38 CIRCULATION

And Then My Heart Stood Still

In the nineteenth century, physiologist Augustus Waller put the paws of his pet bulldog Jimmie in bowls of salty water, which wires connected to a simple recording device. Salt water is a good conductor of electricity. It picked up the faint electric signals from Jimmie's beating heart, and the recording device scratched out the world's first graph of a heartbeat—an *electrocardiogram* (Figure 38.1).

Now fast-forward to the present. A graph of your heart's normal activity would look much the same as Jimmie's. The pattern emerged a few weeks after you started growing from a fertilized egg and developing into an embryo. Early on, some of the embryonic cells differentiated into cardiac muscle cells and started to contract on their own. The first patch of cells to do so set the pace for all of the others, and they have acted as the natural pacemaker ever since. If all goes well, that patch of cardiac muscle cells will continue to contract and make your heart beat steadily, about seventy times per minute, until the day you die.

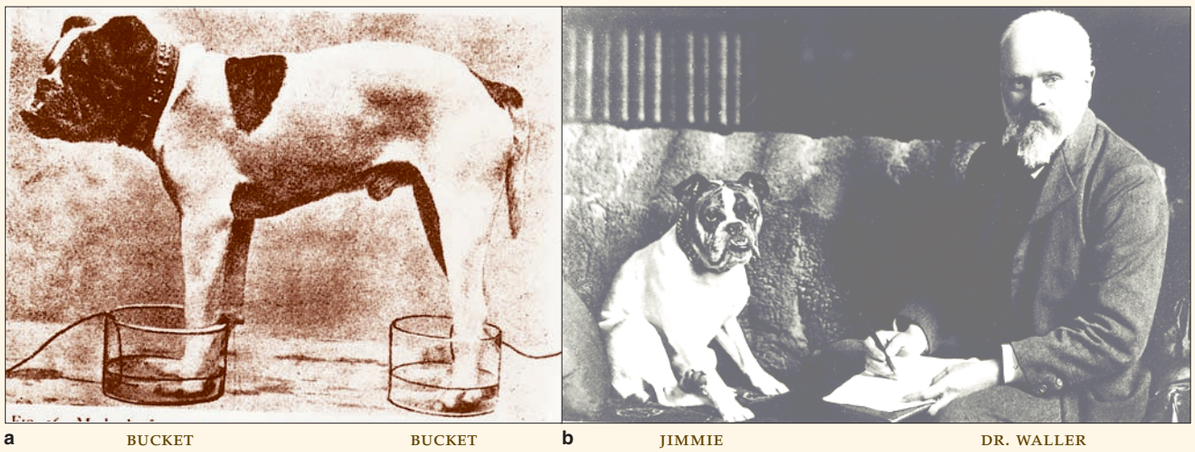
However, with *sudden cardiac arrest*, the heart abruptly stops beating in many people who are not expecting it, in a lot more places than hospitals. In the United States alone, the cases of sudden cardiac arrest exceed 250,000 per year. Tammy Higgins became one of those cases before she was thirty years old. Just after leaving a church service, Tammy abruptly collapsed and stopped breathing.

Her husband could not find her pulse. With his training as a lifeguard, he knew the flow of oxygen-rich blood to her brain had stopped and had to resume fast. He started cardiopulmonary resuscitation, or *CPR*, a method of mouth-to-mouth respiration and repetitive compressions of the chest. He kept her alive until an ambulance arrived.

The emergency crew used a portable defibrillator. This device delivers an electric shock to the chest, which often can jump-start the heart into beating again (Figure 38.1). In the hospital, Tammy found out that her heartbeat is abnormal. She also found out that she was pregnant.

Surgeons implanted a tiny defibrillator in her chest wall. It constantly monitors her heart and shocks it when it stops beating. The implant saved her during pregnancy and once more during the three years that followed.

Tammy was lucky; her brain escaped damage and she did not die. Her husband and a few bystanders knew how to perform CPR. The chance of surviving sudden cardiac arrest increases by 50 percent when CPR starts within four to six minutes. For every minute that passes without defibrillation, the chance of survival decreases by about 7 to 10 percent.



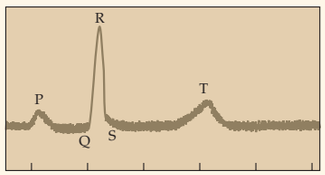
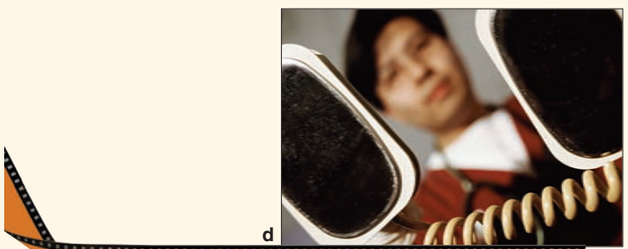


Figure 38.1 A bit of history in the making. (**a**) Jimmie the bulldog taking part in a painless experiment. (**b**) The physiologist Augustus Waller and his beloved pet bulldog sharing a moment in Waller's study after the experiment, which yielded a recording of a heartbeat (**c**). The P, QRS complex, and T designate three waves of electrical activity caused by the spread of action potentials across cardiac muscle, then recovery of the normal resting potential. *Facing page:* (**d**) Defibrillator paddles. With luck, they can shock a heart into beating again after cardiac arrest.

IMPACTS, ISSUES



AEDs (automated external defibrillators) are about the size of a laptop computer. They have been distributed to many senior centers and shopping malls, hotels, and other public places. An AED checks for a heartbeat, and it shocks the heart if required. Its electronic voice commands trained bystanders to carry out appropriate steps. The American Heart Association, the American Red Cross, community groups, and adult education programs offer CPR and AED training to the public. In short, we have come a long way from Jimmie in checking out the heart and in helping the hearts that falter.

With this bit of history, we turn to the structure and function of the circulatory system. In humans, this organ system has a durable pump—a heart. The heart beats incessantly and generates the pressure required to drive blood through two elaborate loops of blood vessels, which lead back to the heart. As you will see, this system has structural and functional links with the lymphatic system.

How Would You Vote?

CPR can make the difference between life and death after a cardiac arrest or a heart attack. Should public high schools in your state require all students to take a course in CPR? Is such a course worth diverting time and resources from the basic curriculum? See BiologyNow for details, then vote online.

Key Concepts

OVERVIEW OF CIRCULATORY SYSTEMS

Animals have an open or a closed circulatory system that helps transport substances to and from cells. Section 38.1

BLOOD COMPOSITION AND FUNCTION

Vertebrate blood is a fluid connective tissue. It consists of red blood cells, white blood cells, platelets, and diverse substances dissolved in plasma, the transport medium. Red blood cells function in gas exchange. White blood cells and platelets defend tissues. Diseases and abnormalities impair blood cell function. Sections 38.2–38.4

THE HUMAN HEART AND TWO FLOW CIRCUITS

The human heart has four chambers. Blood flows into its two atria and is pumped out of its two ventricles, into separate circuits of blood vessels. One circuit extends through all body regions, the other through lung tissue only. Both circuits loop back to the heart. Sections 38.5, 38.6

BLOOD VESSEL STRUCTURE AND FUNCTION

The heart pumps blood rhythmically, on its own. Blood pressure is highest in the ventricles, drops as it flows through arteries, capillaries, and veins, and is lowest in the heart's atria. Different blood vessels function in rapid transport, distribution of flow volume, and gas exchange. Sections 38.7, 38.8

WHEN THE SYSTEM BREAKS DOWN

Ruptured or clogged blood vessels or abnormal heart rhythms cause problems. Some problems have a genetic basis; most are related to age or life-styles. Section 38.9

LINKS WITH THE LYMPHATIC SYSTEM

A lymph vascular system returns excess tissue fluid to blood. Lymphoid organs cleanse blood of infectious agents and other threats to health. Section 38.10

Links to Earlier Concepts

This chapter expands on earlier introductions to circulatory systems (Sections 25.6, 25.9, 26.2, 28.2), cardiac muscle (33.3), and muscle contraction (37.6, 37.7). You will draw on your knowledge of hemoglobin (3.6), diffusion and bulk flow (5.3), gas exchange (28.3), action potentials (34.3, 34.4), and cell junctions (33.1). You will revisit ABO blood typing (11.4). You will be invited to reflect on blood cell disorders (3.6, 18.6) and on connections between cardiovascular function, lipoproteins (3.4), and cholesterol (3.4).

38.1 The Nature of Blood Circulation

LINKS TO SECTIONS 5.3, 25.6, 26.2, 28.1

Imagine an earthquake closing off your neighborhood's highway. Grocery trucks can't enter; waste-disposal trucks can't leave. Your food supplies dwindle and garbage piles up. Cells would be similarly stressed if something were to disrupt the flow along the body's highways.

FROM STRUCTURE TO FUNCTION

The **circulatory system** moves substances to and from cellular neighborhoods. **Blood**, its transport medium, typically flows inside tubular vessels under pressure generated by a muscular pump, a **heart**. Blood makes exchanges with fluid in tissue spaces between cells—or **interstitial fluid**—which exchanges substances with cells. Thus blood and interstitial fluid are functionally inseparable as an *internal* environment for body cells. Many organ systems interact to keep the composition, volume, and temperature of the environment within tolerable ranges for cell activities (Section 28.1).

Circulatory systems are open or closed. In the *open* systems of most mollusks and all arthropods, blood flows out of muscular vessels or one or more hearts, mingles with fluid in body tissues, then flows back in (Figure 38.2*a*,*b*). You and many other animals have a *closed* circulatory system. It confines blood in a heart and blood vessels that vary in thickness and diameter. One example is the earthworm's circulatory system, part of which is shown in Figure 38.2*c*,*d*. We include diagrams of a few other closed systems in Figure 38.3.

Reflect on the overall "design" of a closed system. The total *volume* of blood is pumped continuously out of the heart, through vessels, then back to the heart. It travels fastest in large-diameter transport vessels. It slows in beds of small-diameter vessels called blood capillaries, where the blood and interstitial fluid have enough time to exchange substances by way of simple diffusion (Section 5.3 and Figure 38.3*d*).

EVOLUTION OF VERTEBRATE CIRCULATION

All vertebrates have a closed circulatory system, but fishes, amphibians, birds, and mammals differ in the pumps and plumbing. These differences evolved over hundreds of millions of years after some vertebrates left the water for land. The earliest vertebrates, recall, had gills. Like all respiratory structures, gills have a thin, moist surface, which oxygen and carbon dioxide diffuse across. In time, *internally moistened* sacs called lungs evolved and supported the move to dry land. So did modifications that helped blood move faster in a loop between the heart and lungs (Section 26.2).

In fishes, blood still flows in a single circuit (Figure 38.3*a*). The contractile force of a two-chambered heart drives blood through two capillary beds. Blood flows

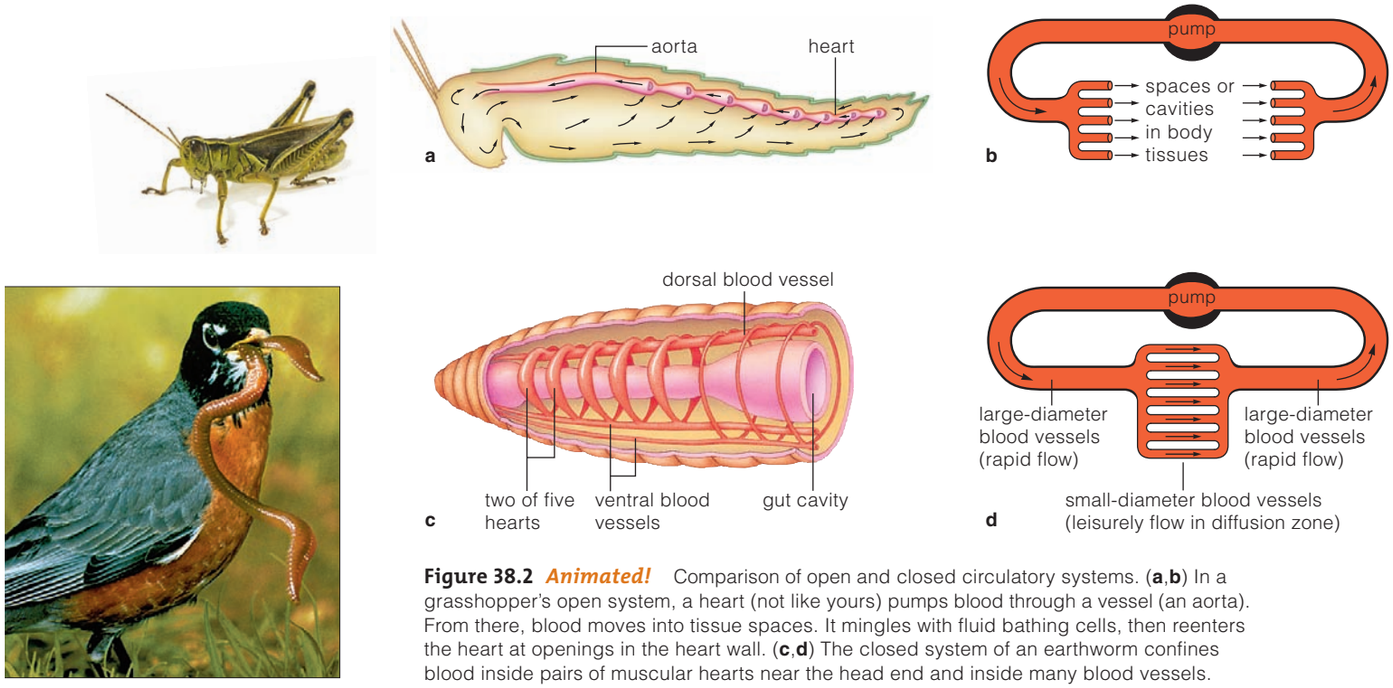
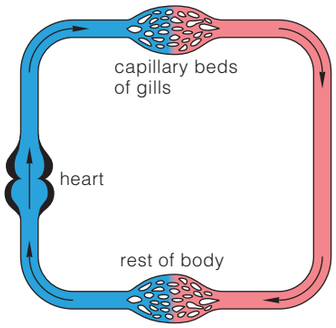
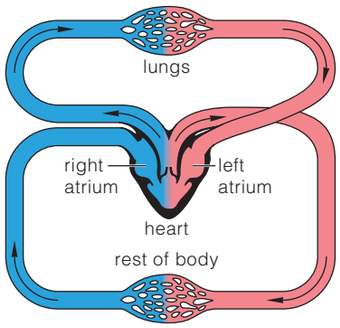


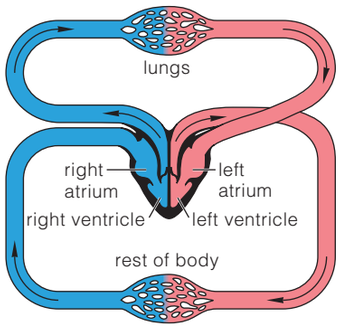
Figure 38.2 ***Animated!*** Comparison of open and closed circulatory systems. (**a**,**b**) In a grasshopper's open system, a heart (not like yours) pumps blood through a vessel (an aorta). From there, blood moves into tissue spaces. It mingles with fluid bathing cells, then reenters the heart at openings in the heart wall. (**c**,**d**) The closed system of an earthworm confines blood inside pairs of muscular hearts near the head end and inside many blood vessels.



