

Anatomy and Physiology of the Cardiovascular System

OUTLINE

Introduction

The Heart

Structures of the Heart

Conduction System

Functions of the Heart

The Blood Vessels and Circulation

Blood Vessels

Blood Pressure

Blood Circulation

Summary

Critical Thinking

Websites

Review Questions

OBJECTIVES

After reading this chapter, readers should be able to:

1. Describe the organization of the cardiovascular system and the heart.
2. Identify the layers of the heart wall.
3. Describe the general features of the heart.
4. Answer the question of why the left ventricle is more muscular than the right ventricle.
5. Describe the components and functions of the conducting system of the heart.
6. Explain the events of the cardiac cycle.
7. Define cardiac output and stroke volume.
8. Distinguish among the types of blood vessels, their structures, and their functions.
9. Identify the major arteries and veins of the pulmonary circuit as well as the areas they serve.
10. Describe the hepatic portal system.

KEY TERMS

Aorta: The largest artery in the body, the aorta originates from the left ventricle of the heart and extends down to the abdomen, where it branches off.

Aortic arch: The second section of the aorta; it branches into the brachiocephalic trunk, left common carotid artery, and left subclavian artery.

Aortic valve: Located at the base of the aorta, the aortic valve has three cusps and opens to allow blood to leave the left ventricle during contraction.

Arteries: Elastic vessels able to carry blood away from the heart under high pressure.

Arterioles: Subdivisions of arteries; they are thinner and have muscles that are innervated by the sympathetic nervous system.

Atria: The upper chambers of the heart; they receive blood returning to the heart.

Atrioventricular node (AV node): A mass of specialized tissue located in the inferior interatrial septum beneath the endocardium; it provides the only normal conduction pathway between the atrial and ventricular syncytia.

AV bundle: The bundle of His; a large structure that receives the cardiac impulse from the distal AV node. It enters the upper part of the interventricular septum.

Blood volume: The sum of formed elements and plasma volumes in the vascular system; most adults have about 5 L of blood.

Capillaries: The smallest-diameter blood vessels, which connect the smallest arterioles to the smallest venules.

Cardiac conduction system: The initiation and distribution of impulses through the myocardium that coordinates the cardiac cycle.

Cardiac cycle: A heartbeat; it consists of a complete series of systolic and diastolic events.

Cardiac output: The volume discharged from the ventricle per minute, calculated by multiplying stroke volume by heart rate, in beats per minute.

Cardiac veins: Those veins that branch out and drain blood from the myocardial capillaries to join the coronary sinus.

Carotid sinuses: Enlargements near the base of the carotid arteries that contain baroreceptors and help to control blood pressure.

KEY TERMS CONTINUED

Cerebral arterial circle: The circle of Willis; it connects the vertebral artery and internal carotid artery systems.

Chordae tendineae: Strong fibers originating from the papillary muscles that attach to the cusps of the tricuspid valve.

Coronary arteries: The first two aortic branches, which supply blood to the heart tissues.

Coronary sinus: An enlarged vein joining the cardiac veins; it empties into the right atrium.

Diastole: The relaxation of a heart structure.

Diastolic pressure: The lowest pressure that remains in the arteries before the next ventricular contraction.

Electrocardiogram (EKG): The recording of electrical changes in the myocardium during the cardiac cycle. The EKG machine works by placing nodes on the skin that connect via wires and respond to weak electrical changes of the heart. The abbreviation EKG is more commonly used than ECG.

Endocardium: The inner layer of the heart wall.

Epicardium: The outer layer of the heart wall.

Functional syncytium: A mass of merging cells that functions as a unit.

Hepatic portal system: The veins that drain the abdominal viscera, originating in the stomach, intestines, pancreas, and spleen, to carry blood through a hepatic portal vein to the liver.

Inferior vena cava: Along with the superior vena cava, one of the two largest veins in the body; it is formed by the joining of the common iliac veins.

Mitral valve: The bicuspid valve; it lies between the left atrium and left ventricle, preventing blood from flowing back into the left atrium from the ventricle.

Myocardium: The thick middle layer of the heart wall that is mostly made of cardiac tissue.

Pacemaker: The term used to refer to the sinoatrial node (SA node).

Papillary muscles: Those muscles that contract as the heart's ventricles contract, pulling on the chordae tendineae to prevent the cusps from swinging back into the atrium.

Pericardium: A membranous structure that encloses the heart and proximal ends of the large blood vessels and that consists of double layers.

Peripheral resistance: A force produced by friction between blood and blood vessel walls.

Pulmonary circuit: The venules and veins, which send deoxygenated blood to the lungs to receive oxygen and unload carbon dioxide.

Pulmonary valve: Lying at the base of the pulmonary trunk, this valve has three cusps and allows blood to leave the right ventricle while preventing backflow into the ventricular chamber.

Purkinje fibers: Consisting of branches of the AV bundle that spread and enlarge, these fibers are located near the papillary muscles; they continue to the heart's apex and cause the ventricular walls to contract in a twisting motion.

Septum: A solid, wall-like structure that separates the left atria and ventricle from the right atria and ventricle.

Sinoatrial node (SA node): A small mass of specialized tissue just beneath the epicardium in the right atrium that initiates impulses through the myocardium to stimulate contraction of cardiac muscle fibers.

Stroke volume: The volume of blood discharged from the ventricle with each contraction; it is usually about 70 mL.

Superior vena cava: Along with the inferior vena cava, one of the two largest veins in the body; the superior vena cava is formed by the joining of the brachiocephalic veins.

Systemic circuit: The arteries and arterioles, which send oxygenated blood and nutrients to the body cells while removing wastes.

Systole: The contraction of a heart structure.

Systolic pressure: The maximum pressuring during ventricular contraction.

Thyrocervical arteries: Those that branch off to the thyroid and parathyroid glands, larynx, trachea, esophagus, pharynx, and muscles of the neck, shoulder, and back.

Tricuspid valve: Lying between the right atrium and ventricle, this valve allows blood to move from the right atrium into the right ventricle while preventing backflow.

Vasoconstriction: The contraction of blood vessels, which reduces their diameter.

Vasodilation: The relaxation of blood vessels, which increases their diameter.

Veins: Blood vessels that carry blood back to the atria; they are less elastic than arteries.

Ventricles: The lower chambers of the heart; they receive blood from the atria, which they pump out into the arteries.

Venules: Microscopic vessels that link capillaries to veins.

Vertebral arteries: One of the main divisions of the subclavian and common carotid arteries; the vertebral arteries run upward through the cervical vertebrae into the skull and supply blood to the vertebrae, their ligaments, and their muscles.

Viscosity: Thickness or stickiness; the resistance of fluid to flow. In a biologic fluid, viscosity is caused by the attraction of cells to one another.

Introduction

The human heart pumps blood through the arteries, which connect to smaller arterioles and then even smaller capillaries. It is here that nutrients, electrolytes, dissolved gases, and waste products are exchanged between the blood and surrounding tissues. The capillaries are thin-walled vessels interconnected with the smallest arteries and smallest veins.

Approximately 7,000 L of blood is pumped by the heart every day. In an average person's life, the heart will contract about 2.5 billion times.

Blood flow throughout the body begins its return to the heart when the capillaries return blood to the venules and then to the larger veins. The cardiovascular system, therefore, consists of a closed circuit: the heart, arteries, arterioles, capillaries, venules, and veins (see **Figure 5–1**). The venules

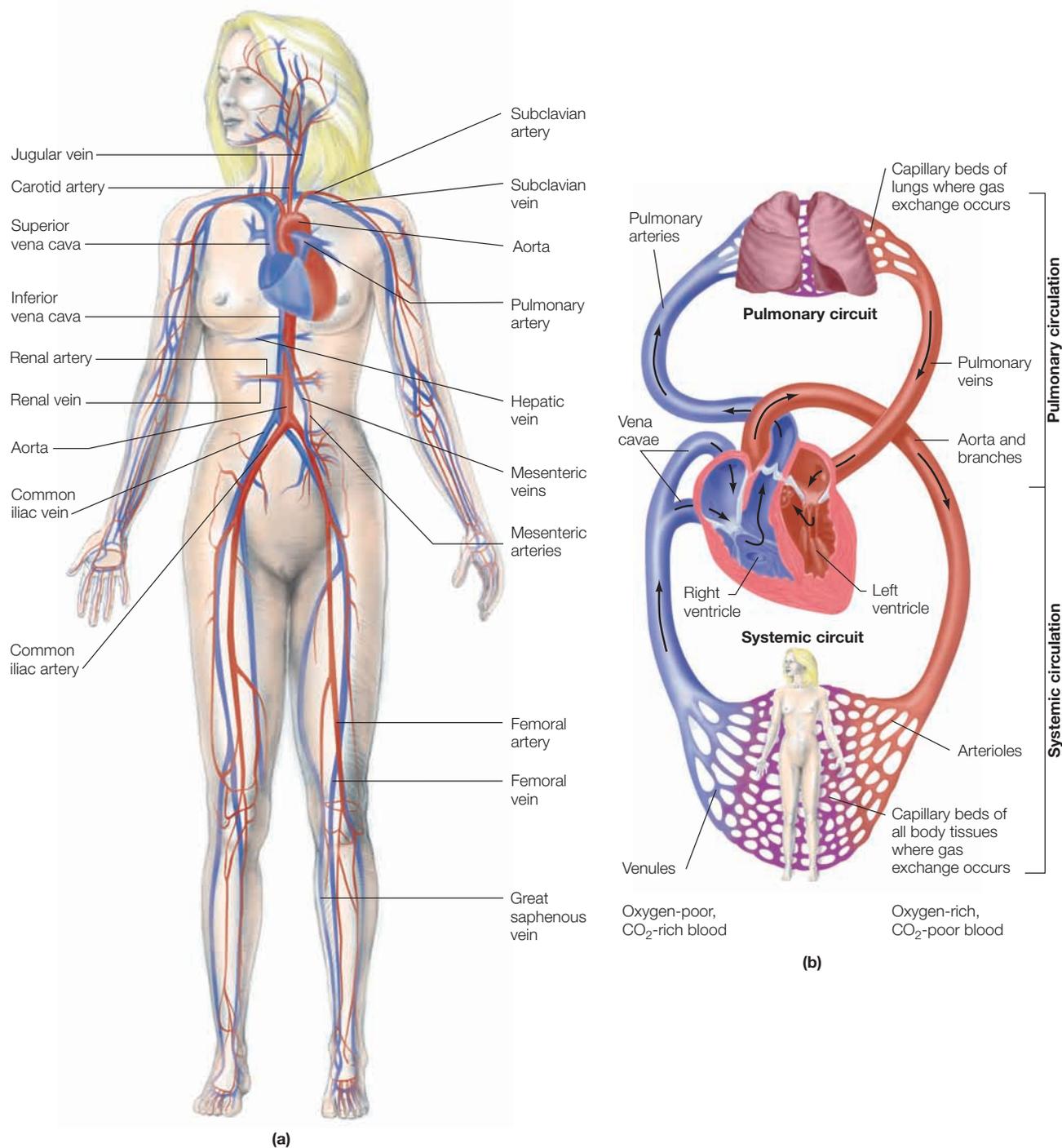


Figure 5-1 The circulatory system. (a) The circulatory system consists of a series of vessels that transport blood to and from the heart, the pump. (b) The circulatory system has two major circuits: the pulmonary circuit, which transports blood to and from the lungs, and the systemic circuit, which transports blood to and from the body (excluding the lungs).

