CHAPTER 23

Circulation

Objectives

Introduction Explain how gravity affects the circulation of terrestrial vertebrates.

23.1 Describe the general need for and functions of a circulatory system.

Mechanisms of Internal Transport

23.2 Compare open and closed circulatory systems and gastrovascular cavities.

23.3 Compare the cardiovascular systems of a fish and a mammal.

The Mammalian Cardiovascular System

23.4 Describe the pathway of blood through the mammalian cardiovascular system.

23.5 Relate the structure of blood vessels to their functions.

23.6 Distinguish between diastole and systole. Explain what keeps blood moving in the correct direction within the heart and what causes heart "beats."

23.7 Explain how heartbeats are controlled.

23.8 Define a heart attack and heart disease and explain the causes of these serious health problems.

23.9 Explain how and why blood pressure changes as blood moves away from the heart.

23.10 Explain how blood pressure is measured. Note normal and high blood pressure readings.

23.11 Explain how blood flow through capillaries is regulated.

23.12 Explain how the structure of a capillary is related to its functions.

Structure and Function of Blood

23.13 Describe the components of blood and their functions.

23.14 Describe the structure, function, and production of red blood cells.

23.15 Describe the five main types of leukocytes and note their functions.

23.16 Describe the process of blood clotting.

23.17 Define leukemia and describe the most common forms of treatment.

Key Terms

circulatory system
capillary
blood
open circulatory system
closed circulatory system
cardiovascular system
artery
vein
atrium
ventricle
arteriole
capillary bed
venule
pulmonary circuit
systemic circuit
pulmonary artery
pulmonary vein
aorta
superior vena cava
inferior vena cava
cardiac cycle
diastole
systole
cardiac output

pacemaker
SA (sinoatrial) node
AV (atrioventricular) node
artificial pacemaker
heart attack
cardiovascular disease
atherosclerosis
blood pressure
pulse
hypertension
plasma
platelet
red blood cell
erythrocyte
anemia
white blood cell
leukocyte
phagocyte
fibrinogen
fibrin
stem cell
leukemia

Word Roots

atrio- = a vestibule; **-ventriculo** = ventricle (*atrioventricular node:* a region of specialized muscle tissue between the right atrium and right ventricle; it generates electrical impulses that primarily cause the ventricles to contract)

cardi- = heart; **-vascula** = a little vessel (*cardiovascular system:* the closed circulatory system characteristic of vertebrates)

fibrino- = a fiber; **-gen** = produce (*fibrinogen:* the inactive form of the plasma protein that is converted to the active form fibrin, which aggregates into threads that form the framework of a blood clot)

Lecture Outline

Introduction *How Does Gravity Affect Blood Circulation?*

A. Most animals have a **circulatory system,** for the internal transport of gases, nutrients, and waste.

B. Gravity has had major effects in shaping the evolution of circulatory systems in terrestrial organisms as different as corn snakes and giraffes.
   1. Strong hearts are able to pump against the force of gravity, even in tall animals.
   2. Muscles used in normal activities contract around veins and force blood back to the heart through one-way valves.
   3. Tight skin and abundant connective tissue keep blood vessels from enlarging.
   4. In the corn snake, veins have no valves, but tail vessels constrict during a climb, and a snake will wriggle after a climb to increase circulation.

Module 23.1 The circulatory system associates intimately with all body tissues.

Review: Chemical exchange between an animal and its environment (Module 20.11).

A. Diffusion is inadequate for transporting chemicals over distances greater than a few cell widths.

B. **Capillaries** are the smallest vessels and form an intricate network of vessels among the cells of every tissue (Figures 23.1A and 23.12A).

C. The various components of blood, particularly red blood cells, come in close enough contact with associated cells that materials can diffuse between them, via the interstitial fluid (Figure 23.1B).

D. In most tissues, O_2 and nutrients diffuse from blood to tissue, and CO_2 and metabolic wastes diffuse from tissue to blood.

E. The circulatory system also functions in homeostasis by exchanging molecules with the interstitial fluid and by moving the blood through organs such as the liver and kidneys, where the blood's contents are regulated.

I. Mechanisms of Internal Transport

Module 23.2 Several types of internal transport have evolved in animals.