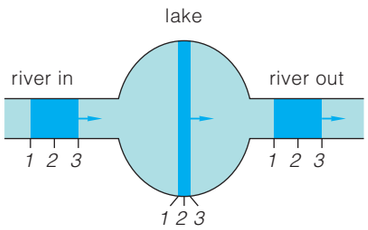
a In fishes, a two-chambered heart (atrium, ventricle) pumps blood in one circuit. Blood picks up oxygen in gills, delivers it to rest of body. Oxygen-poor blood flows back to heart.



b In amphibians, a heart pumps blood through two partially separate circuits. Blood flows to lungs, picks up oxygen, returns to heart. But it mixes with oxygen-poor blood still in the heart, flows to rest of body, returns to heart.



c In birds and mammals, the heart is fully partitioned into two halves. Blood circulates in two circuits: from the heart's right half to lungs and back, then from the heart's left half to oxygen-requiring tissues and back.



d Why have capillary beds? Picture two fast rivers flowing into and out from a lake. The flow *rate* is the same in all three places, with an identical volume of water moving from point *1* to point *3* in the same interval. However, flow *velocity* decreases in the lake. Why? The volume spreads out through a larger cross-sectional area and moves forward a shorter distance in the specified interval.

Figure 38.3 ***Animated!*** Comparison of flow circuits in the closed circulatory systems of fishes, amphibians, birds, and mammals.

through gill capillary beds into a large vessel, through capillary beds in body tissues and organs, and back to the heart. The blood is not under much fluid pressure when it leaves the gill capillaries, so it moves slowly on the way back to the heart.

Blood circulation picked up a bit when the heart of amphibians became partitioned into three chambers. Two atria emptied into a single ventricle. Oxygenated blood and oxygen-poor blood flowed in two circuits but mixed a bit in the ventricle (Figure 38.3*b*).

In birds and mammals, the heart became divided into right and left halves, each with two chambers. It pumps blood in two separate circuits (Figure 38.3*c*). In the **pulmonary circuit**, oxygen-poor, carbon dioxide-rich blood flows from the *right* half of the heart to the lungs. There, blood picks up oxygen, gives up carbon dioxide, and flows into the left half of the heart.

In the main, **systemic circuit**, the heart's *left* half pumps oxygenated blood to all tissues where oxygen is used and carbon dioxide forms. After giving up the oxygen and picking up carbon dioxide, blood flows into the heart's right half, then back to the lungs. A double circuit is a fast, efficient mode of exchanging gases. It supports the high levels of activity typical of vertebrates whose ancestors evolved on land.

LINKS WITH THE LYMPHATIC SYSTEM

The heart's pumping puts pressure on blood flowing through the circulatory system. Partly because of this, some water, nutrients, and a few proteins dissolved in blood are forced from capillaries into interstitial fluid. Some fluid and reclaimable solutes move back into capillaries. Any excess interstitial fluid drains into the circulatory system by way of lymph vessels, which are components of a **lymphatic system**. Other components help protect the internal environment (Section 38.10).

In most animals, a circulatory system moves substances to and from interstitial fluid that fills tissue spaces between metabolically active cells. A typical closed system confines blood inside a heart and blood vessels.

In vertebrates, blood flows fastest in large-diameter vessels that connect the heart with capillary beds, where blood slows enough for efficient exchanges with interstitial fluid.

In fishes and amphibians, oxygen-poor and oxygenated blood mix a bit. In birds and mammals, blood flows in two separate circuits, through a heart divided into two side-by-side pumps. Gases are exchanged more efficiently in the double circuit, which supports higher levels of activity.

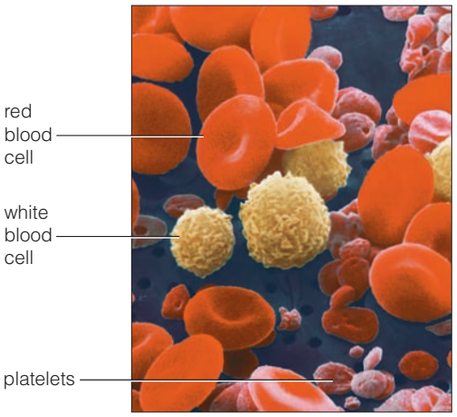
38.2 Characteristics of Blood

LINKS TO SECTIONS 3.6, 33.2, 37.4

Tumbling along in the fluid portion of blood are cells and substances that do more than move gases and nutrients to and from cellular neighborhoods. Many defend the body and help maintain internal operating conditions.

FUNCTIONS OF BLOOD

Blood, a fluid connective tissue, transports oxygen, nutrients, and other solutes to cells. It carries away metabolic wastes and secretions, including hormones. Blood helps stabilize internal pH and is a highway for cells and proteins that defend and repair tissues. In birds and mammals, it helps keep body temperature within tolerable limits by moving excess heat to skin, where it can be dissipated into the surroundings.



BLOOD COMPOSITION AND VOLUME

The volume of blood depends on body size and on the concentrations of water and solutes. In average-sized humans, it is about four or five quarts (6 to 8 percent of the total body weight). In all vertebrates, blood is a viscous fluid, thicker than water and slower flowing. Its components are plasma, red and white blood cells, and platelets. The cells and platelets arise from stem cells in bone marrow. Any **stem cell** is unspecialized, and it retains a capacity for mitotic cell division. Some portion of its daughter cells divide and differentiate into specialized types.

Plasma About 50 to 60 percent of the blood's total volume is plasma (Figure 38.4). **Plasma** is 90 percent water. Besides being the transport medium for blood cells and platelets, it acts as a solvent for hundreds of different plasma proteins, other molecules, and ions. Some of the proteins transport lipids and fat-soluble vitamins through the body. Others function in blood clotting. Other solutes include glucose, lipids, amino acids, vitamins, hormones, as well as oxygen, carbon dioxide, and gaseous nitrogen.

Red Blood Cells Erythrocytes, the **red blood cells**, are biconcave disks about 8 micrometers in diameter and 2 micrometers thick (Figure 38.5). They transport oxygen from lungs to aerobically respiring cells and carry carbon dioxide wastes from them. When oxygen first diffuses into blood, it binds to hemoglobin in red

Components	Relative Amounts	Functions
Plasma Portion (*50%–60% of total volume*):		
1. Water	91%–92% of plasma volume	Solvent
2. Plasma proteins (albumin, globulins, fibrinogen, etc.)	7%–8%	Defense, clotting, lipid transport, roles in extracellular fluid volume, etc.
3. Ions, sugars, lipids, amino acids, hormones, vitamins, dissolved gases	1%–2%	Roles in extracellular fluid volume, pH, etc.
Cellular Portion (*40%–50% of total volume*):		
1. Red blood cells	4,800,000–5,400,000 per microliter	Oxygen, carbon dioxide transport
2. White blood cells:		
Neutrophils	3,000–6,750	Phagocytosis during inflammation
Lymphocytes	1,000–2,700	Immune responses
Monocytes (macrophages)	150–720	Phagocytosis in all defense responses
Eosinophils	100–360	Defense against parasitic worms
Basophils	25–90	Secrete substances for inflammatory response and for fat removal from blood
3. Platelets	250,000–300,000	Roles in clotting

Figure 38.4 Typical components of human blood. The scanning electron micrograph above shows some cellular components.

The sketch of a test tube shows what happens when you keep a blood sample from clotting. The sample separates into the straw-colored plasma, which floats on a reddish-colored cellular portion. Blood makes up 6 to 8 percent of total body weight.

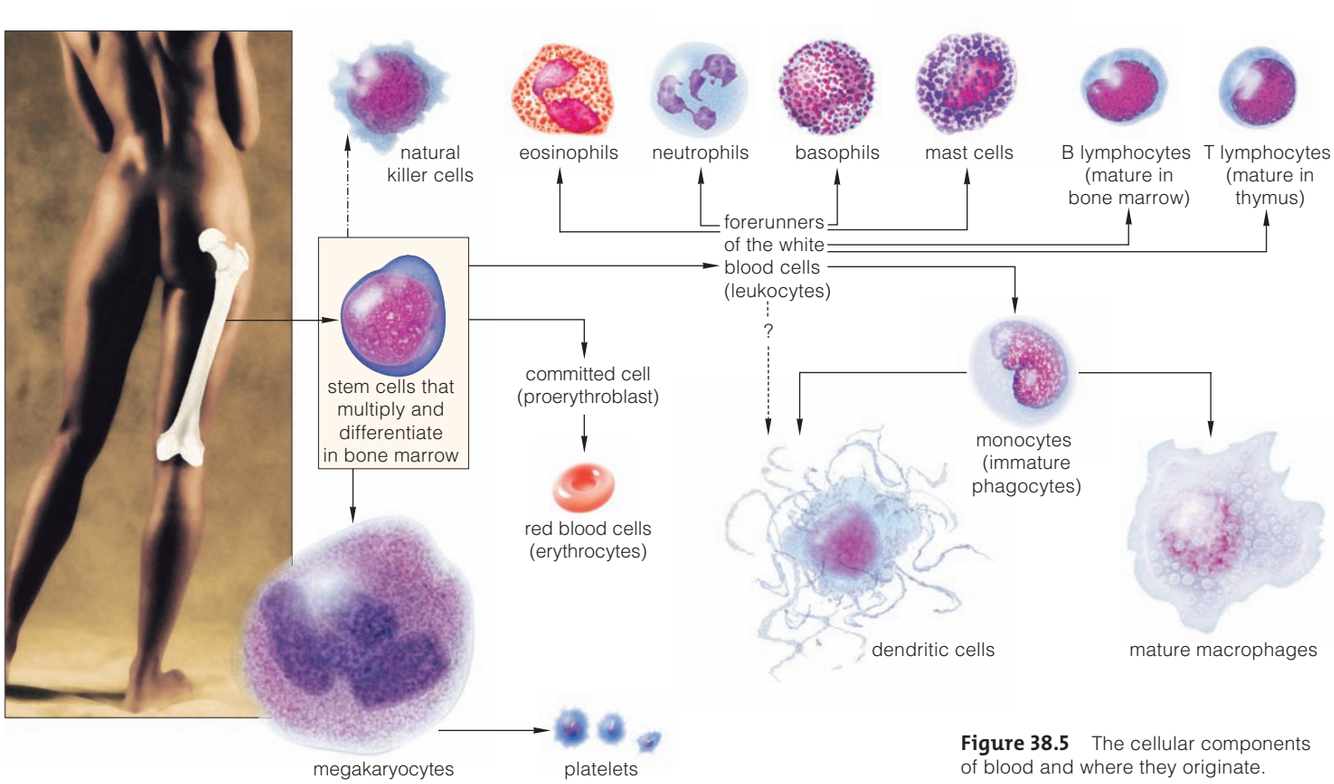


Figure 38.5 The cellular components of blood and where they originate.

blood cells. You learned about this protein in Section 3.6. Stored hemoglobin fills about 98 percent of the interior of red blood cells. It makes both the cells and oxygenated blood appear bright red. Oxygen-poor blood is dark red, and it appears blue through blood vessel walls near the body surface.

Mature red blood cells no longer have a nucleus, nor do they require it. They have enough hemoglobin, enzymes, and other proteins to last about 120 days. Phagocytes engulf the oldest red blood cells and those already dead. In individuals who are in good health, ongoing replacements keep the cell count fairly stable.

A **cell count** is a measure of the quantity of cells of a specified type in 1 cubic millimeter of blood. The number of red blood cells per cubic millimeter averages 5.4 million in human males and 4.8 million in females.

White Blood Cells A variety of leukocytes, or **white blood cells**, functions in housekeeping and defense. Some patrol tissues and engulf damaged or dead cells and anything else chemically recognized as "nonself." Some sound the alarm that tissues are under siege by specific viruses, bacteria, or other threats. Many form highly organized masses inside lymph nodes and the spleen, which are organs of the lymphatic system.

White blood cells differ in size, nuclear shape, and staining traits (Figure 38.5). Their numbers fluctuate with levels of activity and state of health. We consider these cells in the next chapter, but a few examples can give you a sense of what they do. The neutrophils and basophils are phagocytes with roles in inflammation. Macrophages and dendritic cells are phagocytes that can stimulate immune responses to particular threats. Two categories of lymphocytes, the B cells and T cells, are specialized for immune responses. Natural killer cells directly kill body cells that do not have normal self-markers or that have been tagged for destruction.