and veins are part of the **pulmonary circuit** because they send deoxygenated blood to the lungs to receive oxygen and unload carbon dioxide. The arteries and arterioles are part of the **systemic circuit** because they send oxygenated blood and nutrients to the body cells while removing wastes. All body tissues require circulation to survive.

The Heart

The human *heart* is a muscular organ containing four chambers that is situated just to the left of the midline of the thoracic cavity. It is approximately the size of a man's closed fist. The upper two chambers (**atria**) are divided by a wall-

like structure called the *interatrial septum*. The lower two chambers (**ventricles**) are divided by a similar structure called the *interventricular septum*. Between each atrium and ventricle, valves allow blood to flow in one direction, preventing backflow.

Blood flow through the heart is shown in **Figure 5–2**. Blood that is low in oxygen flows into the right atrium from the veins known as the **superior vena cava** and **inferior vena cava**. The superior vena cava carries blood from the head, neck, chest, and arms. The inferior vena cava carries blood from the remainder of the trunk and the legs. Blood in the right atrium then flows through the **right atrioventricular (tricuspid) valve** into the right ventricle. From here it begins the **pulmonary circuit**, with deoxygenated blood flowing into the right and left pulmonary arteries and their smaller branches. The blood becomes oxygenated while moving through the lungs' capillary beds. Also in this part of the system, carbon dioxide is released.

Structures of the Heart

The heart lies inside the thoracic cavity, resting on the diaphragm. It is hollow and cone-shaped, varying in size. The heart is within the mediastinum in between the lungs. Its posterior border is near the vertebral column, and its anterior border is near the sternum.

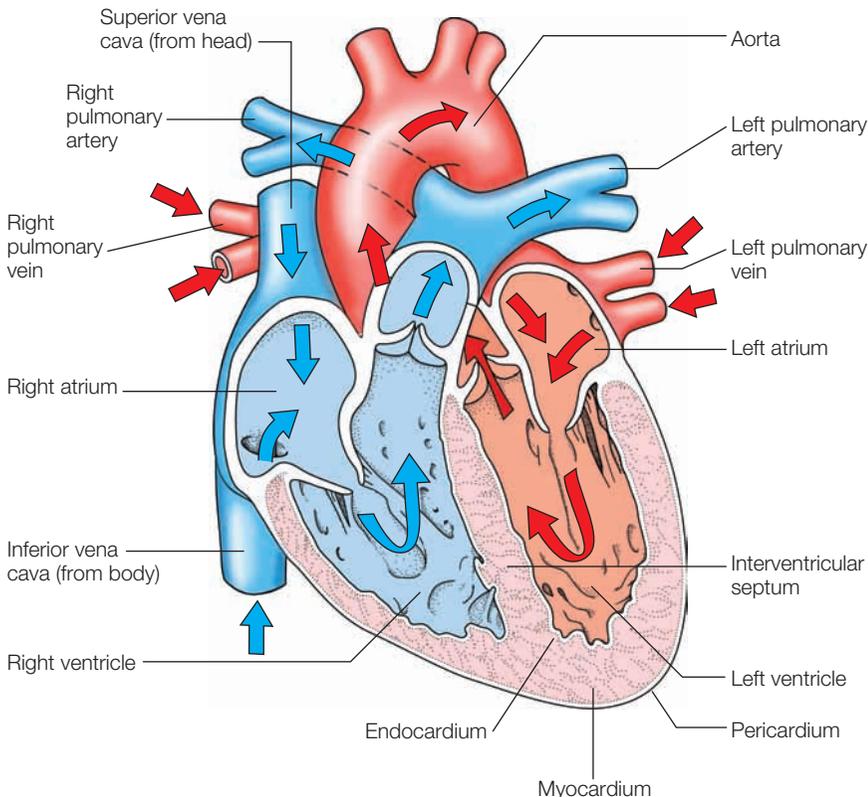


Figure 5–2 Blood flow through the heart. Deoxygenated (carbon-dioxide-enriched) blood (blue arrows) flows into the right atrium from the systemic circulation and is pumped into the right ventricle. The blood is then pumped from the right ventricle into the pulmonary artery, which delivers it to the lungs. In the lungs, the blood releases its carbon dioxide and absorbs oxygen. Reoxygenated blood (red arrows) is returned to the left atrium, then flows into the left ventricle, which pumps it to the rest of the body through the systemic circuit.

An average adult has a heart that is about 14 cm long by 9 cm wide. The *base* of the heart is actually the upper portion, where it is attached to several large blood vessels. This portion lies beneath the second rib. The distal end of the heart extends downward, to the left, ending in a blunt point called the *apex*, which is even with the fifth intercostal space.

The three layers comprising the wall of the heart are the outer **pericardium**, middle **myocardium**, and inner **endocardium** (see Figure 5–2). The pericardium consists of connective tissue and some deep adipose tissue, and it protects the heart by reducing friction. The thick **myocardium** is mostly made of cardiac muscle tissue that is organized in planes and richly supplied by blood capillaries, lymph capillaries, and nerve fibers. It pumps blood out of the chambers of the heart. The **endocardium** is made up of epithelium and connective tissue with many elastic and collagenous fibers. It also contains blood vessels and specialized cardiac muscle fibers known as **Purkinje fibers**.

The inside of the heart is divided into four hollow chambers, with two on the left and two on the right. The upper chambers are called **atria** and receive blood returning to the heart. They have *auricles*, which are small projections that extend anteriorly. The lower chambers are called **ventricles** and receive blood from the atria, which they pump out into the arteries (see Figure 5–2). The left atria and ventricle are separated from the right atria and ventricle by a solid wall-

like structure (**septum**). This keeps blood from one side of the heart from mixing with blood from the other side (except in a developing fetus). The atrioventricular valve (AV valve), which consists of the **mitral valve** on the left and the **tricuspid valve** on the right, ensures one-way blood flow between the atria and ventricles.

The right atrium receives blood from two large veins called the superior vena cava and the inferior vena cava as well as a smaller vein (the **coronary sinus**), which drains blood into the right atrium from the heart's myocardium. The tricuspid valve has projections (*cusps*) and lies between the right atrium and ventricle. This valve allows blood to move from the right atrium into the right ventricle while preventing backflow. The cusps of the tricuspid valve are attached to strong fibers called **chordae tendineae**, which originate from small **papillary muscles** that project inward from the ventricle walls. These muscles contract as the ventricle contracts. When the tricuspid valve closes, they pull on the chordae tendineae to prevent the cusps from swinging back into the atrium.

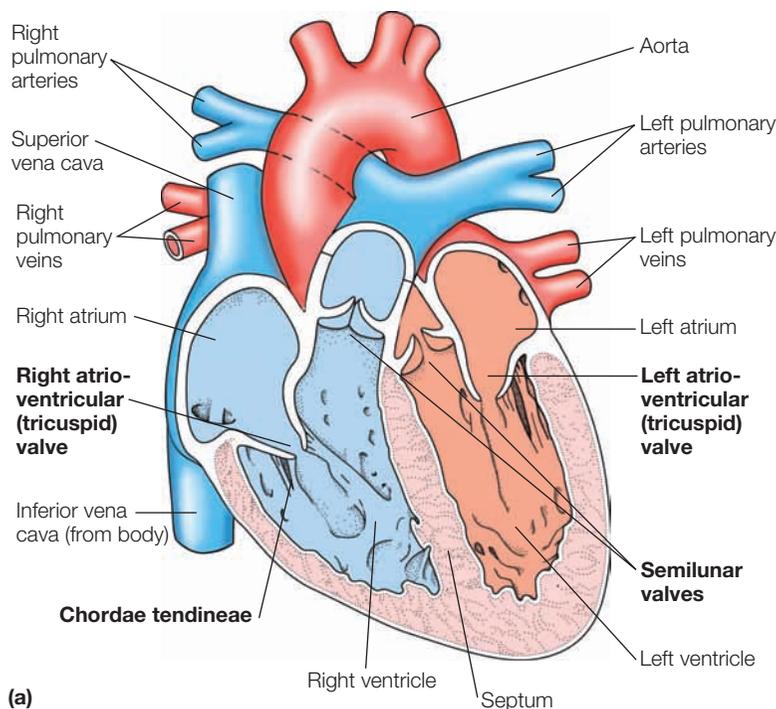
The right ventricle's muscular wall is thinner than that of the left ventricle, as it only pumps blood to the

lungs with a low resistance to blood flow. The left ventricle is thicker because it must force blood to all body parts, with a much higher resistance to blood flow. As the right ventricle contracts, its blood increases in pressure to passively close the tricuspid valve. Therefore, this blood can only exit through the *pulmonary trunk*, which divides into the left and right *pulmonary arteries* that supply the lungs. At the trunk's base, there is a **pulmonary valve** with three cusps that allow blood to leave the right ventricle while preventing backflow into the ventricular chamber (see **Figure 5–3**).