A. The gastrovascular cavity of the cnidarians provides a path for external water to bathe all the cells (Module 21.3). Digestion also occurs in this cavity, and the contents are moved about by flagella on the cells lining it. In jellyfish, this path can be intricately branched, but it is not closed (Figure 23.2A).

B. Many invertebrates (including arthropods and mollusks) have **open circulatory systems. Blood** is pumped by one or more hearts through open-ended vessels and flows out among the cells. There is no separate interstitial fluid. Pores in the hearts function as valves, opening when the hearts relax to pull in blood from the tissues (Figure 23.2B).

C. Other invertebrates and all vertebrates have **closed circulatory systems** (also called **cardiovascular systems**). Blood is confined to vessels, which keeps it distinct from the interstitial fluid (Figure 23.2C).
NOTE: Point out that in the overhead transparencies, O_2-rich blood is indicated by red and O_2-poor blood by blue.

D. In closed systems, **arteries** carry blood away from the heart, **veins** return blood to the heart, and capillaries convey blood between these two vessel types within each organ.

E. A fish system includes four gills, each with thousands of gill capillaries, on each side of the head, and a two-chambered heart (**atrium** receives and **ventricle** pumps out). Large arteries branch out into smaller arterioles and then out into the **capillary beds.** Once past the capillaries, the blood converges into **venules** and then finally back to veins.

Module 23.3 Vertebrate cardiovascular systems reflect evolution.

A. The switch from gill breathing in aquatic vertebrates to lung breathing in terrestrial vertebrates was accompanied by drastic changes in the circulatory systems.
NOTE: Although just fish and mammal systems are compared in this module, a progression of evolutionary adaptations in the circulatory systems of amphibians and reptiles links these two extremes.

B. Fish have a single circuit of blood flow, with the heart receiving and pumping only O_2-poor blood (Figure 23.3A).
NOTE: Point out that the overhead transparencies show the circulatory system as though the animal were facing you, with its right side on your left. Historically such illustrations are oriented to illustrate animal dissections, with the open body cavity facing up.

C. Mammals have two circuits, with a four-chambered heart having two atria and two ventricles. The **pulmonary circuit** carries blood from the right side of the heart to the lungs, and the **systemic circuit** carries blood from the left side of the heart to the rest of the body. This double system provides rapid delivery of O_2-rich blood to body tissues of highly active mammals, endotherms (Figure 23.3B). Endotherms use approximately 10x more energy than exotherms; therefore, they need comparable amounts of oxygen and nutrients for the cells to be delivered by a large and powerful heart.

II. The Mammalian Cardiovascular System

Module 23.4 The human heart and cardiovascular system typify those of mammals.

A. The heart (Figure 23.4A) is composed mostly of cardiac muscle tissue (Module 20.6). *Review:* Specialized cell junctions connect cardiac muscle fibers to one another (Module 4.19). These specialized cell junctions are called *intercalated discs.* Intercalated discs are a combination of anchoring junctions and communicating junctions.

B. Thin-walled atria receive blood, which then flows to the ventricles.

C. Thick-walled ventricles pump blood to other organs.

D. Valves between chambers and between ventricles and main arteries maintain the flow in one direction.

E. The flow of blood through the body (Figure 23.4B) follows this path:

1. Right ventricle to lungs via **pulmonary arteries**
2. Lungs to left atrium via **pulmonary veins**
3. Left atrium to left ventricle
4. Left ventricle to all body organs via the **aorta**
5. Body organs to right atrium via **superior vena cava** and **inferior vena cava**
6. Right atrium to right ventricle

F. The left ventricle is correspondingly larger because it pumps blood to a larger, more distant volume of tissue than the right ventricle.

G. The aorta is the largest vessel in the human body, and branches from it supply blood to various body regions.
NOTE: The first arteries that branch off the aorta supply blood to critically important organs: first the heart itself, and then the head, including the brain and many sense organs. Also point out that any RBCs that are in an organ must return to the heart and lungs before traveling to another organ. There is an exception, however—the hepatic portal system.

Module 23.5 The structure of blood vessels fits their functions.

A. Capillaries, which supply cells, have thin walls composed of a single layer of epithelial cells wrapped in a thin basement membrane. Such a thin surface facilitates the diffusion of molecules to and from the interstitial fluid.