Platelets Megakaryocytes originate from some stem cells. They later shed membrane-wrapped cytoplasmic fragments of themselves as **platelets**. A platelet lasts five to nine days. Hundreds of thousands are always circulating in blood. When activated, platelets release substances that initiate blood clotting.

Blood, a fluid connective tissue, functions as a transport medium and solvent. Diverse proteins, gases, sugars, and other substances are dissolved in it. Its cellular components include red blood cells, white blood cells, and platelets.

38.3 Blood Disorders

FOCUS ON HEALTH

LINKS TO SECTIONS 3.6, 5.2, 11.4, 12.1, 18.6

The body continually replaces blood cells for good reason. Besides aging and dying off regularly, blood cells may become hosts to diverse pathogens that complete the life cycle inside them. In addition, sometimes blood cells malfunction as a result of gene mutations.

Red Blood Cell Disorders Too few red blood cells or deformed ones result in the disorders collectively called **anemias**. Abnormally low oxygen levels in blood cannot support metabolism. Shortness of breath, fatigue, and chills follow. *Hemorrhagic* anemias follow sudden blood loss, as from a bad wound; chronic anemias result from low red blood cell production or a slight but persistent blood loss, as happens from a bleeding ulcer.

Bacteria and protozoans that replicate in blood cells cause some *hemolytic* anemias; they kill infected cells as they escape, by lysis. Insufficient iron in the diet causes *iron deficiency* anemia; red blood cells cannot make enough normal hemoglobin without iron. *Sickle-cell anemia* arises from a mutation that modifies hemoglobin (Section 3.6). In *thalassemias*, mutations disrupt or stop synthesis of globin chains of hemoglobin. Too few red blood cells form. Those that do form are thin and fragile.

Polycythemias, or having far too many red blood cells, makes blood more viscous and elevates blood pressure. So does *blood doping*. Some athletes withdraw and store their red blood cells and reinject them a few days before competing in strenuous events. The withdrawal triggers red blood cell formation; the body attempts to replace the "lost" cells. When withdrawn cells are put back in the body, the cell count shoots up. The idea is to increase oxygen-carrying capacity and endurance. Other athletes elevate red cell counts artificially by injecting hormones that stimulate red cell production.

White Blood Cell Disorders An Epstein–Barr virus is the agent of *infectious mononucleosis*, a highly contagious disease that causes too many monocytes and lymphocytes to form. Most people recover after a few weeks of fatigue, muscle aches, low-grade fever, and a chronic sore throat.

Recovery is dicey for *leukemias*. These cancers originate in bone marrow and interfere with the formation of white blood cells (Figure 38.6). Either chemotherapy or radiation therapy kills the cancer cells, but side effects can be severe. Remissions, or symptom-free periods in chronic illness, may last months or years. New gene therapies put some leukemias into remission, but they are still experimental.

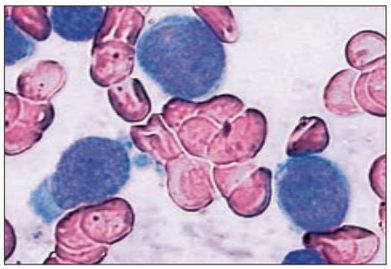


Figure 38.6 Blood sample typical of chronic myelogenous leukemia. Abnormal, immature white blood cells are starting to crowd out normal cells.

38.4 Blood Typing

Blood from donors can be transfused into patients who are affected by severe blood loss or a blood disorder. Such blood transfusions cannot be hit-or-miss. Red blood cells of a potential donor and recipient must bear the same kinds of recognition proteins at their surface.

Each kind of cell bears "self" markers, or recognition proteins at its surface that give it a unique identity (Section 5.2). If donated red blood cells have markers that are not also on the recipient's red blood cells, the recipient's immune system will attack them.

In a normal defense response called **agglutination**, proteins called antibodies bind foreign cells and make them form clumps that attract phagocytes. However, Figure 38.7 shows what happens when the blood from incompatible donors and recipients intermingles. Free antibodies circulating in the recipient's plasma bind to the nonself markers on the introduced cells and make them clump. There are so many foreign cells that the clumps clog small blood vessels and damage tissues. Without treatment, death may follow. The same thing can happen during a pregnancy if a mother and child differ in some red blood cell markers. The mother's immune system will attack the child's cells.

Blood typing—the analysis of the surface markers on red blood cells—can help prevent such problems.

ABO BLOOD TYPING

Molecular variations in one kind of self marker on red blood cells are analyzed with **ABO blood typing**. The genetic basis of such variation is described in Section 11.4. People with one form of the marker have type A blood; those with a different form have type B blood. If they have both forms of the marker on their red blood cells, their blood is type AB. If they have neither form of the marker, their blood is type O.

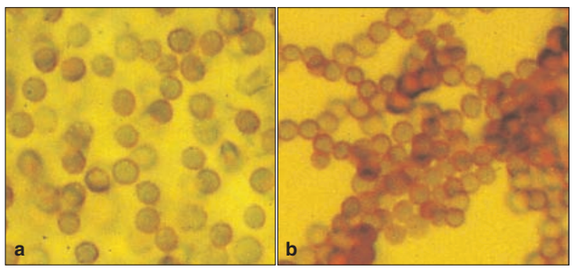


Figure 38.7 Light micrographs showing (**a**) an absence of agglutination in a mixture of two different yet compatible blood types and (**b**) agglutination in a mixture of incompatible types.

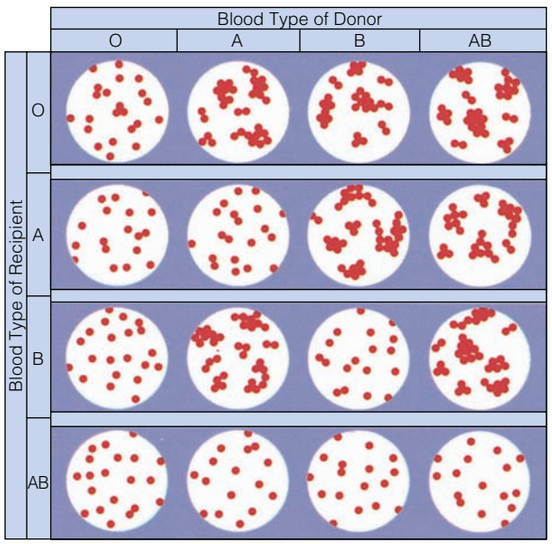


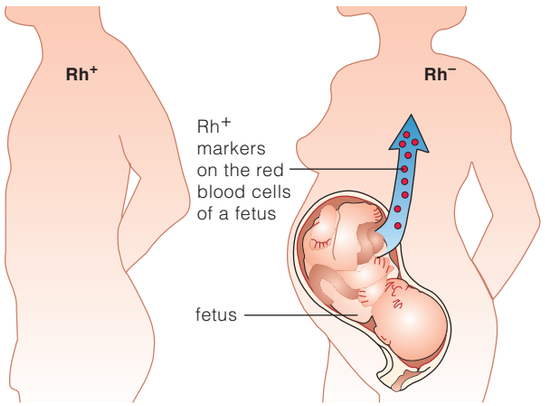
Figure 38.8 ***Animated!*** Responses in blood types A, B, AB, and O when mixed with samples of the same and different types.

Consider Figure 38.8. If you are blood type A, your immune system will recognize blood cells with type B markers as foreign. If type B, it will react against cells with type A markers. If you are blood type AB, your immune system is familiar with both markers, and it will not react against either type, so you can receive blood transfusions from anyone. If you are blood type O, it will recognize both A and B markers as foreign. You can accept blood only from other people who are type O, but you can donate blood to anyone.

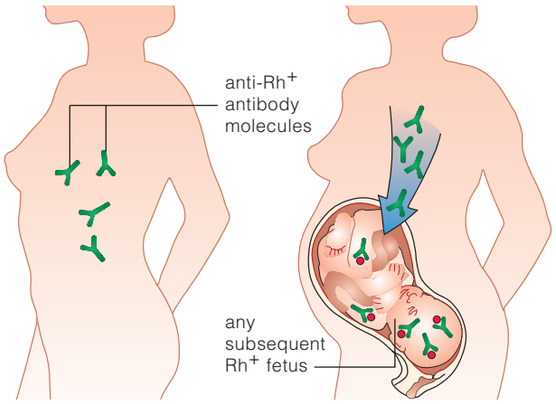
Rh BLOOD TYPING

Rh blood typing is based on the presence or absence of the Rh marker (first identified in blood of *Rh*esus monkeys). If you are type Rh^+, your blood cells bear this marker. If you are type Rh^-, they do not. People normally do not have antibodies against Rh markers, because their body has never been exposed to them. However, an Rh^- recipient of transfused Rh^+ blood will make antibodies that will remain in the blood.

If an Rh^- woman is impregnated by an Rh^+ man, there is a chance the fetus will be Rh^+. Some fetal red blood cells usually leak into a woman's blood during childbirth, and her body makes antibodies against Rh (Figure 38.9). If she becomes pregnant again, some of her Rh antibodies may enter the blood of her fetus. If the fetus is Rh^+, then her antibodies will cause its red blood cells to swell, rupture, and release hemoglobin.



a A forthcoming child of an Rh^- woman and Rh^+ man inherits the gene for the Rh^+ marker. During childbirth, some of its cells bearing the marker may leak into the maternal bloodstream.



b The foreign marker stimulates antibody formation. If the same woman becomes pregnant again and if her second fetus (or any other) inherits the gene for the marker, her circulating anti-Rh^+ antibodies will act against it.

Figure 38.9 ***Animated!*** Maternal production of antibodies in response to Rh^+ markers on red blood cells of her fetus.

Erythroblastosis fetalis is the name for any hemolytic disorder in a fetus caused by blood incompatibilities. Some newborns do not display any symptoms; others die not long after birth. Whether it be an ABO or Rh mismatch, diagnosis before birth can help. Fetal blood can be slowly replaced by transfusions of blood from a compatible donor.

Markers on red cell surfaces are the basis for ABO and Rh blood typing. Incompatible blood types cause problems in transfusions and in some pregnancies.

38.5 Human Cardiovascular System

LINKS TO SECTIONS 28.1, 28.5, 33.5

"Cardiovascular" comes from the Greek kardia *(for heart) and Latin* vasculum *(vessel). In the human cardiovascular system, a muscular heart pumps blood to the lungs and the tissues by way of two completely separate circuits.*

In humans, as in all mammals, the heart is a double pump that drives blood through two cardiovascular circuits. Arteries, arterioles, capillaries, venules, and veins make up each circuit (Figures 38.10 and 38.11). A short loop, the pulmonary circuit, oxygenates blood. Again, it leads from the heart's right half to capillary beds in both lungs, then back to the heart's left half.

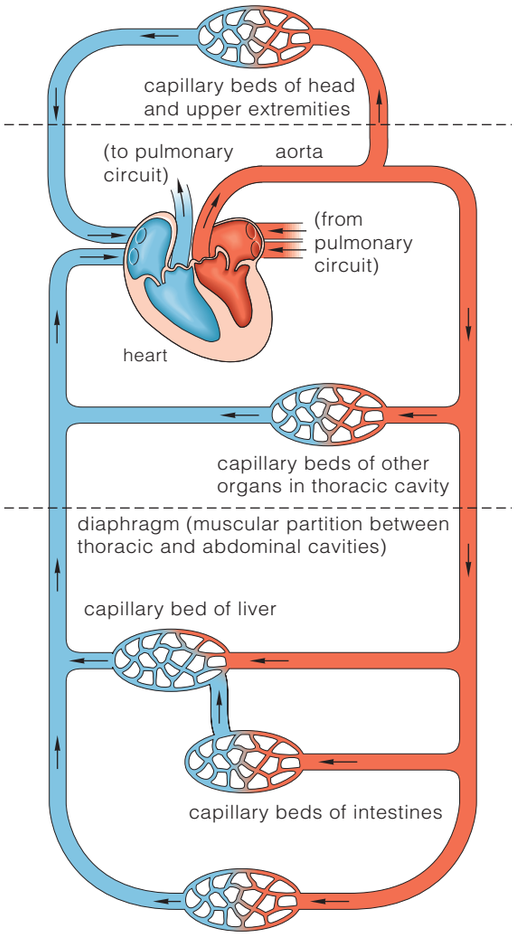
The systemic circuit is a longer loop. The heart's left half pumps oxygenated blood into the main artery, the **aorta**. That blood gives up oxygen in all tissues, then oxygen-poor blood flows back to the heart's right half.

Most blood flows through only one capillary bed. Some flows through two. Blood picks up glucose and other substances at capillaries in the intestines, then flows to and through a capillary bed inside the liver. This organ has vital roles in metabolizing and storing nutrients. It also neutralizes many toxins.

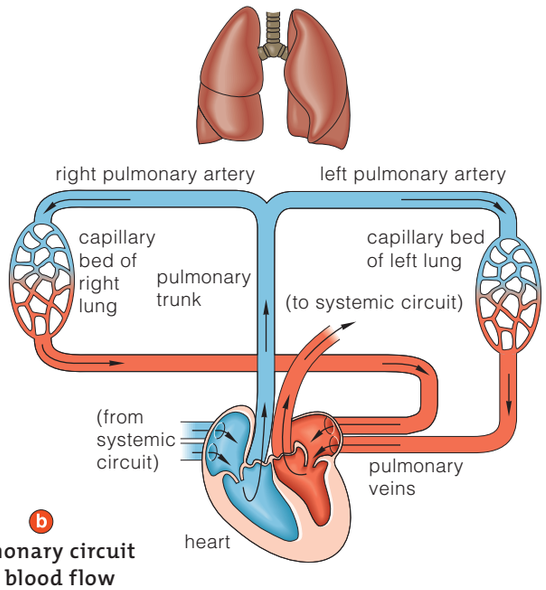
As Figure 38.12 shows, the cardiovascular system rapidly distributes oxygen, nutrients, and many other substances that enter the body through the digestive and respiratory systems. It moves carbon dioxide and other metabolic wastes to the respiratory and urinary systems for disposal. Interactions among these organ systems help keep operating conditions of the internal environment within tolerable ranges. That is the state we call homeostasis (Sections 28.1 and 28.3).