Four *pulmonary veins* (two from each of the lungs) supply the left atrium with blood. Blood passes from the left atrium into the left ventricle through the mitral valve (bicuspid valve), preventing blood from flowing back into the left atrium from the ventricle. Like the tricuspid valve, the papillary muscles and chordae tendineae prevent the mitral valve's cusps from swinging back into the left atrium when the ventricle contracts. The mitral valve closes passively, directing blood through the large artery known as the **aorta**.

At the base of the aorta is the **aortic valve**, with three cusps. This valve opens to allow blood to leave the left ventricle during contraction. When the ventricle relaxes, the valve closes to prevent blood from backing up into the ventricle. The mitral and tricuspid valves are known as atrioventricular valves because they lie between the atria and ventricles. The pulmonary and aortic valves have “half-moon” shapes and are therefore referred to as *semilunar valves*. **Table 5–1** summarizes the various heart valves.

The right atrium receives low-oxygen blood through the vena cava and coronary sinus. As the right atrium contracts, the blood passes through the tricuspid valve into the right ventricle (see **Figure 5–3**). As the right ventricle contracts, the tricuspid valve closes. Blood moves through the pulmonary valve into the pulmonary trunk and pulmonary arteries. It then enters the capillaries of the alveoli of the lungs, where gas exchanges occur. This freshly oxygenated blood then returns to the heart through the pulmonary veins, into the left atrium.



(a)



(b)

Figure 5–3 Heart valves. (a) A cross-section of the heart showing the four chambers and the location of the major vessels and valves. (b) Photograph of chordae tendineae.

The left atrium contracts, moving blood through the mitral valve into the left ventricle. When the left ventricle contracts, the mitral valve closes. Blood moves through the aortic valve into the aorta and its branches. The first two aortic branches are called the right and left **coronary arteries**.

Table 5–1 The Heart Valves

Heart Valve	Location	Action
Tricuspid valve	Between right atrium and right ventricle	During ventricular contraction, it prevents blood from moving from right ventricle into right atrium.
Pulmonary valve	At entrance to pulmonary trunk	During ventricular relaxation, it prevents blood from moving from pulmonary trunk into right ventricle.
Mitral (bicuspid) valve	Between left atrium and left ventricle	During ventricular contraction, it prevents blood from moving from left ventricle into left atrium.
Aortic valve	At entrance to aorta	During ventricular relaxation, it prevents blood from moving from aorta into left ventricle.

They supply blood to the heart tissues, with openings lying just beyond the aortic valve.

The body tissues require continual beating of the heart because they need freshly oxygenated blood to survive. Coronary artery branches supply many capillaries in the myocardium. These arteries have smaller branches with connections called *anastomoses* between vessels providing alternate blood pathways (*collateral circulation*). These pathways may supply oxygen and nutrients to the myocardium when blockage of a coronary artery occurs. Branches of the **cardiac veins** drain blood from the myocardial capillaries, joining an enlarged vein, the coronary sinus, which empties into the right atrium.

Conduction System

Strands and clumps of specialized cardiac muscle contain only a few myofibrils and are located throughout the heart. These areas initiate and distribute impulses through the myocardium, comprising the **cardiac conduction system** that coordinates the **cardiac cycle** (see **Figure 5–4**). The **sinoatrial node (SA node)** is a small mass of specialized tissue just beneath the **epicardium**, in the right atrium. It is located near the opening of the superior vena cava, with fibers continuous with those of the atrial syncytium.

The SA node's cells can reach threshold on their own, initiating impulses through the myocardium, stimulating contraction of cardiac muscle fibers. Its rhythmic activity occurs 70 to 80 times per minute in a normal adult. Since it generates the heart's rhythmic contractions, it is often referred to as the **pacemaker**.

The path of a cardiac impulse travels from the SA node into the atrial syncytium, and the atria begin to contract

almost simultaneously. The impulse passes along junctional fibers of the conduction system to a mass of specialized tissue called the atrioventricular node (AV node), located in the inferior interatrial septum, beneath the endocardium. The AV node provides the only normal conduction pathway between the atrial and ventricular syncytia. Impulses are slightly delayed due to the small diameter of the junctional fibers. The atria, therefore, have more time to contract and empty all of their blood into the ventricles before ventricular contraction occurs.

When the cardiac impulse reaches the distal AV node, it passes into a large **AV bundle (bundle of His)**, entering the upper part of the interventricular septum. Nearly half-way down the septum, these branches spread into enlarged Purkinje fibers, extending into the papillary muscles. They continue to the heart's apex, curving around the ventricles and passing over their lateral walls. The Purkinje fibers have numerous small branches that become continuous with cardiac muscle fibers and irregular *whorls*. Purkinje fiber stimulation causes the ventricular walls to contract in a twisting motion, to force blood into the aorta and pulmonary trunk.

An **electrocardiogram (EKG)** is used to record electrical changes in the myocardium during the cardiac cycle. Although ECG is the correct abbreviation for *electrocardiogram*, the abbreviation EKG is more commonly used. Because phlebotomists do not generally perform this procedure, it is not discussed in depth in this chapter. The most important ions that influence heart action are potassium and calcium. Excess extracellular potassium ions (*hyperkalemia*) decrease contraction rates and forces, while deficient extracellular potassium ions (*hypokalemia*) may cause a potentially life-

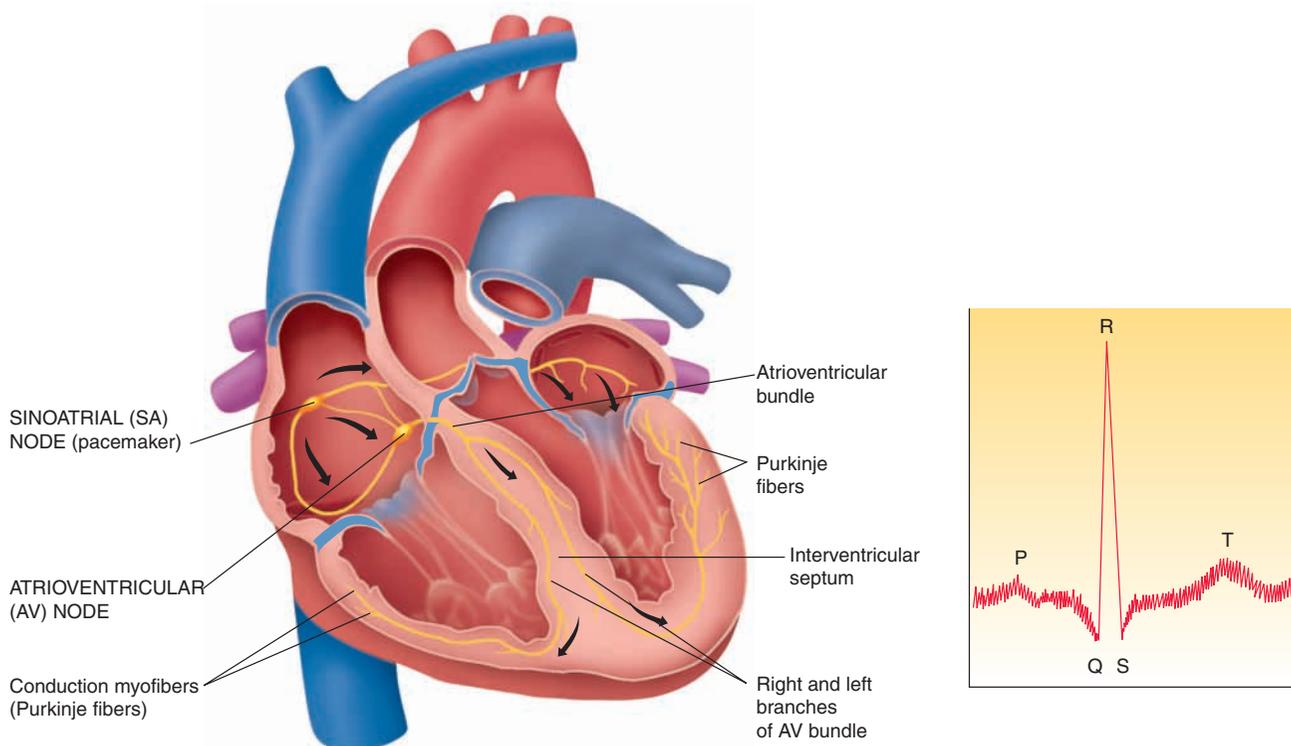


Figure 5–4 The cardiac conduction system. Also shown is a tracing of an EKG. The P wave corresponds to atrial depolarization, the QRS complex to ventricular depolarization, and the T wave to ventricular repolarization.

threatening abnormal heart rhythm (arrhythmia). Excess extracellular calcium ions (*hypercalcemia*) can cause the heart to contract for an abnormally long time, while low extracellular calcium ions (*hypocalcemia*) depress heart action.

Functions of the Heart

The heart chambers are coordinated so that their actions are effective. The atria contract (atrial **systole**) as the ventricles relax (ventricular **diastole**). Likewise, ventricles contract (ventricular systole) as atria relax (atrial diastole). Then a brief period of relaxation of both atria and ventricles occurs. This complete series of events makes up a heartbeat, also called a cardiac cycle.

One cardiac cycle causes pressure in the heart chambers to rise and fall and valves to open and close. Early during diastole, pressure in the ventricles is low, causing the AV valves to open and the ventricles to fill with blood. Nearly 70% of returning blood enters the ventricles before contraction. As the atria contract, the remaining 30% is pushed into the ventricles. As the ventricles contract, ventricular pressure rises. When ventricular pressure exceeds atrial pressure, the AV valves close and papillary muscles contract, preventing the cusps of the AV valves from bulging into the atria excessively. During ventricular contraction, the AV valves are closed, and atrial pressure is low. Blood flows into the atria while the ventricles are contracting, so that the atria are prepared for the next cardiac cycle.

