the red bone marrow, which all contain lymphocytes.

Lymphoid Organs

The lymphoid organs of special interest are the lymph nodes, the tonsils, the spleen, the thymus gland, and the bone marrow (Fig. 14.2).

Lymph nodes, which are small (about 1–25 mm) ovoid or round structures, are found at certain points along lymphatic vessels. A capsule surrounds two distinct regions known as the cortex and medulla which contain many lymphocytes. Macrophages, which occur along lymph capillaries called lymph sinuses, purify lymph of infectious organisms and any debris. Antigens which leak into the cortex and medulla activate the lymphocytes to mount an immune response to them. Lymph nodes are named for their location. Inguinal nodes are in the groin and axillary 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. This is a noninvasive preliminary way to help make such a diagnosis.

The **tonsils** are partially encapsulated lymphatic tissue located in a ring about the pharynx. The well-known pharyngeal tonsils are also called *adenoids,* while the larger palatine tonsils located on either side of the posterior oral cavity are most apt to be infected. The tonsils perform the same functions as lymph nodes inside the body, but because of their location they are the first to encounter pathogens and antigens that enter the body by way of the nose and mouth.

The **spleen** is located in the upper left region of the abdominal cavity just beneath the diaphragm. It is much larger than a lymph node, about the size of a fist. Whereas the lymph nodes cleanse lymph, the spleen cleanses blood. A capsule surrounds tissue known as white pulp and red pulp. White pulp contains lymphocytes and performs the immune functions of the spleen. The red pulp contains red blood cells and plentiful macrophages. The red pulp helps to purify blood that passes through the spleen by removing bacteria and worn-out or damaged red blood cells.

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