In the human cardiovascular system's pulmonary circuit, oxygen-poor blood flows from the heart's right half, through both lungs, then back to the heart. It takes up oxygen and gives up carbon dioxide in the lungs.

In the systemic circuit, oxygenated blood flows from the heart's left half and aorta to capillary beds of all tissue regions. There it gives up oxygen and takes up carbon dioxide, then moves to the heart's right half.



a systemic circuit for blood flow



b pulmonary circuit for blood flow

Figure 38.10 ***Animated!*** (**a**,**b**) Systemic and pulmonary circuits for blood flow through the human cardiovascular system. Blood vessels carrying oxygenated blood are color-coded *red*. Those carrying oxygen-poor blood are color-coded *blue*.

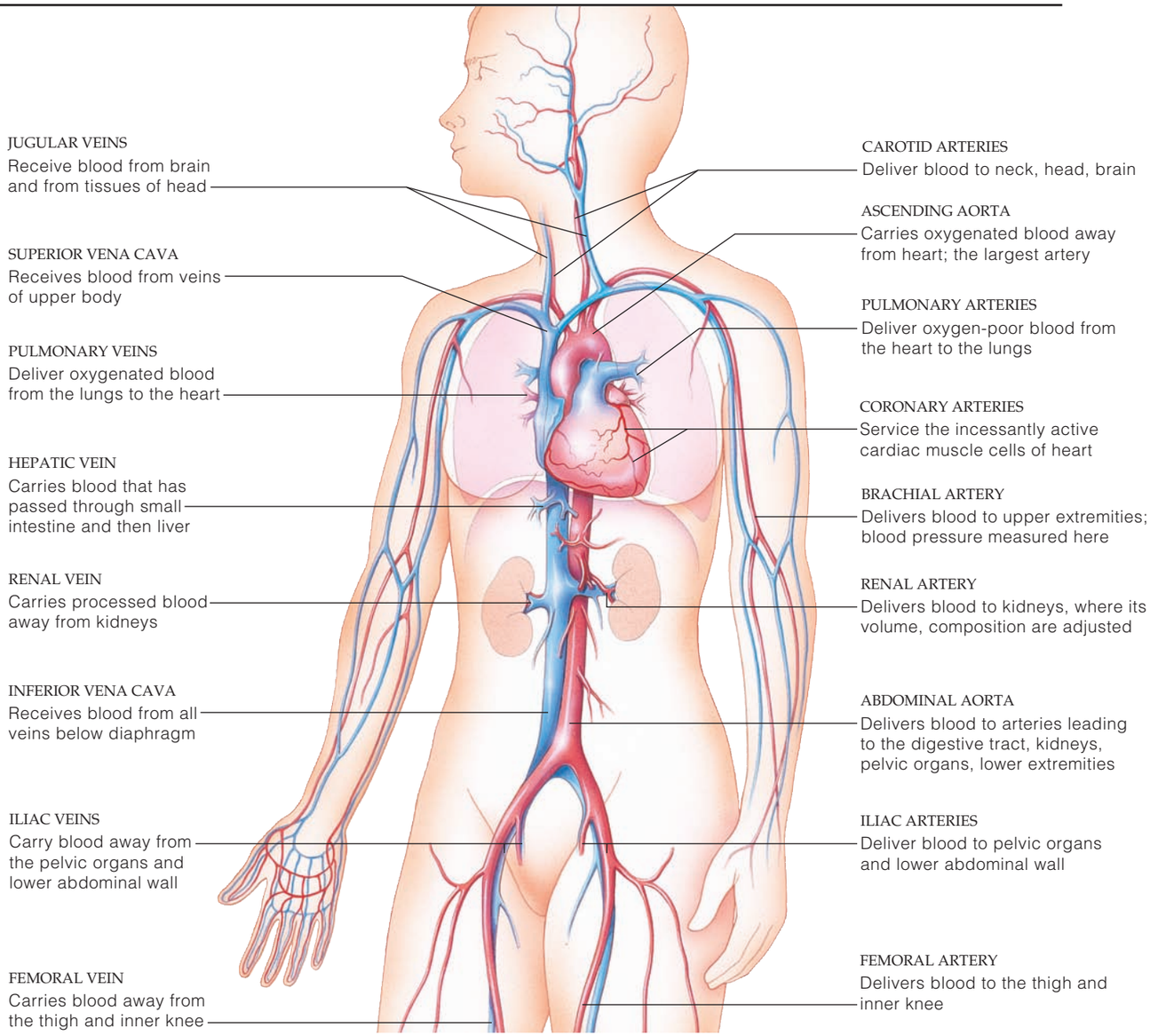


Figure 38.11 ***Animated!*** Major blood vessels of the human cardiovascular system. This art is greatly simplified for clarity. For example, each arm has a complete set of the arteries and veins listed, and so does each leg. Humans, remember, have bilateral ancestry (Section 25.2).

Carotid bodies are located at the first branch point of the carotid arteries, and aortic bodies are in the aorta, where it arches above the heart. Both kinds of sensory receptors monitor chemical changes in blood. Baroreceptors in the same locations monitor blood pressure. In response to the receptor signals, the brain adjusts the heart's output and flow resistance in arterioles and veins.

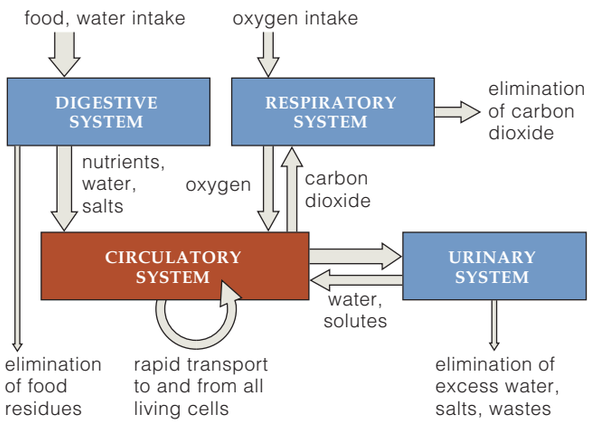


Figure 38.12 Functional links between the circulatory system and other organ systems that maintain the internal environment.

38.6 The Heart Is a Lonely Pumper

LINKS TO SECTIONS 33.3, 34.3, 37.6–37.9

The human heart is a durable pump that spontaneously beats 2.5 billion times in a seventy-year life span.

HEART STRUCTURE

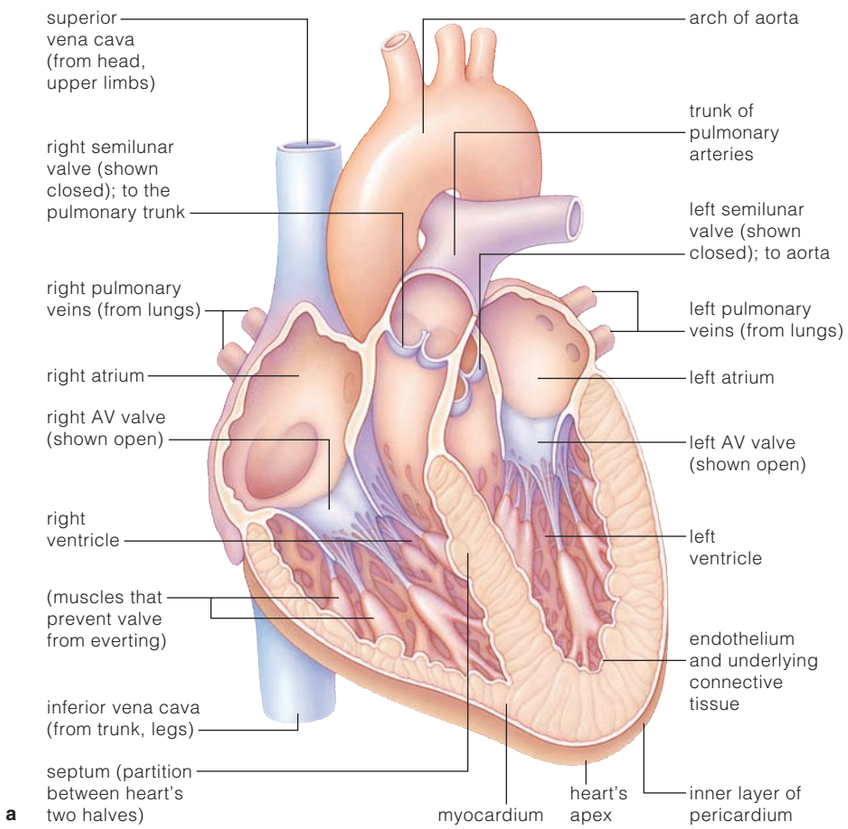
The human heart's durability arises from its structure. Outermost is the *pericardium*, a tough, double-layered, connective tissue sac that anchors the heart to nearby structures (Figure 38.13). In between the two layers is a fluid that lubricates the heart during its perpetual wringing motions. The sac's inner layer is part of the heart wall. Most of the wall is *myocardium*, or cardiac muscle cells tethered to fibers of elastin and collagen. The densely crisscrossed fibers are like a skeleton that accepts the force of contraction. The inner wall has an epithelial lining called *endothelium*. Coronary arteries branch off the aorta and move nutrients and oxygen to a capillary bed dedicated to cardiac muscle cells.

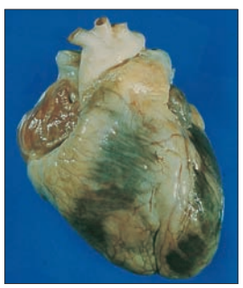
Each half of the heart has two chambers: an atrium (plural, atria) that receives blood, and a ventricle that pumps it out. Between each atrium and ventricle is an atrioventricular (AV) valve. Between each ventricle and the artery that leads away from it is a semilunar valve. Both are *one-way* valves. Fluid pressure forces them open and shut in an alternating way that helps keep the blood moving in the forward direction only.

Heart muscle alternately relaxes and contracts in a recurring **cardiac cycle**. All four chambers go through *diastole* (expansion) and *systole* (contraction). First, the relaxed atria expand with blood, and fluid pressure forces the AV valves to open. Blood now flows into the relaxed ventricles, which expand as the atria contract (Figure 38.14). The ventricles contract, and the fluid pressure in them rises so sharply above the pressure in the great arteries that both semilunar valves open, and so blood flows out. The ventricles relax while the atria are already filling for a new cycle. In short, atrial contraction only helps fill the ventricles. *Contraction of the ventricles is the driving force for blood circulation.*

HOW DOES CARDIAC MUSCLE CONTRACT?

Reflect on Sections 37.6 through 37.9, which explain how skeletal muscle contracts. **Cardiac muscle**, found only in the heart, contracts by the same ATP-driven sliding filament mechanism. Its cells, too, look striated





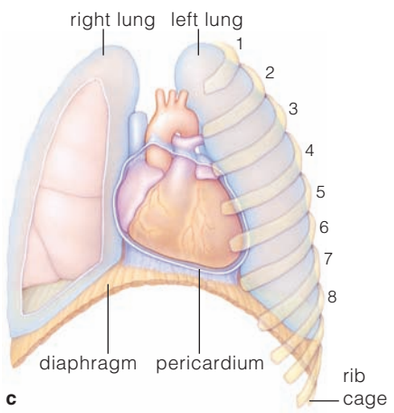


Figure 38.13 ***Animated!*** (**a**) Cutaway view of the heart, showing its wall and internal organization. (**b**) A human heart and (**c**) its location in the thoracic cavity.

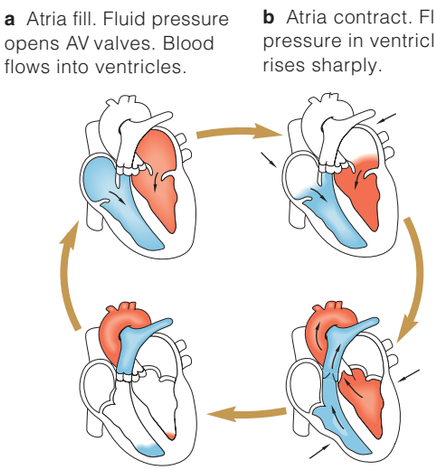


Figure 38.14 ***Animated!*** Cardiac cycle. We hear it as a "lub-dup" near the chest wall. At each "lub," AV valves are closing as ventricles are contracting. At each "dup," semilunar valves are closing as ventricles are relaxing.