As ventricular pressure exceeds pulmonary trunk and aorta pressure, the pulmonary and aortic valves open. Blood is ejected from the ventricles into these arteries, and ventricular pressure drops. When ventricular pressure is lower than in the aorta and pulmonary trunk, the semilunar valves close. When ventricular pressure is lower than atrial pressure, the AV valves open, and the ventricles begin to refill.

A heartbeat makes a characteristic double thumping sound when heard through a stethoscope. This is due to the vibrations of the heart tissues related to the valves closing. The first thumping sound occurs during ventricular contraction when the AV valves close. The second sound occurs during ventricular relaxation when the pulmonary and aortic valves close.

Cardiac muscle fibers are similar in function to skeletal muscle fibers, but are connected in branched networks. If any part of the network is stimulated, impulses are sent throughout the heart, and it contracts as a single unit. A **functional syncytium** is a mass of merging cells that functions as a unit. There are two of these structures in the heart: one in the atrial walls and another in the ventricular walls. A small area of the right atrial floor is the only part of the heart's muscle fibers that is not separated by the heart's fibrous skeleton. Here, cardiac conduction system fibers connect the atrial syncytium and the ventricular syncytium.

Newly oxygenated blood flows into the left and right pulmonary veins, returning to the left atrium (see Figure 5–3). Blood then flows through the *left atrioventricular (bicuspid or mitral) valve* into the left ventricle, passing through the *aortic semilunar valve* into the systemic circuit (via the *ascending aorta*). The systemic circuit moves blood to the body tissues, supplying their required oxygen. Should blood

flow backward at this point due to a valve malfunction, a *heart murmur* will result. To summarize, the right side of the heart pumps oxygen-poor blood to the lungs, and the left side pumps oxygen-rich blood toward the body tissues.

The contraction of the heart is called *systole*, and its relaxation is called *diastole*. The **systolic** blood pressure is the first number in a blood pressure reading, measuring the strength of contraction. The **diastolic** blood pressure is the second number in a blood pressure reading, measuring the strength of relaxation. The right ventricle does not need to pump blood with as much force as the left ventricle. This is so because the right ventricle supplies blood to the nearby lungs and the pulmonary vessels are wide and relatively short. This means that the walls of the right ventricle are thinner and less muscular than those of the left ventricle, which must pump blood to the entire body.

The Blood Vessels and Circulation

The blood vessels of the human body carry blood to every type of tissue and organ. Vessels decrease in size as they move away from the heart (arteries and arterioles), ending in the capillaries, and then increase in size as they move toward the heart (venules and veins). The largest artery in the body is the aorta, with the largest veins being the venae cavae, each being approximately 1 in wide.

Blood Vessels

There are five general classes of blood vessels in the cardiovascular system: arteries, arterioles, capillaries, venules, and veins (see **Figure 5–5**). **Arteries** are elastic vessels that are very strong, able to carry blood away from the heart under high pressure. They subdivide into thinner tubes that give rise to branched, finer **arterioles**. An artery's wall consists of three distinct layers, as shown in **Figure 5–6**. The innermost *tunica interna* is made up of a layer of simple squamous epithelium known as *endothelium*. It rests on a connective tissue membrane with many elastic, collagenous fibers. The endothelium helps prevent blood clotting and may also help in regulating blood flow. It releases nitric oxide to relax the smooth muscle of the vessel. Vein walls are similar but not identical to artery walls.

The middle *tunica media* makes up most of an arterial wall, including smooth muscle fibers and a thick elastic connective tissue layer. The outer *tunica externa (tunica adventitia)* is thinner, mostly made up of connective tissue with irregular fibers—it is attached to the surrounding tissues. Smooth artery and arteriole muscles are innervated by the sympathetic nervous system. *Vasomotor fibers* receive impulses to contract and reduce blood vessel diameter (**vasoconstriction**). When inhibited, the muscle fibers relax and the vessel's diameter increases (**vasodilation**). Changes in artery and arteriole diameters greatly affect blood flow and pressure.

Larger arterioles also have three layers in their walls, which get thinner as arterioles lead to capillaries. Very small arteriole walls only have an endothelial lining and some smooth muscle fibers, with a small amount of surrounding connective tissue.

The smallest-diameter blood vessels are **capillaries**, which connect the smallest arterioles to the smallest venules. The

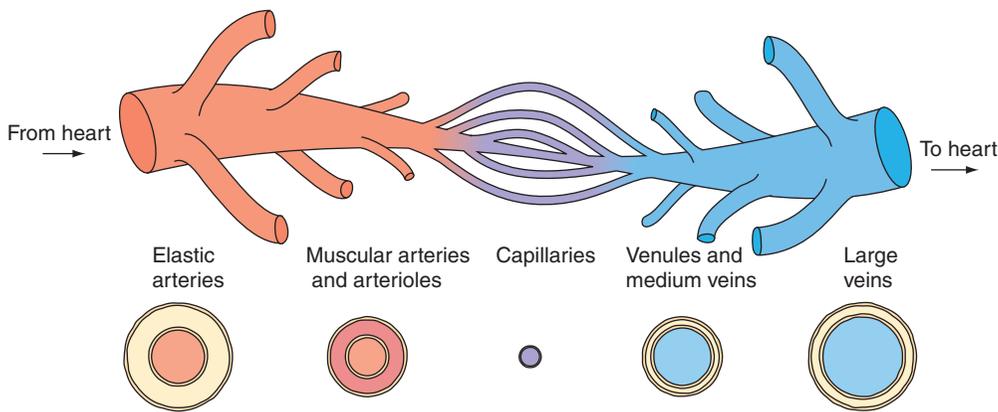


Figure 5-5 The structure and diameter of blood vessel walls

walls of capillaries are also composed of endothelium and form the semipermeable layer through which substances in blood are exchanged with substances in tissue fluids surrounding cells of the body.

Capillary walls have thin slits where endothelial cells overlap. These slits have various sizes, affecting permeability. Capillaries of muscles have smaller openings than those of the glands, kidneys, and small intestine. Tissues with higher metabolic rates (such as muscles) have many more capillaries than those with slower metabolic rates (such as cartilage).

Some capillaries pass directly from arterioles to venules while others have highly branched networks (see **Figure 5-7**). *Precapillary sphincters* control blood distribution through capillaries. Based on the demands of cells, these sphincters constrict or relax so that blood can follow specific pathways to meet tissue cellular requirements.

Gases, metabolic by-products, and nutrients are exchanged between capillaries and the tissue fluid surrounding body

cells. Capillary walls allow the diffusion of blood with high levels of oxygen and nutrients. They also allow high levels of carbon dioxide and other wastes to move from the tissues into the capillaries. Plasma proteins usually cannot move through the capillary walls due to their large size, so they remain in the blood. Blood pressure generated when capillary walls contract provides force for filtration via hydrostatic pressure.

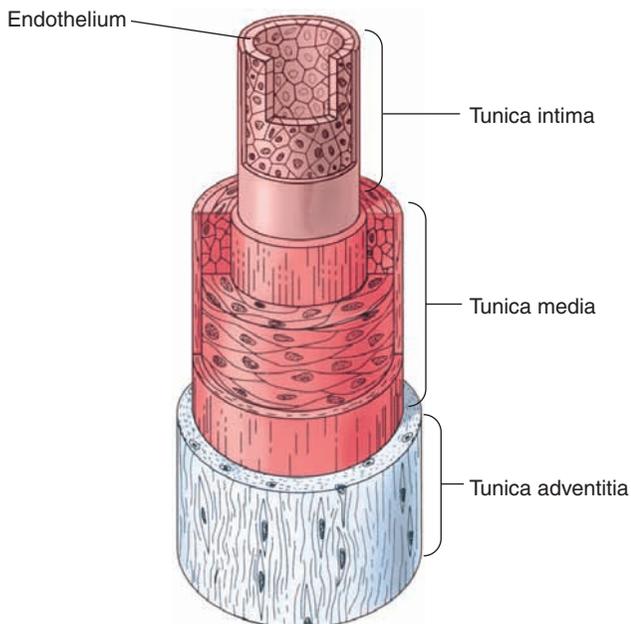


Figure 5-6 General structure of the blood vessel. The artery shown here consists of three major layers, the tunica intima, tunica media, and tunica adventitia.

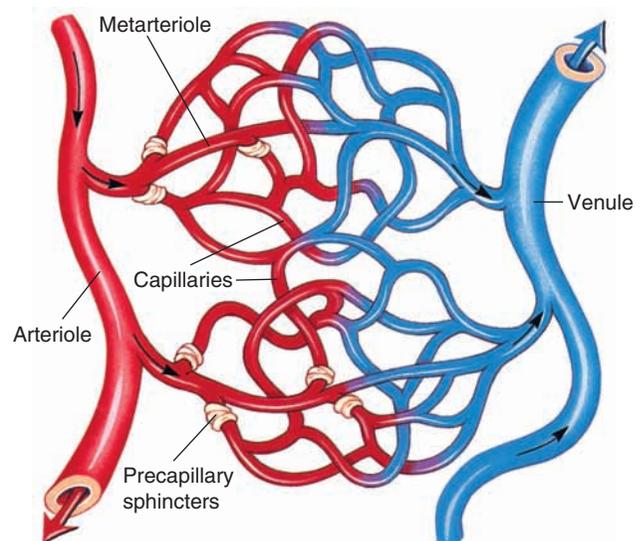


Figure 5-7 Similar to the way roadways are designed, larger arterioles and venules are interconnected with smaller capillaries.

Blood pressure is strongest when blood leaves the heart and weaker as the distance from the heart increases because of friction (peripheral resistance) between the blood and the vessel walls. Therefore, blood pressure is highest in the arteries, less so in the arterioles, and lowest in the capillaries. Filtration occurs mostly at the arteriolar ends of capillaries because the pressure is higher than at the venular ends. Plasma proteins trapped in capillaries create an osmotic pressure that pulls water into the capillaries (*colloid osmotic pressure*).