B. Arteries contain blood under the pressure produced by the heart; they are thick walled, with a smooth epithelial layer and layers of connective and smooth muscle tissue for reinforcement and to regulate blood flow by constriction.

C. Veins contain blood under pressure and are similar in structure to arteries, but many also contain valves to prevent backflow (Figure 23.5).
Preview: Veins are under less direct pressure from the heart. Thus, it is not direct pressure from the heart that is responsible for the venous return of blood, but several other factors. Factors that play a role include negative pressure created by the enlargement of the thoracic cavity during inhalation, skeletal muscle movement pushing blood along, and valves assuring unidirectional blood flow. See Module 23.9 and Figure 23.9B.

Module 23.6 The heart contracts and relaxes rhythmically.

A. The heart passively fills with returning blood and actively contracts, pumping out blood. The whole sequence is called the **cardiac cycle** (Figure 23.6).

B. During **diastole** (which lasts about 0.4 sec), the heart is relaxed, and blood flows into all four chambers, with all valves open.

C. **Systole** begins as the atria contract (about 0.1 sec), forcing blood into the ventricles, and continues as the ventricles contract (about 0.3 sec), forcing the atrioventricular (AV) valves closed and the semilunar valves open.
NOTE: The AV valves are opened by the weight of the blood in the atria. Therefore, most ventricular filling is accomplished prior to atrial contraction. This is why atrial fibrillation is not as immediately serious as ventricular fibrillation (though atrial fibrillation is an indicator of risk of stroke).

D. **Cardiac output** is about 75 mL per beat, or 5.25 liters per minute in the average person.

E. The "lub-dupp" sound of a beating heart is from the closing of the AV valves ("lub") and the closure of the semilunar valves ("dupp").

F. A heart murmur sounds like a quiet hiss to the trained ear and occurs when a valve malfunctions, allowing blood to squirt back into a preceding chamber.

Module 23.7 The pacemaker sets the tempo of the heartbeat.

A. The **pacemaker** is a specialized region of cardiac muscle in the wall of the right atrium, also known as the **sinoatrial (SA) node** (Figure 23.7).

B. When the SA node contracts, it sends out electrical signals, first to the atria, making them contract, and then to the **AV (atrioventricular node),** which acts as a relay.
NOTE: The relay function of the AV node is needed because the atria and ventricles are separated by nonconductive connective tissue. Also note that the conduction system of the ventricles is more extensive than that of the atria.

C. The signals are delayed 0.1 sec in the AV node and then travel along specialized muscle fibers to the cardiac muscles of the ventricles, causing them to contract.

D. The SA node sets the normal rate of contractions. The brain also can send signals to modify the basic rate, depending on body activity.

E. If the pacemaker does not function correctly, an **artificial pacemaker** can be implanted next to the heart. This provides a regular electrical signal to trigger the beat.
Preview: The medulla oblongata is also involved in the regulation of heart rate (Module 28.15).

Module 23.8 Connection: What is a heart attack?

A. A **heart attack** is the death of cardiac muscle cells and the resulting failure of the heart to deliver enough blood to the rest of the body. Heart attacks follow clogging of the coronary arteries, blocking blood flow to regions of cardiac muscle (Figure 23.8A).
Review: Dietary influence (Module 21.20) and the influence of smoking (Module 22.7) on cardiovascular fitness.

B. Such clogs occur if blood clots back up behind constrictions (due to lipid buildup) in these arteries.

C. Cardiac muscle cells do not regenerate but leave noncontracting scar tissue.

D. The sudden onset of a heart attack (aka myocardial infarction, or MI) takes the patient by surprise because the build up of plaques on the inner epithelial lining of the artery **(atherosclerosis)** is insidious. Plaques are composed of lipids and appear for a variety of reasons (Module 21.20, Module 9.9, and Module 3.9).

E. Lifestyle changes can reduce the risk of heart disease. Increase exercise, lower fat intake, increase fruits and vegetables and don't smoke.

F. Relief to heart disease patients includes coronary artery bypass surgery, and angioplasty and laser surgery to open up constricted coronary arteries.