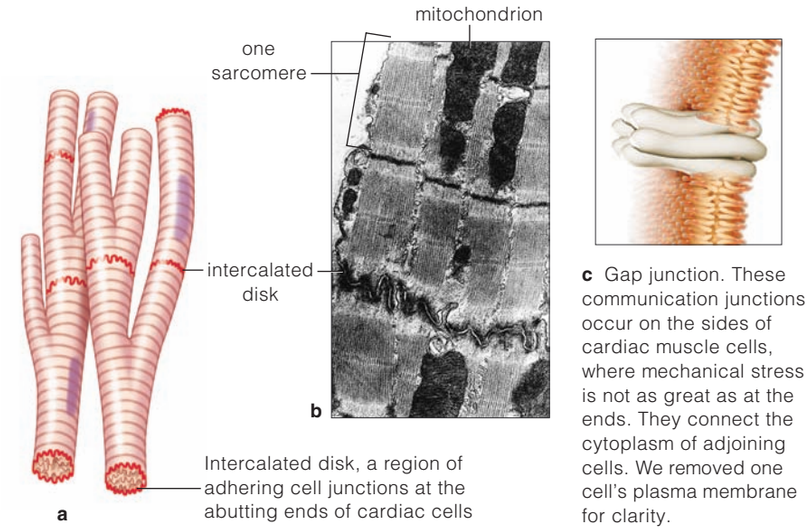


Figure 38.15 (**a**) Branching cardiac muscle cells. (**b**) Intercalated disk, where a profusion of adhering junctions in the plasma membrane keeps abutting ends of cells from getting ripped apart by the heart's wringing motions. (**c**) On the sides of these cells, vast arrays of gap junctions across the plasma membrane are a pathway of low electrical resistance. Excitation spreads swiftly from cell to cell.

because of repeated contractile units (sarcomeres) that form a transverse banding pattern along their length. Unlike skeletal or smooth muscle, cardiac muscle has branching, nucleated cells that abut at their ends, and it has far more mitochondria. On the sides of cardiac muscle cells, action potentials pass right on through gap junctions, so that waves of excitation wash swiftly over the entire heart (Section 33.3 and Figure 38.15).

Where do the signals come from? In cardiac muscle, some specialized cells do not contract. They are part of the **cardiac conduction system**, which initiates and distributes signals that tell regular cardiac muscle cells to contract. As Figure 38.16 shows, the system consists of a sinoatrial (SA) node and an atrioventricular (AV) node, functionally linked by junctional fibers. These fibers are bundles of long, thin cardiac muscle cells.

The SA node, a clump of noncontracting cells in the right atrium's wall, is the **cardiac pacemaker**. Its cells have specialized membrane channels that let them fire action potentials again and again, seventy or so times a minute. The rhythmic firing rate starts in embryos and is on autopilot until death. Each firing triggers one cardiac cycle. First, a signal spreads through the atria and makes them contract. At the same time, the signal activates junctional fibers, which conduct it to the AV node. This clump of cells is the only electric bridge to the ventricles, which are insulated everywhere else by connective tissue. The time it takes for each signal to cross the bridge is enough to keep the ventricles from contracting before they fill. From this node, the signal

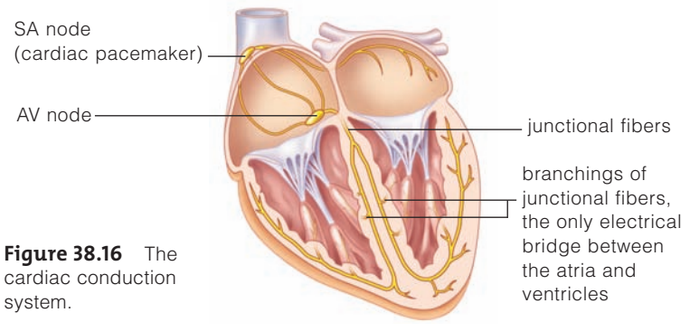


Figure 38.16 The cardiac conduction system.

flows along a bundle of fibers. The fibers branch inside the septum, a partition between the heart's halves. The two branchings extend down to the heart apex and up the ventricle walls. Starting at the apex, cardiac muscle responds by contracting in a twisting motion, which ejects blood into the aorta and pulmonary arteries.

The nervous system can only adjust the rate and strength of contractions set by the natural pacemaker, which can keep the heart beating even when an injury severs all nerves to the heart. Those defibrillators you read about earlier work by resetting the SA node.

The four-chambered heart is partitioned into two halves, each with an atrium and a ventricle. Contraction of the ventricles pumps blood out of the heart, into arteries.

The SA node is the cardiac pacemaker. Its spontaneous, rhythmic signals make the branching, abutting cardiac muscle cells contract almost as if they were a single unit.

38.7 Pressure, Transport, and Flow Distribution

LINKS TO SECTIONS 33.3, 35.1

During any specified interval, the pressure driving blood through your body depends on how fast and how strongly the heart is beating. It depends also on the total resistance to flow through the vascular system.

Figure 38.17 compares the structure of blood vessels. **Arteries** are rapid-transport vessels for blood pumped out of the heart's ventricles. They grade into **arterioles**, smaller vessels where controls over the distribution of blood flow operate. These grade into **capillaries**, the small blood vessels that form diffusion zones. **Venules** are small vessels located between capillaries and veins. **Veins** are large vessels that transport blood back to the heart, and they also are blood volume reservoirs.

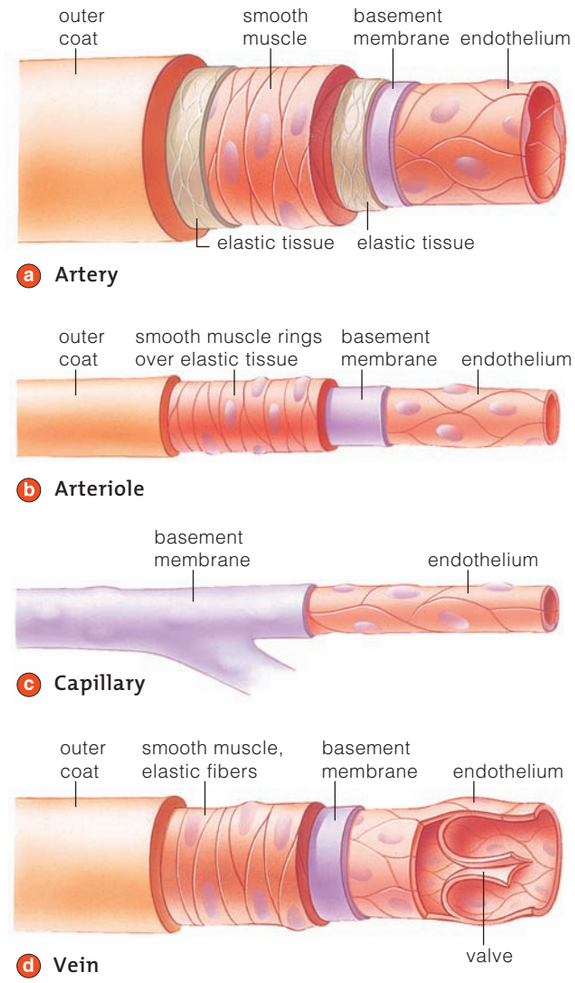


Figure 38.17 Structural comparison of human blood vessels. Capillaries grade into venules (not shown), which have a similar function. These drawings are not drawn to the same scale.

Blood pressure is fluid pressure imparted to blood by ventricular contractions. It is highest in contracting ventricles, still high at the start of arteries, and lowest in the relaxed atria (Figure 38.18). In the pulmonary or systemic circuit, the difference in pressure between any two points affects the flow rate. Heartbeats establish high pressure at the start of either circuit. Blood rubs against the vessel walls, and friction impedes its flow. Resistance to flow depends mainly on the blood vessel diameter. Simply put, resistance rises as tubes narrow. A twofold decrease in the radius of a blood vessel will increase the resistance to flow sixteenfold.

RAPID TRANSPORT IN ARTERIES

With their large diameter and low resistance to flow, arteries are fast, efficient transporters of oxygenated blood. They also are pressure reservoirs that smooth out pulsations in pressure that are generated by each cardiac cycle. An artery's thick, muscular, elastic wall bulges from the large volume of blood forced into it by ventricular contraction. As the elastic wall recoils, it forces oxygen-rich blood farther through the circuit between contractions.

DISTRIBUTING BLOOD FLOW

No matter what you are doing, all of the blood from the heart's right half is flowing to your lungs. The flow distribution from the heart's left half to one organ or another along the systemic circuit can vary, but when you are just lounging around, it is probably close to the values shown in Figure 38.19.

What happens when you go for a run? A greater volume of blood is diverted to your skeletal muscles relative to the volume being distributed to your skin,

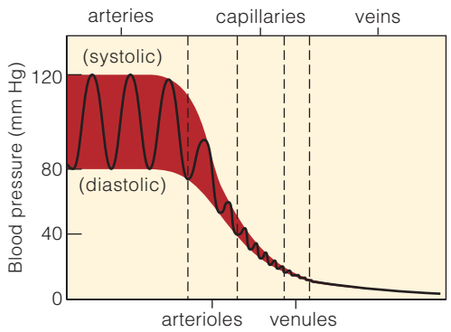


Figure 38.18 Plot of the decline in fluid pressure for a volume of blood that flowed through the systemic circuit.

kidneys, and gut. Like traffic cops, arterioles guide the flow according to instructions from a command post. The nervous and endocrine systems send signals that act on rings of smooth muscle cells in arteriole walls (Figure 38.17*b*). Specific signals make these cells relax, causing **vasodilation**; the diameter of the blood vessel enlarges. Different signals make them contract, causing **vasoconstriction**; the diameter shrinks. Dilate all arterioles in one tissue, and more blood flows to it. Constrict them, and less blood flows to the tissue.

Arterioles also respond to metabolic activities that shift the concentrations of substances in a tissue. Such local chemical changes are "selfish" in that they invite or divert blood flow to meet a tissue's own metabolic needs. For instance, as you run, your skeletal muscle cells use up oxygen, and the levels of carbon dioxide, hydrogen and potassium ions, and other solutes rise. The increase in ion levels causes arterioles in skeletal muscle tissues to dilate. More blood flowing through the region delivers more raw materials and carts off cell products and metabolic wastes. When the skeletal muscles relax, their demand for oxygen declines. Now the oxygen level rises and the arterioles constrict.

CONTROLLING BLOOD PRESSURE

We generally measure blood pressure at the brachial artery in an upper arm (Figure 38.20). In each cardiac cycle, *systolic* (peak) pressure is exerted by contracting ventricles against the arterial wall. *Diastolic* pressure, the lowest arterial blood pressure of the cardiac cycle, is reached when the ventricles are relaxed. An average resting blood pressure is recorded as 120/80, which is the systolic pressure/diastolic pressure.

Blood pressure depends on the total blood volume, how much blood is being pumped out of the heart (cardiac output), and arteriole resistance. *Baroreceptors* in the wall of some arteries, such as the carotids, signal a control center in the brain when fluid pressure rises or falls (Section 35.1). In response, the brain calls for changes in cardiac output and arteriole diameter. This reflex response is a key short-term control over blood pressure. Long-term controls, exerted in the kidneys, adjust the total volume and composition of the blood.

The rate and strength of heartbeats and resistance to flow through blood vessels dictates blood pressure. Pressure is greatest in contracting ventricles and at the start of arteries.

Flow distribution is controlled mainly by adjustments in the diameter of arterioles in different tissues.

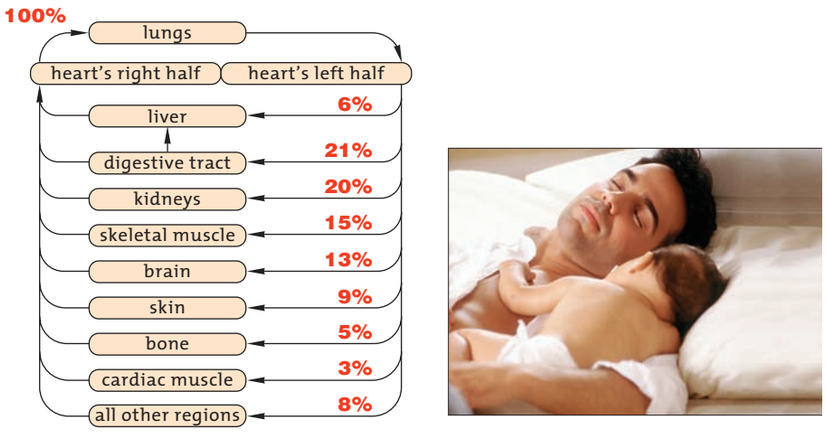


Figure 38.19 Distribution of the heart's output in people napping. How much flows through a given region is adjusted through selective vasodilation and vasoconstriction at many arterioles all along the systemic circuit.

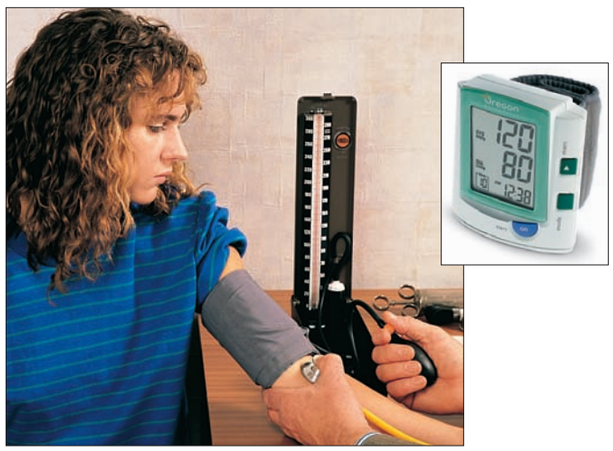


Figure 38.20 ***Animated!*** Measuring blood pressure. First, a hollow inflatable cuff attached to a pressure gauge is wrapped around the upper arm. A stethoscope is placed over the brachial artery, just below the cuff.

The cuff is inflated with air to a pressure above the highest pressure of the cardiac cycle, when ventricles contract. Above this pressure, you will not hear sounds through the stethoscope, because no blood is flowing through the vessel.

Air in the cuff is slowly released until the stethoscope picks up soft tapping sounds. The sounds are caused by blood spurting into the artery under the force of the strongest ventricular contraction. When sounds start, the gauge's value is typically about 120 mm Hg. That measured amount of pressure would force mercury (Hg) to move up 120 millimeters in a narrow glass column of standardized size.