Capillary blood pressure favors filtration while plasma colloid osmotic pressure favors reabsorption. At the venular ends of capillaries, blood pressure has decreased due to resistance so that reabsorption can occur.

More fluid usually leaves capillaries than returns to them. Lymphatic capillaries have closed ends and collect excess fluid to return it via lymphatic vessels to the venous circulation. Unusual events may cause excess fluid to enter spaces between tissue cells, often in response to chemicals such as histamine. If enough fluid leaks out, lymphatic vessels can be overwhelmed, and affected tissues swell and become painful.

Venules are microscopic vessels that link capillaries to **veins**, which carry blood back to the atria. Vein walls are similar to arteries but have poorly developed middle layers. Because they have thinner walls that are less elastic than arteries, their lumens have a greater diameter.

Many veins have flaplike *valves* projecting inward from their linings. These valves often have two structures that close if blood begins to back up in the vein. They aid in returning blood to the heart, opening if blood flow is toward the heart, but closing if it reverses. Unlike the arteries, veins do not have sufficient pressure from the contractions of the heart to keep blood moving through them. To keep blood flowing, the veins rely on the movement of nearby skeletal muscles, as well as the opening and closing of the valves within them. Therefore, a major structural difference between veins and arteries is that arteries do not have valves.

Veins also act as reservoirs for blood in certain conditions, such as during arterial hemorrhage. Resulting venous constrictions help to maintain blood pressure by returning more blood to the heart, ensuring an almost normal blood flow even when up to one-quarter of the blood volume is lost. See **Table 5–2** for a summary of blood vessel characteristics.

Blood Pressure

Blood pressure is defined as the force that blood exerts against the inner walls of blood vessels. It most commonly refers to pressure in arteries supplied by the aortic branches, even though it actually occurs throughout the vascular system. Arterial blood pressure rises and falls according to cardiac cycle phases. The maximum pressure during ventricular contraction is called the **systolic pressure**.

The lowest pressure that remains in the arteries before the next ventricular contraction is called the **diastolic pressure**. Arterial blood pressure is measured with a device called a *sphygmomanometer* (blood pressure cuff). Its results are reported as a fraction of the systolic pressure over the diastolic pressure, such as 120/80. The upper (first) number indicates the arterial systolic pressure in millimeters of mercury (mm Hg), and the lower (second) number indicates the arterial diastolic pressure, also in millimeters of mercury. A millimeter of mercury is a unit of pressure that is equal to 0.001316 of normal atmospheric pressure. This means that a blood pressure of 120/80 displaces 120 mm Hg on a sphygmomanometer, showing the systolic pressure, and also displaces 80 mm Hg on the same device, showing diastolic pressure. **Figure 5–8** shows changes in blood pressure as the distance from the left ventricle increases.

The artery walls are distended as blood surges into them from the ventricles, but they recoil almost immediately. This expansion and recoiling can be felt as a *pulse* in an artery near the surface of the skin. Most commonly, the radial artery is used to take a person's pulse, although the carotid, brachial, and femoral arteries are also checked. Arterial blood pressure depends on heart rate, stroke volume, blood volume, peripheral resistance, and blood viscosity.

Heart action determines the amount of blood entering the arterial system with each ventricular contraction. **Stroke volume** is defined as the volume of blood discharged from the ventricle with each contraction. An average adult male's stroke volume is about 70 mL. The **cardiac output** is defined as the volume discharged from the ventricle per minute. It is calculated by multiplying the stroke volume by the heart rate, in beats per minute. So if the stroke volume is 70 mL and the heart rate is 75 beats per minute (bpm), the cardiac output is 5,250 mL/min. Blood pressure varies with cardiac output

Table 5–2 Characteristics of Blood Vessels

Type of Vessel	Vessel Wall	Actions
Artery	Three-layer thick wall (endothelial lining, middle smooth muscle and elastic connective tissue layer, and outer connective tissue layer)	Carries relatively high-pressure blood from the heart to the arterioles
Arteriole	Three-layer thinner wall (smaller arterioles have an endothelial lining, some smooth muscle tissue, and a small amount of connective tissue)	Helps control blood flow from arteries to capillaries by vasoconstriction or vasodilation
Capillary	One layer of squamous epithelium	Has a membrane allowing nutrients, gases, and wastes to be exchanged between blood and tissue fluid
Venule	Thinner wall than arterioles, with less smooth muscle and elastic connective tissue	Connects capillaries to veins
Vein	Thinner wall than arteries but similar layers; poorly developed middle layer; some have flaplike valves	Carries relatively low-pressure blood from venules to the heart; valves prevent blood backflow; veins serve as blood reservoirs

and increases or decreases based upon similar changes in stroke volume or heart rate.

Blood volume is defined as the sum of formed elements and plasma volumes in the vascular system. Blood volume varies with age, body size, and gender. Most adults have approximately 5 L of blood, which makes up 8% of the body weight in kilograms. Blood pressure and volume are usually directly proportional. Any changes in volume can initially alter pressure. When measures are taken to restore normal blood volume, normal blood pressure can be reestablished. Fluid balance fluctuations may also affect blood volume.

The resistance of arteries to blood flow is defined as **peripheral resistance**. The degree of peripheral resistance is determined by the blood vessel diameter and the force of contraction exerted by vascular smooth muscle. Therefore, peripheral resistance is a factor that accounts for blood pressure.

Viscosity is defined as the resistance of a fluid to flow. In a biologic fluid, viscosity is caused by the attraction of molecules or cells to one another. The higher the viscosity, the greater the resistance to flowing. Blood viscosity is increased by blood cells and plasma proteins. The greater the resistance, the greater the force needed to move the blood. Blood pressure rises as blood viscosity increases, and vice versa.

Blood pressure (BP) is calculated by multiplying cardiac output (CO) by peripheral resistance (PR). Normal arterial pressure is maintained by regulating these two factors. Ideally, the volume of blood discharged from the heart should be equal to the volume entering the atria and ventricles. Fiber length and force of contraction are interrelated because of the stretching of the cardiac muscle cell just before contraction. This is known as the *Frank-Starling law of the heart*, and it is important during exercise when greater amounts of blood return to the heart from the veins.

Peripheral resistance also controls blood pressure. Changes in the diameters of arterioles regulate peripheral resistance. The *vasomotor center* of the medulla oblongata controls peripheral resistance. When arterial blood pressure increases suddenly, baroreceptors in the aorta and carotid arteries alert the vasomotor center, which vasodilates the vessels to decrease peripheral resistance. Carbon dioxide, oxygen, and hydrogen ions also influence peripheral resistance by affecting precapillary sphincters and smooth arteriole wall muscles.

Blood flow through the venous system depends only slightly on heart action, but more so on skeletal muscle contraction, movements of breathing, and the vasoconstriction of veins (*venoconstriction*). As skeletal muscles press on veins with valves, some blood moves from one valve section to another, helping to push blood forward through the venous system to the heart. During inspiration, thoracic cavity pressure is reduced while abdominal cavity pressure is increased. Blood is then squeezed out of abdominal veins and forced into thoracic veins. When venous pressure is low, the walls of the veins contract to help force blood out toward the heart.

Blood Circulation

Blood enters the *pulmonary circuit* from the right ventricle through the pulmonary trunk, which extends upward posteriorly from the heart. It divides into right and left pulmonary

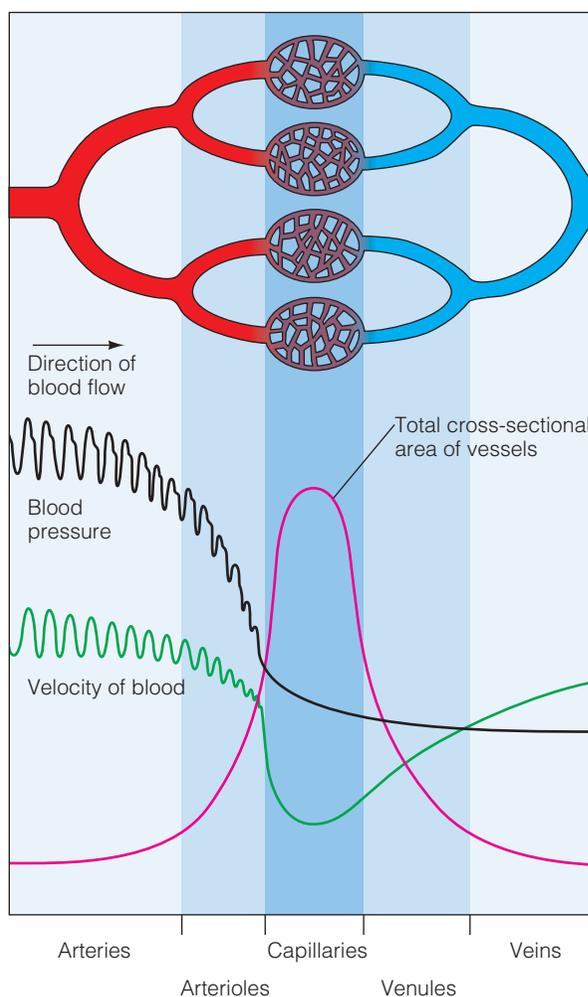


Figure 5-8 Blood pressure in the circulatory system. Blood pressure declines in the circulatory system as the vessels branch. Arterial pressure pulses because of the heartbeat, but pulsation is lost by the time the blood reaches the capillary networks, creating an even flow through body tissues. Blood pressure continues to decline in the venous side of the circulatory system.

arteries, which enter the right and left lungs, respectively. Repeated divisions connect to arterioles and capillary networks associated with the walls of the alveoli, where gas is exchanged between blood and air. The pulmonary capillaries lead to venules and then veins. Four pulmonary veins, two from each lung, return blood to the left atrium, completing the vascular loop of the pulmonary circuit.

The *systemic circuit* involves the movement of freshly oxygenated blood from the left atrium to left ventricle, then into the aorta and its branches, leading to all body tissues. Eventually it makes its way to the companion vein system that returns blood to the right atrium.

