

CHAPTER 1

THE HEART AND CIRCULATION

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INTRODUCTION

The cardiovascular system is an elaborate network that performs two major tasks: It delivers oxygen and nutrients to body organs and removes waste products of metabolism from tissue cells. Its major components are the heart—a hollow muscular pump—and a circulatory system of large and small elastic vessels or conduits that transport blood throughout the body. In the course of one day, the amount of blood pumped through the heart of a normal healthy adult at rest reaches approximately 2,100 gallons. (See box, “The Amazing Heart and Blood Vessels.”)

HEART

The heart, the central organ of the cardiovascular system, is located between the two lungs in the middle of the chest. (See color atlas, #1.) Two-thirds of the heart lies to the left of the breastbone and one-third to the right. Placing a hand on the chest, we can feel the heartbeat on the left side of the rib cage because in that spot, the bottom left corner of the heart, which is somewhat tilted forward, comes closest to

the surface of the body. The adult heart is about the size of two clenched fists. It is shaped like a cone and weighs about 7 to 15 ounces, depending on the size and weight of the individual.

THE HEART CHAMBERS

The human heart is divided into four chambers—the right atrium and right ventricle and the left atrium and left ventricle. (See color atlas, #3A.) The walls of the chambers are made of a special muscle, the myocardium, that contracts rhythmically under the stimulation of electrical currents. The left and right atria and the left and right ventricles are separated from each other by a wall of muscle called the septum (atrial septum for the atria and ventricular septum for the ventricles).

The circulation system is described in greater detail later in this chapter, but basically it works as follows. (See color atlas, #5A to 5D.) Blood returning from the body through the venous system enters the heart through the right atrium, where it collects and is then pumped to the right ventricle. Each time the right ventricle contracts, it propels this blood, which is low in oxygen content, into the lungs, where it is enriched with oxygen. Pulmonary veins return the blood to the left atrium, which contracts and sends it to the left ventricle. The left ventricle, the main pumping chamber of the heart, ejects the blood

The Amazing Heart and Blood Vessels

- The adult human heart is about the size of two clenched fists.
- In an average lifetime, the heart pumps 1 million barrels of blood—enough blood to fill 3.3 supertankers. This only takes into account its work at rest. During exercise or stress, the heart may pump ten times as much blood as it does at rest.
- In one year, the human heart beats 3 million times. The heart of a 70-year-old has beaten more than 2.5 billion times.
- Even when a person is at rest, the muscles of the heart work twice as hard as the leg muscles of a person running at top speed.
- The amount of energy expended by the heart in 50 years is enough to lift a battleship out of the water.
- The electrical signal produced by the sinus node travels over the entire surface of the heart in only 21/100 to 26/100 of a second.
- Stretched end to end, the vessels of the circulatory system—arteries, arterioles, capillaries, venules, and veins—would measure about 60,000 miles.
- The oxygen and nutrients transported in the bloodstream and delivered with each beat of the heart nourish 300 trillion cells.
- The capillaries, the smallest blood vessels in the body, are so tiny that ten of them together are only as thick as a human hair.
- In total area, the capillary walls are equal to about 60,000 to 70,000 square feet, or roughly the area of one and a half football fields.

through the aorta into the major circulatory network. Because it delivers blood to the entire body, this ventricle works harder than all other chambers; as a result, its walls can be more than 1/2 inch thick two to three times thicker than the walls of the right ventricle.

THE VALVES

Blood in the heart is kept flowing in a forward direction by a system of four one-way valves, each closing off one of the heart's chambers at the appropriate time in the cardiac cycle. The valves open to let the blood through when the chambers contract, and snap shut to prevent it from flowing backward as the

chambers relax. The valve system also helps maintain different pressures on the right and left sides of the heart.

The valves differ significantly in structure. The two valves separating the ventricles from the circulatory system are called semilunar because of their crescent-shaped cusps. At the juncture of the right ventricle and the pulmonary artery lies the pulmonary valve. It consists of three cusps, or flaps of tissue, that open freely when the right ventricle contracts and blood is ejected into the lungs, and then fall back as the ventricle relaxes. The other semilunar valve, the aortic valve, lies between the left ventricle and the aorta and also has three cusps. It is flung open when the left ventricle squeezes down to propel blood into the main circulation. When the left ventricle relaxes, the pressure in the aorta pushes the valve closed.