G. **Cardiovascular disease** has decreased somewhat (50% in the last 50 years) as a result of increased awareness of the roles of diet and exercise in health, early diagnosis of problems, and the availability of automatic external defibrillators (AED) and trained personnel to help in emergencies.

Module 23.9 Blood exerts pressure on vessel walls.

Preview: The hypothalamus plays a role in the regulation of blood pressure (Module 28.15).

A. **Pulse** is the rhythmic stretching of the arteries caused by the pressure of blood from the heart during systole.

B. **Blood pressure** is caused by the pumping of the heart against the resistance offered by smaller vessels in the tissues supplied with blood.

C. Blood pressure is greatest in the aorta and decreases along the path back to the venae cavae (Figure 23.9A). Blood pressure depends on several factors, such as physical and emotional stress, and is controlled by changes in hormone levels and arteriole constriction and dilation.

D. Velocity decreases sequentially into the capillaries, and then increases in the pattern shown because of frictional resistance and because the cross-sectional area of the capillary beds is greater than that of larger vessels.

E. Blood pressure in veins is near zero, but blood returns to the heart with the aid of muscular contraction, valves, and the lifting of the chest cavity during breathing (Figure 23.9B).

Module 23.10 Connection: Measuring blood pressure can reveal cardiovascular problems.

A. A blood pressure of 120/70 indicates that the force of the heart's beat during systole is 120 mm of mercury (mm Hg) and the general background pressure of the blood in arteries during diastole is 70 mm Hg. Optimal blood pressure ($<$120/80) is an indication of a healthy cardiovascular system. Conversely, abnormal blood pressure (too high or too low) is an indication of cardiovascular disease.
NOTE: Normal blood pressure is usually considered to be 120/80. Blood pressure slightly lower than this may be an indicator of good cardiovascular fitness. Healthy young females tend to have blood pressures ≈8–10 mm Hg less than this.

B. Blood pressure is measured with a sphygmomanometer. Pressure of the cuff cuts off the blood flow in outer arteries (no pulse is heard). Pressure is reduced in the cuff until the force of systole first pushes blood through (the turbulent sounds of blood flow are heard). Further reduction in the cuff's pressure reaches a point where the sounds of turbulent blood flow are no longer heard; this marks diastole (Figure 23.10 and Figure 23.9A).
NOTE: The sounds that are heard when measuring blood pressure are referred to as Korotkoff sounds.

C. Low blood pressure is a persistent systolic blood pressure below 100. This is usually not dangerous, but may result from poor nutrition or glandular disorders.

D. High blood pressure (hypertension) is a persistent blood pressure of $>$140/90. It makes the heart work harder against greater resistance due to blockages and reduced flexibility.

E. **Hypertension** is called the silent killer because its damaging effects take many years to be clinically apparent. Once the damage is done, it is often too late to fix the problem. Hypertension-related diseases include heart failure, stroke, heart attack, and kidney failure.

F. Causes of hypertension can be difficult to diagnose; however, in spite of a predisposition for hypertension, one can reduce the risk factors by changes in lifestyle:

1. Eat a heart-healthy diet.
2. Lose excess weight and maintain the ideal body weight once obtained.
3. Exercise several times each week.
4. Do not smoke or indulge in excessive drinking.

If these lifestyle changes fail to reduce blood pressure readings, then medication may help.

Module 23.11 Smooth muscle controls the distribution of blood.

Review: Types of muscle, including smooth muscle, are discussed in Module 20.6.

A. In all tissues except the brain, liver, kidneys, and heart, blood supply varies greatly.

B. Arteriole constriction can reduce the flow to capillaries. This flow is under the control of nerves and hormones.

C. In another mechanism, some blood flows through the center of a capillary bed, but precapillary sphincter muscles control the passage of most blood into the bed. For example, after a meal, precapillary sphincters let more blood pass into the capillaries that supply the villi of the small intestine (Figure 23.11).
NOTE: At the same time, blood supply may be diverted from the outer extremities. Thus, on a cold day, you will feel extra chilled after a meal.

Module 23.12 Capillaries allow the transfer of substances through their walls.

A. *Review:* Movement of materials across membranes by diffusion, endocytosis, and osmosis (Modules 5.14, 5.15, 5.17, and 5.19).