The Arteries

The largest-diameter artery in the body is the aorta, extending upward from the left ventricle to arch over the heart to the left, descending anterior and to the left of the vertebral column. The first portion of the aorta is called the *ascending aorta*. It begins at the aortic valve of the left ventricle. The left and right coronary arteries originate in the aortic sinus.

This origination occurs at the base of the ascending aorta, slightly superior to the aortic valve.

The **aortic arch** curves across the superior surface of the heart. It connects the ascending aorta with the *descending aorta* (see **Figure 5–9**). Three arteries originate along the aortic arch. They deliver blood to the head, neck, shoulders, and upper limbs. These arteries are as follows:

1. The brachiocephalic trunk
2. The left common carotid artery
3. The left subclavian artery

The brachiocephalic trunk ascends only for a short distance before it branches to form the right subclavian and right common carotid arteries. The descending aorta is continuous with the aortic arch. The diaphragm divides the descending aorta into a superior *thoracic aorta* and an inferior *abdominal aorta*. The branches of the thoracic aorta include the bronchial, pericardial, esophageal, mediastinal, and intercostal arteries.

The abdominal aorta, beginning immediately inferior to the diaphragm, is a continuation of the thoracic aorta (see **Figure 5–9**). It delivers blood to the abdominopelvic organs and structures. The abdominopelvic branches of the aorta include the following: celiac, phrenic, superior mesenteric, suprarenal, renal, gonadal, inferior mesenteric, lumbar, middle sacral, and common iliac arteries. **Table 5–3** summarizes the major branches of the aorta.

The subclavian and common carotid arteries supply blood to the neck, head, and brain. The main divisions of these arteries are the vertebral and thyrocervical arteries. The **vertebral arteries** run upward through the cervical vertebrae into the skull and supply blood to the vertebrae and to their ligaments and muscles. They unite in the cranial cavity to form the *basilar artery*, which branches to the pons, midbrain, and cerebellum. It ultimately divides into the two *posterior cerebral arteries*.

The posterior cerebral arteries help form the **cerebral arterial circle** (also known as the *circle of Willis*), connecting the vertebral artery and internal carotid artery systems (see **Figure 5–10**). These united systems provide alternate blood pathways to circumvent blockages and reach brain tissues and to equalize blood pressure in the brain's blood supply.

The **thyrocervical arteries** give off branches to the thyroid and parathyroid glands, larynx, trachea, esophagus, pharynx, and muscles of the neck, shoulder, and back. The left and right *common carotid arteries* separate into the internal and external carotid arteries. **Table 5–4** discusses these arteries. Near the base of the carotid arteries are enlargements (**carotid sinuses**) that contain baroreceptors and help to control blood pressure.

The subclavian artery, which is a branch of the brachiocephalic artery, continues into the arm, passing between the clavicle and first rib to become the *axillary artery*. It becomes the *brachial artery* and gives rise to a *deep brachial artery*. The *ulnar artery* leads down to the lower arm, on the ulnar side of the forearm to the wrist. Some of its branches supply the elbow joint, while others supply the muscles of the forearm. The *radial artery* provides blood to the wrist and hand, traveling along the radial side of the forearm to the wrist. It also supplies the lateral muscles of the forearm. Near the wrist, it approaches the surface, providing a point where the radial pulse may easily be taken.

The *internal thoracic artery* branches into two *anterior intercostal arteries* supplying the intercostal muscles and mammary glands. The *posterior intercostal arteries* supply other intercostal muscles as well as the vertebrae, spinal cord, and deeper back muscles. The *internal thoracic artery* and *external iliac artery* provide blood to the anterior abdominal wall while the *phrenic artery* and *lumbar artery* supply blood to posterior and lateral abdominal wall structures. The major vessels of the arterial system include the *common iliac*

Table 5–3 Major Branches of the Aorta

Branch	Area of Aorta	Main Regions or Organs Supplied
Right and left coronary arteries	Ascending aorta	Heart
Brachiocephalic artery Left common carotid artery Left subclavian artery	Arch of the aorta	Right upper limb and right side of head Left side of head Left upper limb
Descending aorta: Bronchial artery Pericardial artery Esophageal artery Mediastinal artery Posterior intercostal artery	Thoracic aorta	Bronchi Pericardium Esophagus Mediastinum Thoracic wall
Descending aorta: Celiac artery Phrenic artery Superior mesenteric artery Suprarenal artery Renal artery Gonadal artery Inferior mesenteric artery Lumbar artery Middle sacral artery Common iliac artery	Abdominal aorta	Upper digestive tract organs Diaphragm Small and large intestines Adrenal gland Kidney Ovaries or testes Lower large intestine Abdominal wall (posterior) Sacrum and coccyx Lower abdominal wall, pelvic organs, lower limbs