More air is released from the cuff. Eventually the sounds stop. Blood is now flowing continuously, even when the ventricles are the most relaxed. The pressure when the sounds stop is the lowest during a cardiac cycle, usually about 80 mm Hg.

Monitors, such as the one shown in the inset, are now available that automatically record the systolic/diastolic blood pressure.

38.8 Diffusion at Capillaries, Then Back to the Heart

LINKS TO SECTIONS 5.3, 5.5, 25.10, 28.3, 34.9

Every capillary bed is a diffusion zone for exchanges between blood and interstitial fluid. Living cells in any body tissue die quickly when deprived of the exchanges. Brain cells start dying off within four minutes.

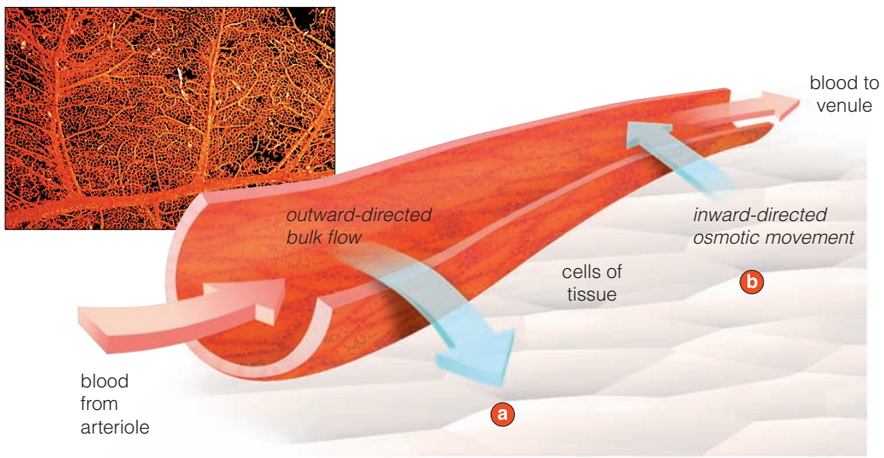
CAPILLARY FUNCTION

Figure 38.21 shows some of the 10 billion to 40 billion capillaries that service the human body. Collectively, they offer a tremendous surface area for exchanging gases. At least one is next to living cells in nearly all tissues. The proximity is critical. Diffusion distributes molecules and ions slowly, and not very far.

Red blood cells are eight micrometers across. They have to squeeze single file through the capillaries. The squeeze puts oxygen-transporting red blood cells and solutes in plasma in direct contact with the exchange area—the capillary wall—or only a very short distance away from it.

A capillary is a sheet of endothelial cells organized as a cylinder, one cell thick, wrapped in a basement membrane. So how do oxygen and carbon dioxide get from blood, across the endothelial cells, and into the interstitial fluid? Like many other small, lipid-soluble substances, they diffuse through the lipid bilayer of each cell's plasma membrane, through its cytoplasm, then on through the bilayer on the other side. Certain proteins cross by way of endocytosis and exocytosis.

The capillaries in most body regions have very thin clefts between endothelial cells. Ions and small, water-soluble molecules squeeze through these clefts. So do white blood cells that are circulating in blood, as the next chapter explains. In capillaries in the brain, tight junctions join endothelial cells together, and clefts are nonexistent. Substances cannot "leak" in between the endothelial cells; they have to pass through them. The junctions help maintain the vital blood–brain barrier, as explained in Section 34.9.



ARTERIOLE END OF CAPILLARY BED	
Outward-Directed Pressure:	
Hydrostatic pressure of blood in capillary:	35 mm Hg
Osmosis due to interstitial proteins:	28 mm Hg
Inward-Directed Pressure:	
Hydrostatic pressure of interstitial fluid:	0
Osmosis due to plasma proteins:	3 mm Hg
Net Ultrafiltration Pressure:	
(35 – 0) – (28 – 3) =	10 mm Hg
ULTRAFILTRATION FAVORED	

VENULE END OF CAPILLARY BED	
Outward-Directed Pressure:	
Hydrostatic pressure of blood in capillary:	15 mm Hg
Osmosis due to interstitial proteins:	28 mm Hg
Inward-Directed Pressure:	
Hydrostatic pressure of interstitial fluid:	0
Osmosis due to plasma proteins:	3 mm Hg
Net Reabsorption Pressure:	
(15 – 0) – (28 – 3) =	–10 mm Hg
REABSORPTION FAVORED	

Figure 38.21 Bulk flow in a capillary bed. Fluid crosses a capillary wall by way of ultrafiltration and reabsorption. (**a**) At the capillary's arteriole end, a difference between blood pressure and interstitial fluid pressure forces out some plasma but few plasma proteins. Bulk flow moves plasma through clefts between endothelial cells of the capillary wall. Ultrafiltration is the bulk flow of fluid *out* of a capillary.

(**b**) Reabsorption is the osmotic movement of some interstitial fluid *into* the capillary. It happens when the water concentration between interstitial fluid and the plasma differs. Plasma, with its dissolved proteins, has a greater solute concentration and therefore a lower water concentration. Reabsorption near the end of a capillary bed tends to balance ultrafiltration at the start of it. Normally there is only a small *net* filtration of fluid, which the lymphatic system returns to the blood.

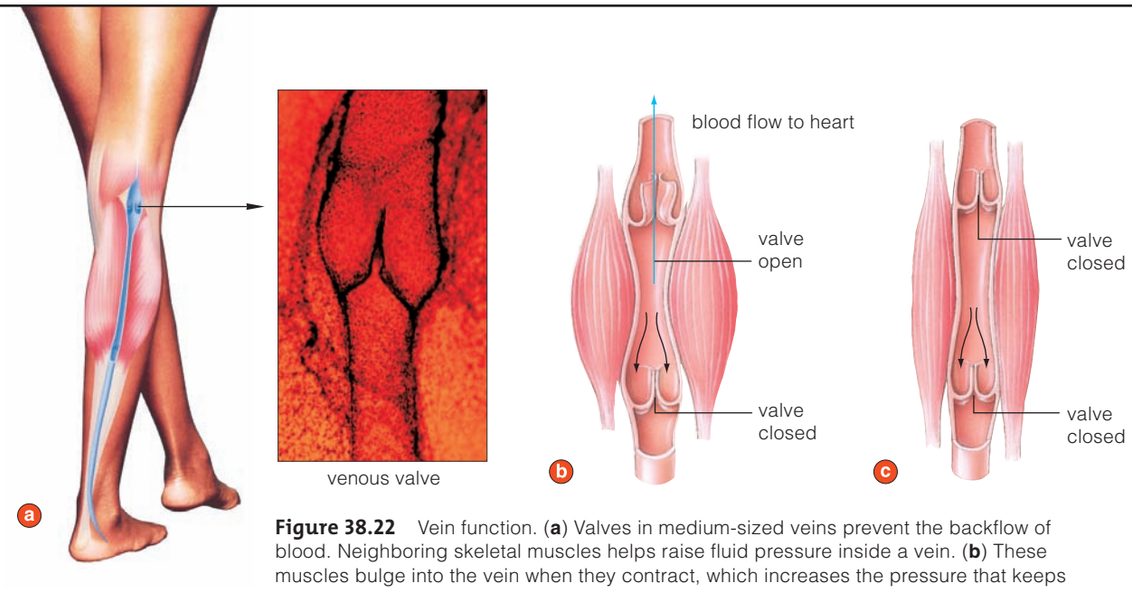


Figure 38.22 Vein function. (**a**) Valves in medium-sized veins prevent the backflow of blood. Neighboring skeletal muscles helps raise fluid pressure inside a vein. (**b**) These muscles bulge into the vein when they contract, which increases the pressure that keeps blood flowing forward. (**c**) When muscles relax, venous valves shut and stop backflow.

Diffusion is not the only process acting at capillary beds. **Bulk flow** is the movement of water and solutes in response to a difference in fluid pressure between regions. It does not affect diffusion much, but it helps maintain the distribution of fluid between blood and interstitial fluid. Figure 38.21 indicates how the water and solutes in blood and interstitial fluid influence the direction of bulk flow. At the start of a capillary bed, a small amount of protein-free plasma is pushed out in bulk through clefts in the capillary wall. This process is called **ultrafiltration**. Farther on, tissue fluid moves back into capillaries through the clefts in the capillary wall. This process is called **capillary reabsorption**.

Normally, there is a tiny *net* outward flow from a capillary bed, which the lymphatic system returns to blood. High blood pressure increases the amount of fluid leaving capillaries. Too much fluid in interstitial spaces is called *edema*. Commonly, gravity causes the fluid to pool in foot and ankle tissues. Edema often follows physical exercise, because arterioles in many tissues have dilated. It also can result from obstructed veins or heart failure. It is dramatic in *elephantiasis*, when roundworm infection slows the return of fluid to lymphatic vessels (Section 25.10).

VENOUS PRESSURE

Blood moving out of capillary beds enters venules, or "little veins," which merge into large-diameter veins. Functionally, venules are a bit like capillaries. Certain solutes diffuse across their thin walls.

Veins are large-diameter, low-resistance transport tubes that carry blood toward the heart. Within many veins, especially in the leg, valves prevent backflow (Figure 38.22). When gravity causes blood in the vein to reverse direction, the valves are pushed shut.

The vein wall can bulge quite a bit under pressure, far more so than an arterial wall. Thus, veins can act as reservoirs for variable volumes of blood. About 60 percent of the total blood volume is in the veins.

The vein wall contains some smooth muscle. When blood must be circulated faster, as during exercise, this smooth muscle contracts. It stiffens the wall, so that the vein cannot bulge out as much. As pressure in the lumen rises, more blood is driven toward the heart. Also, when limbs move, contracting skeletal muscles bulge against neighboring veins. This helps raise the venous pressure that moves blood toward the heart (Figure 38.22). Rapid breathing also contributes to an increase in venous pressure. Inhaling pushes air down on internal organs, which alters the pressure gradient between the heart and veins.

Sometimes venous valves lose their elasticity. The veins become enlarged and bulge near the surface of skin. Such *varicose veins* are common in legs. Around the anus, such bulges are called *hemorrhoids*. Exercise and maintaining an ideal weight reduce the risk.

Capillary beds are diffusion zones for exchanges between blood and interstitial fluid. Here, bulk flow contributes to the fluid balance between blood and interstitial fluid.

Venules overlap somewhat with capillaries in function. Veins are highly distensible blood volume reservoirs where the flow volume back to the heart can be adjusted.

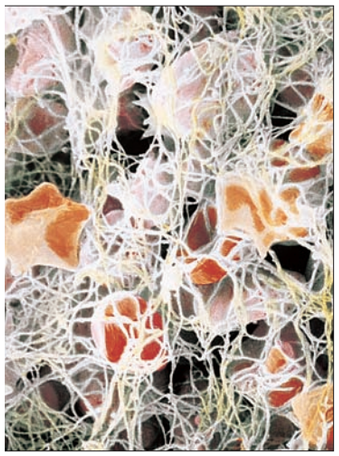
38.9 Cardiovascular Disorders

LINKS TO SECTIONS 3.5, 36.7

A stroke results from a blood clot or ruptured blood vessel in the brain. A heart attack occurs when the small blood vessels that service the heart become clogged. High blood pressure and atherosclerosis increase the risks, many of which can be minimized by changes in life-styles.

Good Clot, Bad Clot A process called **hemostasis** can stop blood loss from small blood vessels that have become ruptured or cut, and it can build a framework for repairs. As Figure 38.23 shows, in the first phase of hemostasis, smooth muscle in a damaged wall goes into spasm. This involuntary, abnormal contraction lasts for about thirty minutes and may stop the blood loss. In the second phase, platelets clump together briefly at the damaged site. They release substances that prolong the spasm and attract more platelets. In the third phase, plasma proteins help convert blood to a gel. Then fibrinogens (rodlike plasma proteins) form. They form long, insoluble threads that stick to exposed collagen fibers at the damaged site. Together, they form a net that traps blood cells and platelets (Figure 38.23). The entire mass, a *blood clot*, retracts as a compact mass that seals the breach in the blood vessel wall.

Clot formation is essential for repairing blood vessels. However, clots cause problems when they completely block blood flow through a vessel, as you will now see.



Stimulus

Blood vessel damage

Phase 1 response

Half-hour vascular spasm constricts vessel at site of damage, slows blood loss.

Phase 2 response

Platelets aggregate and stick together within fifteen seconds, thus plugging the site.

Phase 3 response

Clot formation starts after thirty seconds:

1. Enzymes activate factor X; prothrombin forms.
2. Prothrombin converts an enzyme precursor to thrombin.
3. Thrombin converts fibrinogen, a plasma protein, to insoluble protein threads (fibrin).
4. Fibrin forms a net that entangles blood cells and platelets; the entire mass is a blood clot.

Figure 38.23 Hemostasis. The photomicrograph shows a fibrous protein net that helps blood clots form.

Atherosclerosis With *arteriosclerosis*, arteries thicken and lose elasticity. With **atherosclerosis**, the condition worsens as lipids build up in the arterial wall and narrow the lumen. You have probably heard that cholesterol plays a role in this "hardening of the arteries." To be sure, the human body requires cholesterol to make cell membranes, myelin sheaths, bile salts, and steroid hormones. The liver makes enough cholesterol for cell structure and function, but more cholesterol is absorbed from food in the gut. People differ in how the excess is handled.

Most of the cholesterol dissolved in blood is bound to protein carriers. The complexes are known as *low-density lipoproteins*, or LDLs, and most cells can take them up. A lesser amount is bound up in *high-density lipoproteins*, or HDLs. Cells in the liver metabolize HDL. The metabolic wastes are eliminated by way of bile, which the liver secretes into the gut lumen for disposal (Section 41.4).