B. Capillaries are the only vessels with walls thin enough to allow transfer of substances though the epithelium (Figure 23.12A).

C. Some substances simply diffuse across the capillary wall to and from blood and interstitial fluid; others are moved across by exocytosis.

D. Water and some small molecules (salts, sugars, and O_2) "leak" through small cracks between the epithelial cells surrounding capillaries.
Preview: This fluid is returned to the cardiovascular system via the lymphatic system (Module 24.3).

E. Blood pressure tends to actively force fluid out of capillaries. Osmosis (Module 5.15) tends to cause fluids to move in. At the arterial ends of capillary beds, blood pressure is relatively higher, and at the venous ends, osmotic pressure is higher (Figure 23.12B).

III. Structure and Function of Blood

Module 23.13 Blood consists of cells suspended in plasma.

A. An average adult human contains 4–6 liters of blood (Figure 23.13).

B. About 45% of blood is cellular (red and white blood cells and **platelets**).

C. About 55% of blood is **plasma,** of which 90% is water and 10% dissolved molecules. Ions of salts and albumin maintain osmotic balance and pH and regulate the permeability of membranes. Proteins help in blood clotting and are important in body defense, among other things (such as transport of substances).

D. *Preview:* The function of these important immune system proteins is covered in Chapter 24.

Module 23.14 Red blood cells transport oxygen.

A. **Erythrocytes (red blood cells)** are the most numerous blood cell type; there are about 25 trillion present at one time in the average person. They are formed in the bone marrow and lose their nuclei as they develop. Each cell circulates about 3–4 months before being removed by the spleen; the molecules are recycled in the liver.

B. The biconcave-disk structure of red blood cells provides for a maximum ratio of surface area to volume, allowing maximum gas exchange.

C. Each red blood cell contains about 250 million molecules of hemoglobin.

D. *Review:* The function of red blood cells in exchanging and carrying gases (Modules 22.10, 22.11).

E. Low levels of hemoglobin or number of red blood cells is known as **anemia.** A person who is anemic feels tired with no energy. There are a variety of causes for anemia, the most common of which is iron deficiency. Iron deficiency can usually be treated with iron supplements.

F. Red blood cell production is under the control of a negative-feedback mechanism that is sensitive to the amount of oxygen reaching tissues. This mechanism is mediated by production of the hormone erythropoietin (EPO) in the kidneys.

G. Kidney dialysis patients often receive EPO shots to stimulate RBC production. In an effort to improve performance, athletes take injections of EPO; however, the consequences can be lethal.

Module 23.15 White blood cells help defend the body.

A. Five types of **leukocytes (white blood cells)** are distinguished by nuclear shape and staining properties. They are also produced in the bone marrow. As a group, they spend most of their time outside the circulatory system fighting infections and preventing cancer cells from growing (Figure 23.13).

B. Basophils help fight infections by releasing chemicals (e.g., histamines).

C. Neutrophils and monocytes are **phagocytic** cells that move into tissues, searching out and "eating" foreign bacteria and other debris. When a monocyte moves out of the blood, it is called a macrophage.

D. Eosinophils are phagocytic cells that search out parasitic protozoans and worms and may help reduce allergy attacks.
Preview: These, and other white blood cells, are discussed in Module 24.1.

E. Lymphocytes, some of which produce antibodies, are key cells in the immune process (see Chapter 24).

Module 23.16 Blood clots plug leaks when blood vessels are injured.

A. The blood-clotting mechanism involves materials carried in the blood: platelets, the plasma protein **fibrinogen,** and clotting factors.
NOTE: Blood clotting also requires Ca^{2+}.

B. Minor damage to a blood vessel exposes connective tissue to blood. Platelets adhere to this tissue and release a substance that makes nearby platelets sticky. If major damage occurs, a chain of enzymatically regulated reactions forms a more complex plug, a fibrin clot (Figure 23.16A).

C. The platelet clot activates a protein, prothrombin, converting it to the enzyme thrombin, which in turn converts fibrinogen into the threadlike protein **fibrin.** These threads trap additional blood cells (Figure 23.16B).

NOTE: Blood clotting is one of the few examples of a positive feedback mechanism, another being labor (Module 27.18).