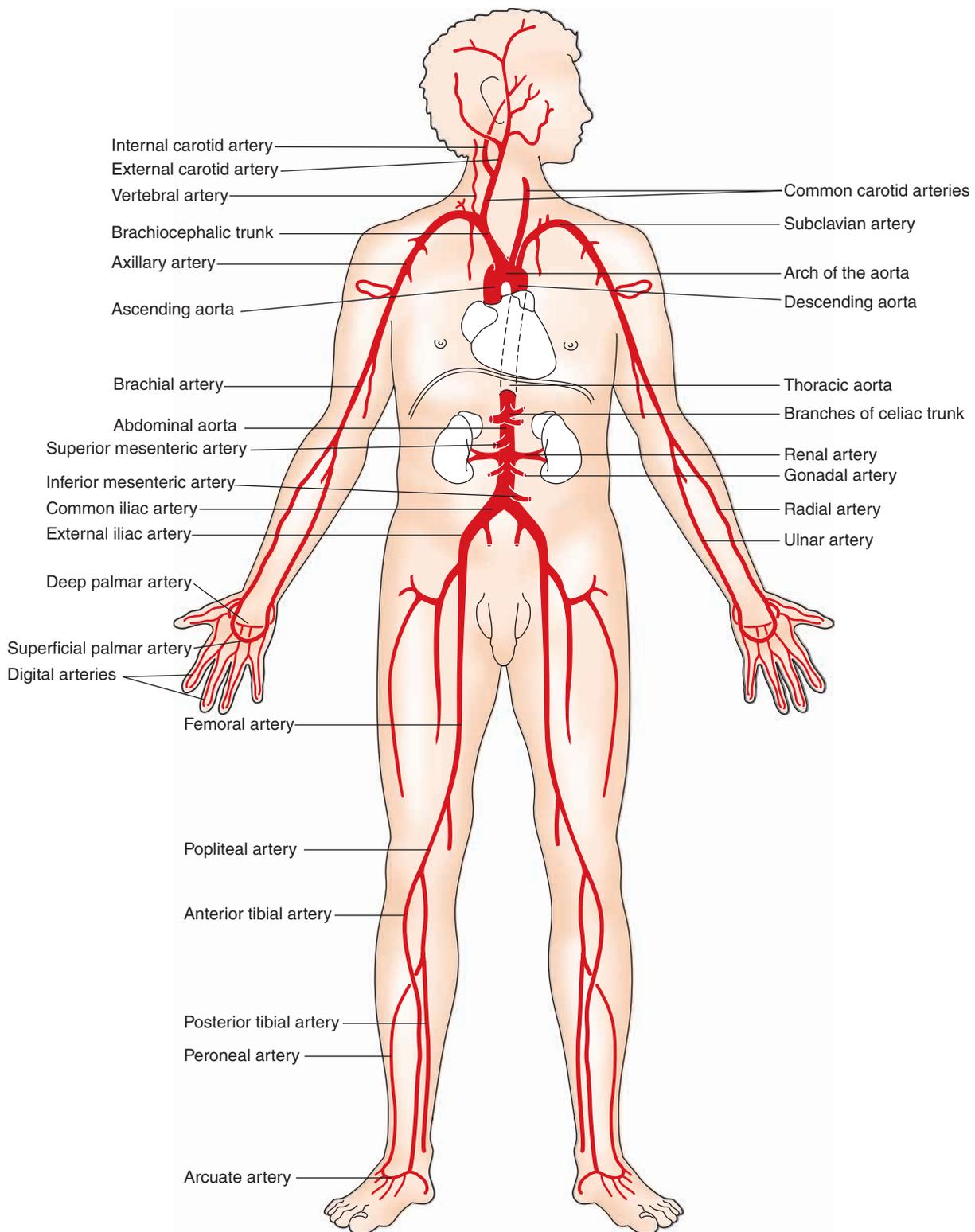


Figure 5-9 Overview of the arteries

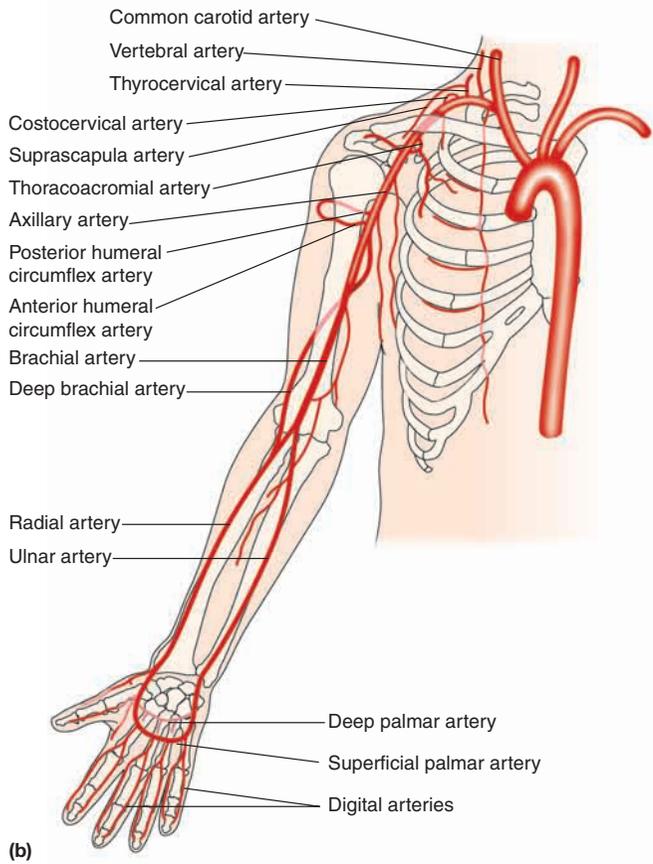
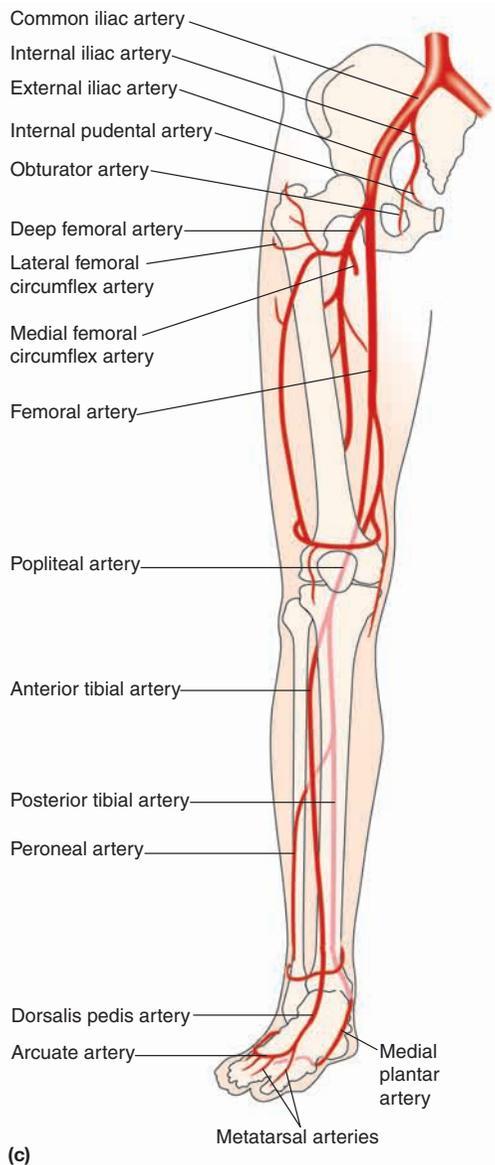
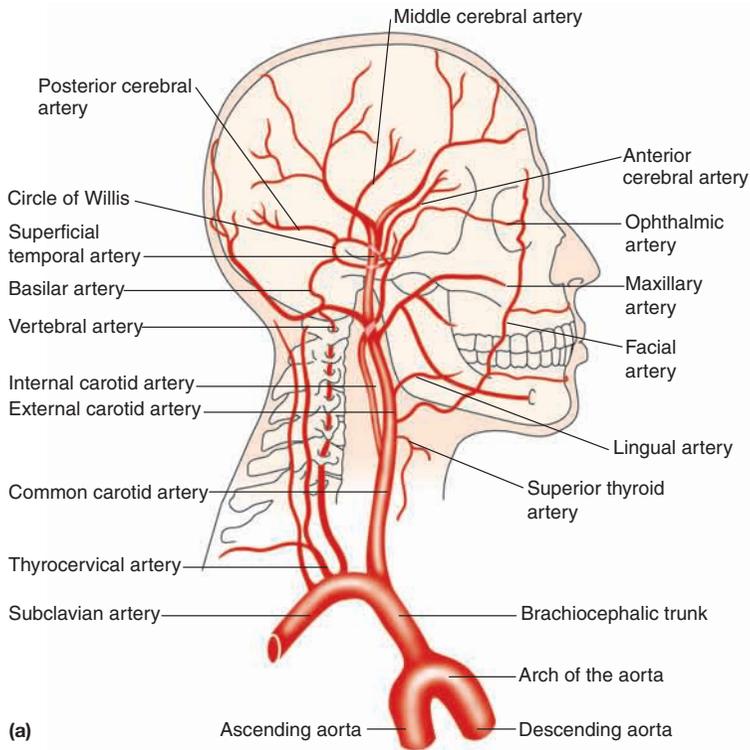


Figure 5-10 Detailed views of the arteries in the body

Table 5–4 Major Branches of the Carotid Arteries

Branch	Carotid Artery	Main Regions or Organs Supplied
Superior thyroid artery	External	Larynx and thyroid gland
Lingual artery		Salivary glands and tongue
Facial artery		Chin, lips, nose, palate, and pharynx
Occipital artery		Meninges, neck muscles, and posterior scalp
Posterior auricular artery		Ear and lateral scalp
Maxillary artery		Cheeks, eyelids, jaw, and teeth
Superficial temporal artery		Parotid salivary gland and surface of face and scalp
Ophthalmic artery	Internal	Eyes and eye muscles
Anterior choroid artery		Brain and choroid plexus
Anterior cerebral artery		Frontal and parietal lobes of brain

arteries, *internal iliac artery*, *femoral artery*, *popliteal artery*, *anterior tibial artery*, and *posterior tibial artery*.

The Veins

The vessels of the venous system are more difficult to follow than those of the arterial system. They connect in irregular networks, with many unnamed vessels joining to form larger veins. Larger veins typically parallel the locations of arteries and have similar names. The veins from all parts of the body besides the lungs and heart converge into the superior vena cava and inferior vena cava, leading to the right atrium.

The *external jugular veins* descend on either side of the neck and empty into the *right subclavian vein* and *left subclavian vein* (see **Figure 5–11**). The *internal jugular veins* descend through the neck to join the subclavian veins, forming *brachiocephalic veins* on each side, above the clavicles. They then merge to form the superior vena cava.

Deep and superficial veins drain the upper limbs and shoulders. The superficial veins connect via complex networks just under the skin and communicate with the deeper vessels (see **Figure 5–12**). The *basilic vein* ascends to join the *brachial vein*, merging to form the *axillary vein*. The *cephalic vein* ascends upward to empty into the axillary vein, and later it becomes the subclavian vein.

The brachiocephalic and azygos veins drain the abdominal and thoracic walls. The *azygos vein* ascends through the mediastinum to join the superior vena cava. Its tributaries include the *posterior intercostal veins*, *superior hemiazygos veins*, and *inferior hemiazygos veins*. The right and left *ascending lumbar veins* have vessels from the lumbar and sacral regions.

Most veins carry blood directly to the heart's atria, except for veins that drain the abdominal viscera (see **Figure 5–13**). They originate in the stomach, intestines, pancreas, and spleen to carry blood through a *hepatic portal vein* to the liver. This pathway is called the **hepatic portal system**. It includes the right and left *gastric veins*, *superior mesenteric vein*, and *splenic vein*.

The liver helps to regulate blood concentrations of absorbed amino acids and lipids. It modifies them into usable cells, oxidizes them, or changes them into forms that can be stored. Hepatic portal venous blood usually contains bacteria from intestinal capillaries. Large *Kupffer cells* in the liver phagocytize microorganisms before they can leave the liver. This blood then travels through merged vessels into *hepatic veins*, emptying into the inferior vena cava.

Veins that drain blood from the lower limbs are also subdivided, like those of the upper limbs, into deep and superficial groups. The deep *anterior tibial vein* and *posterior tibial vein* merge to form the *popliteal vein* (which is located deep in the leg, behind the knee), continuing upward as the *femoral vein* and then the *external iliac vein*.

The *saphenous veins* of the lower leg communicate with one another as well as the deeper veins of the leg and thigh, allowing blood to return to the heart from the lower extremities by several routes. In the pelvis, vessels carry blood away from the reproductive, urinary, and digestive organs via the *internal iliac veins*. These unite with the external iliac veins to form the *common iliac veins* and eventually the inferior vena cava. The great saphenous vein runs the entire length of the leg (see **Figure 5–12c**) and is considered the longest vein in the body.

Summary

The cardiovascular system consists of the heart and blood vessels. It provides oxygen and nutrients to tissues while removing wastes. The heart is located within the mediastinum, resting on the diaphragm. The wall of the heart has three layers: the epicardium, myocardium, and endocardium. The heart is divided into two atria and two ventricles. Blood low in oxygen and high in carbon dioxide enters the right side of the heart and is pumped into the pulmonary circulation. After oxygenation in the lungs and some removal of carbon dioxide, it returns to the left side of the heart. The left ventricle pumps blood out of the heart to the rest of the body.

The cardiac cycle consists of the atria contracting while the ventricles relax, and vice versa. Electrical activity of the cardiac cycle can be recorded via an electrocardiogram. The cardiac cycle consists of the P wave, QRS complex, and T wave. Blood vessels form a closed circuit of tubes that carry blood from the heart to the body cells and back again. This circuit consists of arteries, arterioles, capillaries, venules, and veins. Blood pressure is the force that blood exerts against the insides of blood vessels. It is measured as systolic pressure over diastolic pressure, meaning the pressure produced during ventricular contraction over the pressure produced when the ventricles relax.