When the LDL levels in blood go up, so does the risk of atherosclerosis. The first sign of trouble is a build-up of lipids in an artery's endothelium (Figure 38.24). As lipids accumulate, smooth muscle proliferates in the arterial wall, which becomes inflamed. Fibrous connective tissue forms over the entire mass. The mass is an atherosclerotic plaque, and it makes the arterial wall bulge inward and narrow the lumen.

A hardened plaque can rupture an artery wall, thereby triggering clot formation. When the clot stays put, we call it a *thrombus*. When it becomes dislodged and travels in blood, we call it an *embolus*, and it can clog small vessels.

Coronary arteries are vulnerable. If they narrow by 25 percent, they invite *angina pectoris* (chest pain) or a heart attack. During an attack, some of the cardiac muscle cells die from lack of oxygen. A first attack is fatal about 30 percent of the time. Survivors often have a badly weakened heart.

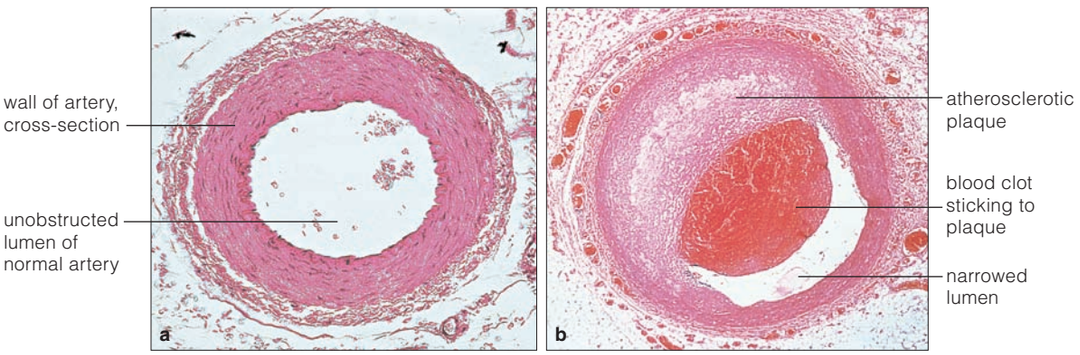


Figure 38.24 Sections from (**a**) a normal artery and (**b**) an artery with a lumen narrowed by an atherosclerotic plaque. A clot clogged this one.

With *coronary bypass surgery*, doctors stitch a section of a blood vessel from elsewhere in the body to the aorta and to the coronary artery below a clogged region (Figure 38.25). With *laser angioplasty*, laser beams vaporize the plaques. With *balloon angioplasty*, doctors inflate a small balloon in a blocked artery to flatten the plaques.

Hypertension—A Silent Killer *Hypertension* refers to chronically high blood pressure even during periods of rest. Blood pressure stays above 140/90, often for unknown reasons. This chronic condition is known as a silent killer, because symptoms do not always show up. Heredity may be a factor; the disorder tends to run in families. Diet and lack of regular exercise are factors. In some people, high salt intake raises blood pressure and makes the heart pump harder. The heart may enlarge and fail to pump efficiently. High blood pressure also may contribute to atherosclerosis, which interferes with the delivery of oxygen to the brain, heart, and other vital organs. Of 23 million hypertensive Americans, most do not seek treatment. About 180,000 die each year.

Rhythms and Arrhythmias As you read in Section 38.6, the SA node controls the rhythmic beating of the heart. Electrocardiograms, or ECGs, record the electrical activity of a beating heart (Figures 38.1 and 38.26*a*).

ECGs can reveal *arrhythmias*, which are abnormal heart rhythms (Figure 38.26*b–d*). Arrhythmias are not always dangerous. For instance, endurance athletes commonly experience *bradycardia*, a below-average resting cardiac rate. In response to ongoing exercise, their nervous system adjusts their cardiac pacemaker's rate of firing downward. Intense exercise or stress often results in 100 or more heartbeats per minute, a condition called *tachycardia*.

In *atrial fibrillation*, the atria do not contract normally. They quiver, which increases the risk of blood clots and stroke. *Ventricular fibrillation* is the most dangerous type of arrhythmia. It caused the collapse of Tammy Higgins, as described at the start of this chapter. Ventricles flutter and their pumping action falters or halts. The individual loses consciousness and faces death. A shock from a defibrillator might be able to restore the heart's normal rhythm.

Risk Factors Cardiovascular disorders are the leading cause of death in the United States. Each year, about 40 million people experience cardiovascular disorders, and each year about 1 million die. Nine factors top the list of risks, and tobacco smoking tops them all (Section 40.8). Other factors include a genetic predisposition to heart attacks, hypertension, a high blood level of cholesterol, obesity, and diabetes mellitus, a condition described in Section 36.7. Advancing age also is a risk factor; the older you get, the greater the risk. Physical inactivity increases the risk. Regular exercise can lower the risk, even when an activity is not particularly strenuous. Gender, too, is a factor; until about age fifty, males are at greater risk.

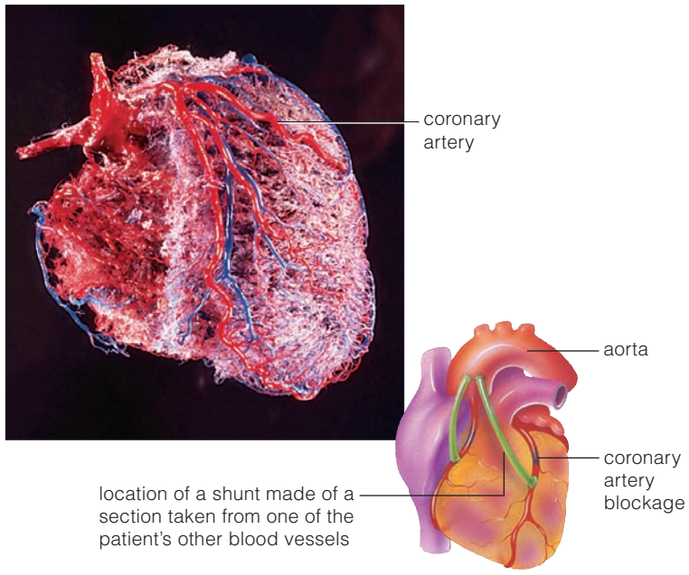


Figure 38.25 Coronary arteries and other blood vessels of the heart. Resins were injected into them, then the rest of the cardiac tissues were dissolved, leaving this accurate, three-dimensional corrosion cast. The sketch shows two coronary bypasses (artificially colored *green*), which extend from the aorta past two clogged parts of the coronary arteries.

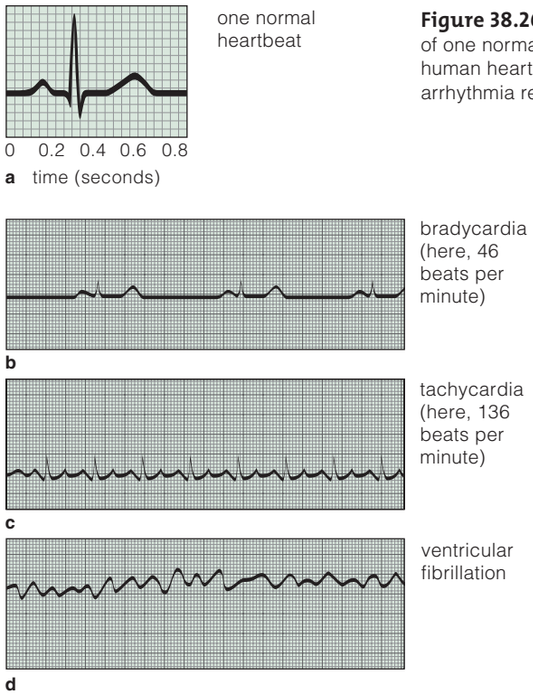


Figure 38.26 (**a**) ECG of one normal beat of the human heart. (**b**–**d**) Three arrhythmia recordings.

38.10 Interactions With the Lymphatic System

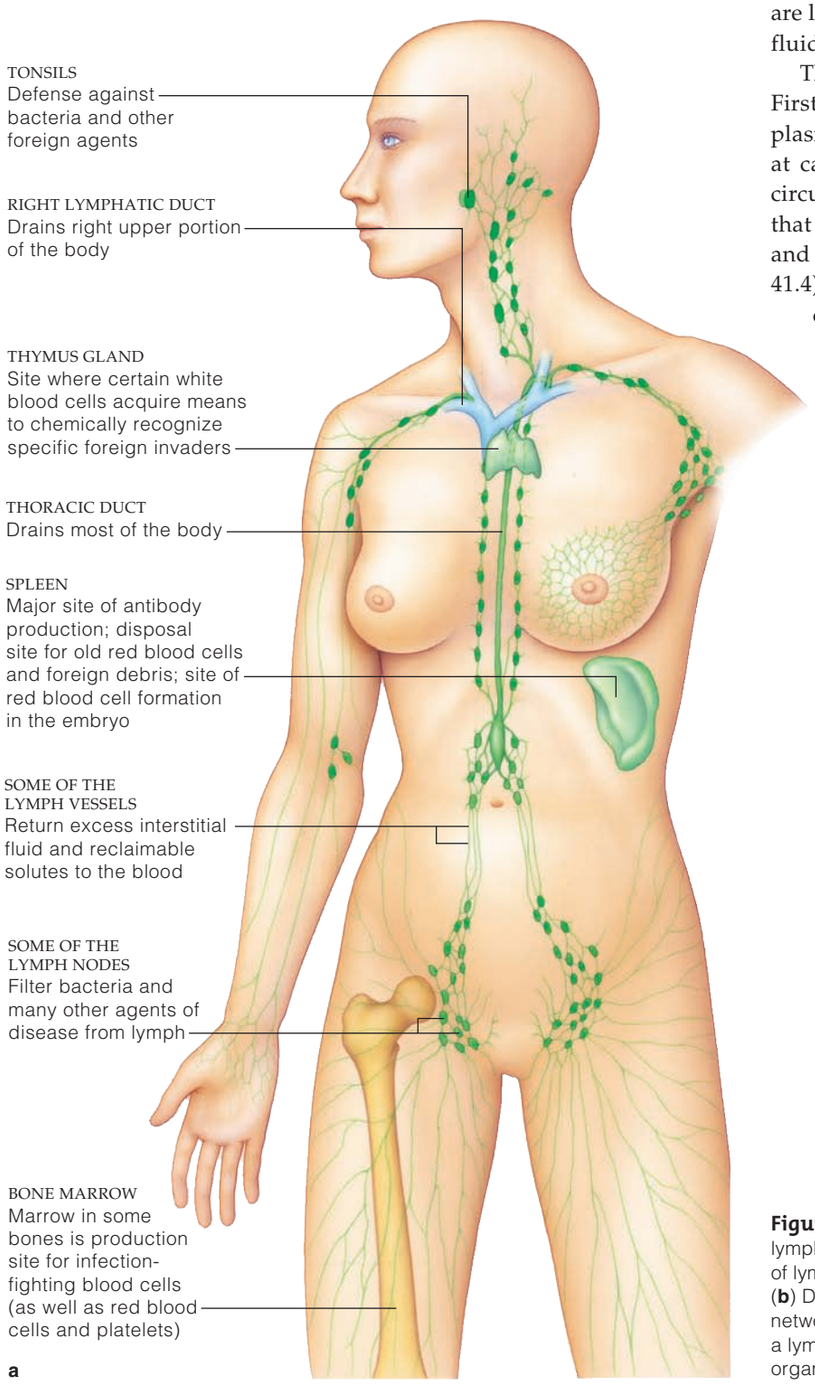
LINK TO SECTION 36.12

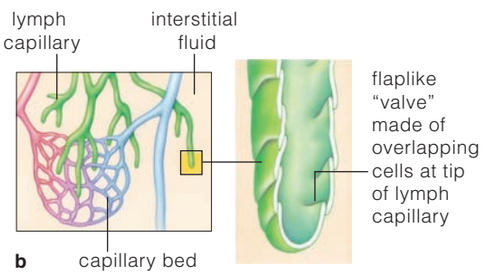
We conclude this chapter with a brief look at how the lymphatic system interacts with blood circulation. Think of this section as a bridge to the next chapter, on immunity, because the lymphatic system also helps defend the body against injury and attack.

LYMPH VASCULAR SYSTEM

A portion of the lymphatic system, called the **lymph vascular system,** consists of many tubes that collect and deliver water and solutes from interstitial fluid to ducts of the circulatory system. Its main components are lymph capillaries and vessels (Figure 38.27). Tissue fluid that moves into these vessels is called **lymph**.

The lymph vascular system serves three functions. First, its vessels are drainage channels for water and plasma proteins that have leaked out from the blood at capillary beds and must be delivered back to the circulatory system. Second, the system takes up fats that the body has absorbed from the small intestine and delivers them to the general circulation (Section 41.4). Third, it delivers pathogens, foreign cells, and cellular debris from tissues to the lymph vascular system's disposal centers, the lymph nodes.





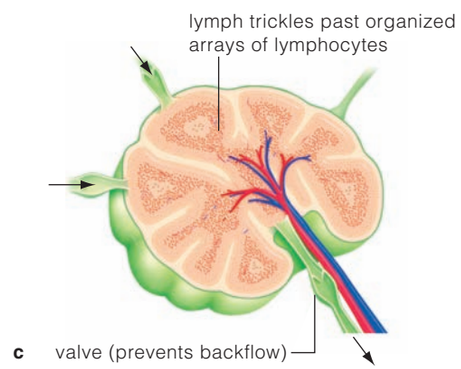


Figure 38.27 ***Animated!*** (**a**) Components of the human lymphatic system and their functions. Not shown are patches of lymphoid tissue in the small intestine and in the appendix. (**b**) Diagram of lymph capillaries at the start of a drainage network, the lymph vascular system. (**c**) Cutaway view of a lymph node. Its inner compartments are packed with organized arrays of infection-fighting white blood cells.