D. Hemophilia is an inherited disease in which individuals lack this mechanism (Modules 9.23).

Module 23.17 Connection: Stem cells offer a potential cure for leukemia and other blood cell diseases.

A. White blood cells, red blood cells, and platelets all arise in the bone marrow from **stem cells** (Figure 23.17).

B. **Leukemia** is cancer of the bone marrow cells that produce white blood cells. The leukocytes are in abnormally high numbers, and these in turn may interfere with red blood cell production, causing the person to be anemic.

NOTE: Leukemia also has adverse effects on the immune system (Chapter 24).

C. Standard treatment for leukemia involves radiation and chemotherapy (Module 8.10) or bone marrow replacement (following radiation, removal, and the introduction of donor marrow). Bone marrow replacement requires the patient to be on lifelong treatment with drugs that suppress the rejection of transplanted cells. Such drugs are not selective and suppress all immune function, making individuals who take these drugs more susceptible to infections.

D. A potential variation on the latter treatment involves a technique to remove and purify bone marrow from a patient with leukemia, isolating the stem cells. These are then reintroduced in bone marrow that has been radiated to kill off all cancerous leukocytes. Since these are the patient's own cells, there is no risk of rejection.

E. Three methods are commonly used to harvest stem cells:

1. Bone marrow aspiration
2. Chemically induced stem cell migration to the blood
3. Stem cell harvesting from a placenta

F. Regardless of the method used, stem cells are powerful cells and can completely repopulate a patient's immune system as well as have other applications. The medical implications are far reaching.

Class Activities

1. To see the effect of the unidirectional valves in veins, let an arm hang down the side of the body. After a short period of time, the veins will be visibly filled with blood. Raise the arm above the head, and the veins will empty of blood.
2. Do the classic: Have the students trace the path of a red blood cell through the body. You can divide the class into groups and give each group a different starting point. Perhaps you can reward the group that comes up with the shortest route, the longest route, or that finds the most alternative routes.
3. Challenge your students to try and think of blood vessels, other than pulmonary vessels, where veins carry oxygenated blood and arteries carry deoxygenated blood.

Transparency Acetates

Figure 23.1B	Diffusion between blood and tissue cells
Figure 23.2A	The gastrovascular cavity (salmon color) in a jelly
Figure 23.2B	The open circulatory system (vessels in gold) in a grasshopper
Figure 23.2C	The closed circulatory system in a fish
Figure 23.3A	Diagram of the cardiovascular system of a fish
Figure 23.3B	Diagram of the cardiovascular system of a mammal
Figure 23.4A	Blood flow through the human heart
Figure 23.4B	Blood flow through the human cardiovascular system
Figure 23.5	Structural relationships of blood vessels
Figure 23.6	The cardiac cycle
Figure 23.7	Control of the heart's rhythm (top) and electrocardiogram (bottom)
Figure 23.8A	Blockage of a coronary artery, resulting in a heart attack
Figure 23.9A	Blood pressure and velocity in the blood vessels
Figure 23.9B	Blood flow in a vein
Figure 23.10	Measuring blood pressure (Layer 1)
Figure 23.10	Measuring blood pressure (Layer 2)
Figure 23.10	Measuring blood pressure (Layer 3)
Figure 23.11	The control of capillary blood flow by precapillary sphincters
Figure 23.12A	A capillary in cross section
Figure 23.12B	The movement of fluid into and out of a capillary
Figure 23.13	The composition of blood
Figure 23.16A	The blood-clotting process

Media

See the beginning of this book for a complete description of all media available for instructors and students. Animations and videos are available in the Campbell Image Presentation Library. Media Activities and Thinking as a Scientist investigations are available on the student CD-ROM and web site.

Activities and Thinking as a Scientist	Module Number
Web/CD Activity 23A: *Mammalian Cardiovascular System Structure*	23.4
Web/CD Activity 23B: *Path of Blood Flow in Mammals*	23.4
Web/CD Activity 23C: *Mammalian Cardiovascular System Function*	23.9
Web/CD Thinking as a Scientist: *Connection: How Is Cardiovascular Fitness Measured?*	23.10
Biology Labs On-Line: *CardioLab*	23.10
Biology Labs On-Line: *HemoglobinLab*	23.14