The pulmonary circuit consists of vessels that carry blood from the right ventricle to the lungs and back to the left atrium. The systemic circuit consists of vessels that lead from the left ventricle to the body cells and back to the heart,

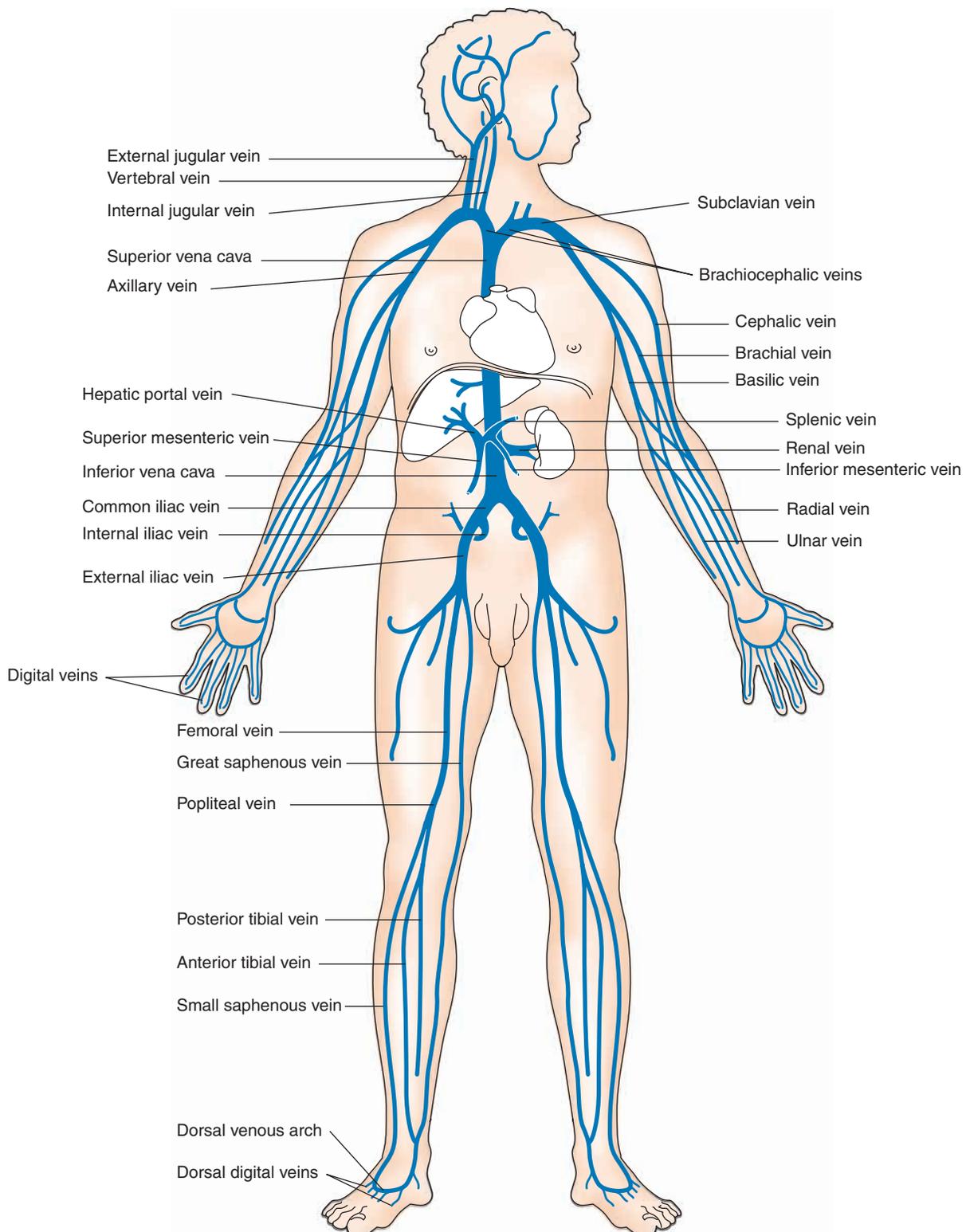


Figure 5-11 Overview of the veins in the body. For clarity, the right kidney is not shown.

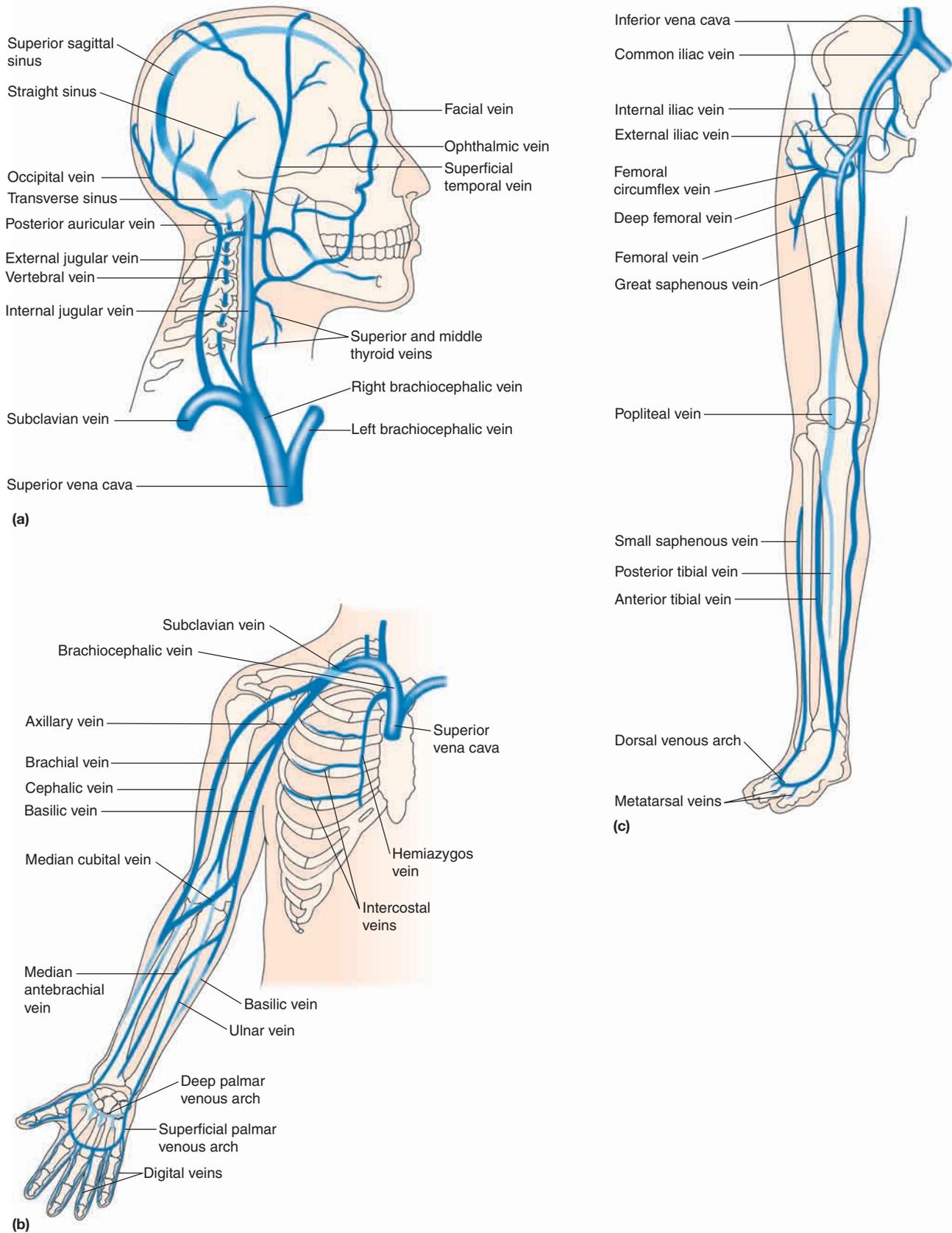


Figure 5-12 Detailed views of the arteries

including the aorta and its branches. The aorta is the largest artery in the body, with respect to diameter.

CRITICAL THINKING

Two phlebotomists were studying together to take the National Certification Exam. One of them was questioning the other about the anatomy and physiology of the heart and circulatory system. The questions that follow were what he asked.

1. How many veins return blood to the right atrium? Name these veins.
2. Where in the heart are the Purkinje fibers located?
3. Where is the lowest blood pressure found in the blood vessels?

WEBSITES

<http://lsa.colorado.edu/essence/texts/heart.html>

<http://www.americanheart.org/presenter.jhtml?identifier=4473>

http://www.ivy-rose.co.uk/HumanBody/Blood/Heart_Structure.php

http://www.nhlbi.nih.gov/health/dci/Diseases/hhw/hhw_circulation.html

<http://www.texasheart.org/hic/anatomy/>

<http://www.thic.com/conduction.htm>

http://www.tpub.com/content/medical/14295/css/14295_36.htm

REVIEW QUESTIONS

Multiple Choice

1. Blood leaving the left ventricle enters the
 - A. pulmonary trunk
 - B. pulmonary artery
 - C. inferior vena cava
 - D. aorta
2. The right ventricle pumps blood to the
 - A. systemic circuit
 - B. lungs
 - C. left atrium
 - D. right atrium
3. The visceral pericardium is the same as the
 - A. epicardium
 - B. endocardium
 - C. myocardium
 - D. parietal pericardium
4. The mitral valve is located between the
 - A. right atrium and right ventricle
 - B. left atrium and left ventricle
 - C. left ventricle and aorta
 - D. right ventricle and pulmonary trunk
5. The heart wall is composed of how many layers?
 - A. two
 - B. three
 - C. four
 - D. five
6. The function of an atrium is to
 - A. pump blood to the lungs
 - B. pump blood into the systemic circuit
 - C. pump blood to the heart muscle
 - D. collect blood
7. The left and right pulmonary arteries carry blood to the
 - A. brain
 - B. liver
 - C. lungs
 - D. kidneys
8. The pacemaker cells of the heart are located in the
 - A. SA node
 - B. AV node
 - C. left ventricle
 - D. left atrium
9. Which of the following blood vessels returns blood to the left atrium?
 - A. inferior vena cava
 - B. superior vena cava
 - C. pulmonary vein
 - D. pulmonary trunk
10. Each of the following factors will increase cardiac output, EXCEPT
 - A. increased parasympathetic stimulation
 - B. increased sympathetic stimulation
 - C. increased venous return
 - D. increased heart rate
11. The difference between the systolic and diastolic pressures is referred to as
 - A. a pulse
 - B. circulatory pressure
 - C. blood pressure
 - D. mean arterial pressure
12. Blood from the brain returns to the heart via a vein called the
 - A. external jugular
 - B. internal jugular
 - C. vertebral vein
 - D. azygos vein
13. Branches off of the aortic arch include the
 - A. brachio and right axillary arteries
 - B. right and left subclavian arteries
 - C. right and left common carotid arteries
 - D. left subclavian and left common carotid arteries
14. Nutrients from the digestive tract enter the
 - A. hepatic vein
 - B. hepatic portal vein
 - C. inferior vena cava
 - D. azygos vein
15. The longest vein in the human body is the
 - A. inferior vena cava
 - B. superior vena cava
 - C. saphenous vein
 - D. femoral vein