The lymph vascular system starts at all capillary beds. There, excess fluid enters the lymph capillaries. These capillaries have no obvious entrance; water and solutes move into clefts between cells. As you can see from Figure 38.27*b*, the endothelial cells overlap, and they form flaplike valves. Lymph capillaries merge into larger diameter lymph vessels. These vessels have some smooth muscle in the wall and valves that stop backflow. The lymph vessels converge into collecting ducts, which drain into veins in the lower neck.

LYMPHOID ORGANS AND TISSUES

The other portion of the lymphatic system has roles in the body's defense responses to injury and attack. We call its components *lymphoid* organs and tissues. They include the lymph nodes, spleen, and thymus, as well as the tonsils, and patches of tissue in the wall of the small intestine and appendix.

Lymph nodes are strategically located at intervals along lymph vessels (Figure 38.27*c*). Before entering blood, the lymph trickles through at least one node for filtration. Masses of lymphocytes take up stations in the nodes after they form in bone marrow. When they contact cellular debris or an invader, they divide rapidly and form large armies that destroy it.

The **spleen** is the largest lymphoid organ; it's about the size of a fist in an average adult. It functions as a site of red blood cell formation only in embryos. After childbirth, it filters pathogens and used-up red cells and platelets from blood vessels that branch through it. Phagocytic white cells inside the spleen engulf and digest defunct cells and alert the body to invaders. Lymphocytes in the spleen make antibodies. Even so, people survive without it. When the spleen has been damaged by trauma and must be removed, a greater risk of infection is the only bad consequence.

In the **thymus gland**, T lymphocytes differentiate in ways that allow them to recognize and respond to particular pathogens. The thymus gland also makes the hormones that influence these actions. It is central to immunity, the focus of the next chapter.

The lymph vascular part of the lymphatic system consists of many vessels that start in capillary beds. They return water and solutes from tissue fluid to blood, deliver absorbed fats to the bloodstream, and deliver pathogens to lymph nodes.

The lymphatic system also includes lymph nodes and other lymphoid organs that have specific roles in defending the body against tissue damage and infectious diseases.

http://biology.brookscole.com/starr11

Summary

Section 38.1 A circulatory system moves substances to and from interstitial fluid faster than simple diffusion could take them. This fluid fills tissue spaces between cells and exchanges substances with them.

Some invertebrates have an open circulatory system, in which blood spends part of the time mingling with tissue fluids. Vertebrates have a closed circulatory system, with blood confined inside a heart and blood vessels. They differ in whether blood flows through one or two circuits of blood vessels and in the number of chambers in their heart. As lungs evolved in the early vertebrates on land, the circulatory system underwent modifications that made gas exchange more efficient. Fluid leaking from blood vessels enters the lymphatic system, which filters it and then returns it to the circulatory system.

BiologyNow

Compare animal circulatory systems with the animation on BiologyNow.

Section 38.2 Blood, a fluid connective tissue, consists of plasma, blood cells, and platelets. Plasma is mostly water in which diverse ions and molecules are dissolved. Red blood cells, or erythrocytes, contain the hemoglobin that functions in the rapid transport of oxygen and, to a lesser extent, carbon dioxide. Different white blood cells, or leukocytes, function in day-to-day tissue maintenance and repair as well as defense of threatened tissues. Platelets release substances that initiate blood clotting. All blood cells and platelets arise from stem cells in bone marrow.

Section 38.3 In a blood disorder, an individual has too many, too few, or abnormal red or white blood cells.

Section 38.4 Among the recognition proteins on the surface of red blood cells are self markers that identify an individual's blood types. ABO blood typing helps match the blood of donors and recipients to avoid blood transfusion problems. Rh blood typing and suitable treatment assure the survival of fetuses of prospective parents who have incompatible Rh blood types.

BiologyNow

Learn about blood types with the animation on BiologyNow.

Section 38.5 The human heart is a durable pump, the contraction of which forces blood through two separate circuits that lead back to the heart.

In the pulmonary circuit, oxygen-poor blood from the heart's right half flows to the lungs, picks up oxygen, then flows to the heart's left half.

In the systemic circuit, the oxygen-rich blood flows from the heart's left half to all body tissues, then oxygen-poor blood flows to the heart's right half.

Most blood flows through one capillary system. In one route, it flows through intestinal capillaries, then

liver capillaries. The liver metabolizes or stores nutrients and neutralizes a number of bloodborne toxins.

Biology Now

Explore the human cardiovascular system with the animation on BiologyNow.

Section 38.6 The human heart is a thick-walled, double pump that beats perpetually. Each half has two chambers: an atrium and a ventricle.

In one cardiac cycle, all of the chambers undergo rhythmic expansion (diastole) and contraction (systole). When a cycle starts, each atria expands as blood fills it and opens a valve to a ventricle. Ventricles are already filling when the atria contract. When ventricles contract, they force blood into the aorta and pulmonary arteries.

The cardiac conduction system is the basis of the heart's beating. It consists of an SA node in the right atrium wall that is functionally linked by bundles of conducting fibers to an AV node.

The SA node is the cardiac pacemaker. Here, action potentials are spontaneously generated and set the pace for contraction. Waves of excitation wash over atria, down fibers in the heart's septum, then up the walls of the ventricles. The nervous system adjusts the rate and strength of contractions but does not initiate them.

Biology Now

Learn about the structure and function of the human heart with the animation on BiologyNow.

Section 38.7 The blood pressure is highest in the contracting ventricles. It falls as blood flows through arteries, arterioles, capillaries, venules, and veins of the systemic or pulmonary circuit. It is lowest in relaxed atria. The flow rate depends on the strength and rate of heartbeat and on resistance to flow in different blood vessels. Adjustments in the diameter of arterioles in different parts of the body can redistribute flow to the tissues requiring the most metabolic support during a given interval.

Biology Now

See how blood pressure is measured with the animation on BiologyNow.

Section 38.8 Capillary beds are zones of diffusion between blood and interstitial fluid. Ultrafiltration pushes a small amount of fluid out of capillaries. Fluid moves back in by capillary reabsorption. Normally, both processes are almost balanced, with just a small net outward flow of fluid from a capillary bed.

Venules overlap capillaries in function. Veins are rapid-transport vessels and a blood volume reservoir for adjusting the flow volume back to the heart.

Section 38.9 Hemostasis, a process that stops blood flow from small vessels after injury, results in clot formation. Blood clotting is beneficial except in some cardiovascular disorders. The most common disorders are atherosclerosis, hypertension (chronic high blood pressure), heart attacks, strokes, and certain arrythmias. Regular exercise, maintaining a normal body weight, and not smoking lower the risks for most people.

Section 38.10 The lymphatic system structurally and functionally supports the circulatory system. The vascular portion of the lymphatic system includes lymph vessels and lymph capillaries. It takes up excess water and plasma proteins from interstitial fluid, as well as absorbed fats, and transports them to blood. It transports bloodborne pathogens and foreign material to lymph nodes and the spleen.

The lymphoid organs and tissues of the lymphatic system are sites of maturation for some white blood cells. Some are battlegrounds where organized arrays of these cells screen lymph and battle disease-causing agents.

Biology Now

Learn about the human lymphatic system with the animation on BiologyNow.

Self-Quiz

Answers in Appendix II

1. Cells directly exchange substances with _____ .
   a. blood vessels
   b. lymph vessels
   c. interstitial fluid
   d. both a and b

2. All vertebrates have _____ .
   a. an open circulatory system
   b. a closed circulatory system
   c. a four-chambered heart
   d. both b and c

3. Which are not found in the blood?
   a. plasma
   b. blood cells and platelets
   c. gases and dissolved substances
   d. All of the above are found in blood.

4. A person who has type O blood _____ .
   a. can receive a transfusion of blood of any type
   b. can donate blood to a person of any blood type
   c. can donate blood only to a person of type O
   d. cannot be a blood donor
   e. both a and b

5. In the blood, most oxygen is transported _____ .
   a. in red blood cells
   b. in white blood cells
   c. bound to hemoglobin
   d. both a and c

6. Blood flows directly from the left atrium to _____ .
   a. the aorta
   b. the left ventricle
   c. the right atrium
   d. the pulmonary arteries

7. Contraction of _____ drives the flow of blood through the aorta and pulmonary arteries.
   a. the atria
   b. arterioles
   c. the ventricles
   d. skeletal muscle

8. Blood pressure is highest in the _____ and lowest in the _____ .
   a. arteries; veins
   b. arterioles; venules
   c. veins; arteries
   d. capillaries; arterioles

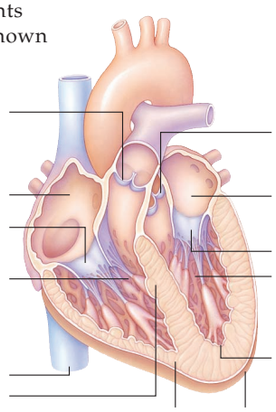
9. At rest, the largest volume of blood is in the _____ .
   a. arteries
   b. capillaries
   c. veins
   d. arterioles

10. Which is not a function of the lymphatic system?
    a. filters out pathogens
    b. returns fluid to the circulatory system
    c. helps certain white blood cells mature
    d. distributes oxygen to the tissues

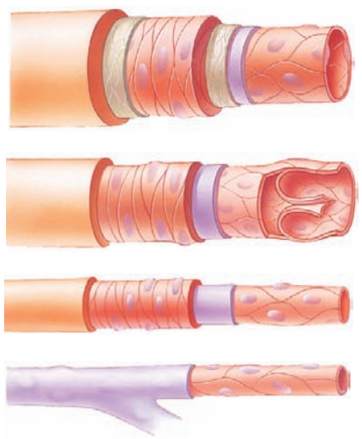
11. Match the components with their functions.

____ capillary bed	a. filters out pathogens
____ lymph node	b. cardiac pacemaker
____ blood	c. main blood volume reservoir
____ ventricle	d. largest artery
____ SA node	e. fluid connective tissue
____ veins	f. zone of diffusion
____ aorta	g. contractions drive blood circulation

12. Label the components of the heart diagram shown to the right:



13. Identify these blood vessels and list their functions:



Additional questions are available on Biology Now™

Critical Thinking

1. The highly publicized deaths of a few airline travelers led to warnings about *economy-class syndrome*. The idea is that sitting motionless for long periods on flights allows blood to pool and clots to form in legs. Low oxygen levels in airline cabins may increase clotting. If a clot gets large enough to block blood flow or breaks free and is carried to the lungs or the brain, the outcome can be deadly.

There might be a time lag between clot formation and health problems, so a connection to air travel might easily have been overlooked. Studies are now under way to determine whether economy-class travel represents a significant risk. Given what you know about blood flow in the veins, explain why periodically getting up and moving around in the plane's cabin during a long flight may lower the risk of clot formation.

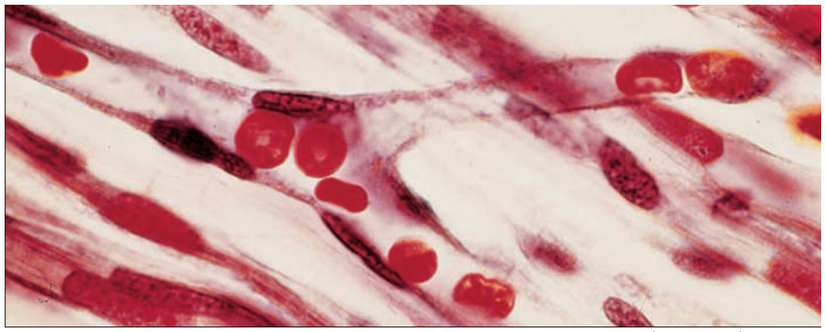


Figure 38.28 Light micrograph of a branching blood vessel.

2. Consider the micrograph in Figure 38.28. It shows red blood cells moving through a blood vessel. What type of vessel is this? Explain how you came to this conclusion.

3. Some membrane proteins of *Streptococcus pyrogenes* are similar to those of cells in connective tissues throughout a human body. When this bacterium causes throat infections, weapons called antibodies go to work against the invader. However, they also go to work against connective tissues of the heart, joints, and elsewhere. Chronic inflammation over the course of a few years or even decades leads to *rheumatic heart disease.* The heart valves become damaged or deformed. Explain how this disease affects the heart's function and what problems might arise as a consequence.

4. Mitochondria occupy about 40 percent of the volume of human cardiac muscle but only 12 percent of the volume of skeletal muscle. Explain why there is such a difference.

5. Like other insects, the fruit fly (*Drosophila melanogaster*) has an open circulatory system. The transport medium is hemolymph, not blood. Contraction of one of the main vessels of the system drives a slow flow of hemolymph through the tiny fly body.

In 1993, researchers found that normal development of the fly "heart" requires the presence of a gene they named *tinman*. The gene's name is a reference to the character in *The Wizard of Oz* who had no heart. If the *tinman* gene is mutated, no heart forms in the embryonic fly, which dies. Genes having a similar base sequence have been found in zebrafish, the African clawed toad, chickens, mice, and humans. In all of these evolutionarily distant species, mutant versions result in abnormal heart development. In humans, mutations cause some genetic defects in the partition dividing the heart chambers and in the cardiac conduction system. Does it surprise you that a single gene would have such a major effect on the development of hearts or heartlike organs in so many different organisms? Explain your answer.

6. Miranda is nineteen, a college student, and a dedicated runner. About a month ago, a friend convinced her to switch to a *strict vegan diet.* She avoids all foods and other products that contain materials from animals, including eggs and milk. As she began training for a race, she found herself feeling unusually fatigued. Her friends commented that she looked pale. When she visited her doctor, she was told that the iron stores in her body were being depleted. Explain how iron deficiency would affect her blood and could cause her symptoms.