The ventricles are separated from the atria by valves that, in addition to the cusps, have thin but strong cords of fibrous tissue. Called chordae tendineae, these cords tether the valves to the ventricular walls. When the ventricles contract, small muscles in their walls, called papillary muscles, pull the cords, which act as guide wires, and control the closure of the valve leaflets, preventing them from flapping too far backward.

The valve located between the left ventricle and left atrium is a cone-shaped funnel that resembles a miter—a triangular head dress worn by bishops and abbots and is therefore called the mitral valve. It has two leaflets that are remarkably mobile and can open and close rapidly. The corresponding valve between the right ventricle and right atrium is called the tricuspid valve. As its name suggests, it has three cusps, or leaflets, that are thinner than those of the mitral valve and just as mobile.

ENDOCARDIUM AND PERICARDIUM

On the inside, the heart is lined with a protective layer of cells that form a smooth membrane called the endocardium. On the outside, the heart is encased in a two-layered fibrous sac (like a cellophane casing) called the pericardium, which extends to cover the roots of the major blood vessels. The inner layer of the pericardium is attached to the heart muscle, while the outer layer, connected by ligaments to the vertebral column, the diaphragm, and other body structures, holds the heart firmly in place. The layers are separated by a thin film of lubricating fluid that allows the heart to move freely within the outer pericardium.

CORONARY ARTERIES AND VEINS

Because the heart never rests while it supplies blood to the rest of the body, it actually works harder than any other muscle in the body and needs a much richer blood supply than other muscles. The heart supplies blood to itself through two coronary arteries, the right and the left, which leave the aorta about 1/2 inch above the aortic valve and run around the outside of the heart. Both arteries lie in grooves on the outside of the heart muscle and branch off into a system of smaller vessels and capillaries that supply the muscle fibers. After giving off its oxygen in the capillaries, the blood travels through coronary veins and drains directly into the right atrium, where it joins the venous blood from the rest of the body.

When the heart is working harder than usual, the coronary arteries dilate to increase oxygen supply to the heart muscle. During extreme physical exertion, flow in these arteries may increase by five to six times.

The better an individual's physical condition, the more efficient is his or her heart in using the blood supply available. When blood supply is insufficient to meet the increased requirements in *oxygen* and nutrients and to wash away waste materials, the heart aches, just as other muscles might ache from an excessive workload. The lack of oxygen stimulates nerve cells, and chest pain, or angina pectoris, is noted. In contrast to other muscles of the body, however, the heart cannot stop for rest without devastating consequences.

THE CONDUCTION SYSTEM

Electrical currents that regulate the heart rhythm originate in cells of the heart muscle (myocardium) and travel through a network of specialized fibers referred to as the heart's conduction system. Its major elements include the sinus or sinoatrial node, the atrioventricular or AV node, the bundle of His, and the Purkinje fibers. (See color atlas, #3B.)

The sinus node, known as the heart's pacemaker, is a microscopic bundle of specialized cells located in the top right corner of the heart. Any portion of the heart muscle can generate electrical impulses, but in normal function, the impulses originate in this pacemaker. If the pacemaker's function is disrupted, another part of the conduction system can take over the impulse-firing task.

Impulses are transmitted through muscle fibers of the two atria to the atrioventricular node, located on

the juncture between the right and left sides of the heart, in the area where the right atrium and right ventricle meet. From the atrioventricular node, they travel along the bundle of His and the Purkinje fibers-fibrous pathways named after the scientists who first described them — through the muscles of the right and left ventricles.

THE CARDIAC CYCLE

Electrical activity coordinates the rhythmic contraction and relaxation of the heart's chambers known as the cardiac cycle. Most currents in the heart are less than a millionth of an ampere (the current running through a 100-watt bulb is approximately 1 ampere), but they exert a powerful influence on the heart muscle.

The cardiac cycle consists of two phases, called diastole and systole. Diastole, during which the heart's ventricles are relaxed, is the longer phase, taking up approximately two-thirds of the cycle. Systole, the phase during which blood is ejected from the ventricles, takes up the remaining one-third.

During diastole, the sinus node generates an impulse that forces the two atria to contract. In this phase, the tricuspid and mitral valves are open, and blood is propelled from the atria into the relaxed ventricles. By the end of diastole, the electric impulse reaches the ventricles, causing them to contract.

During systole, the contracting ventricles close the tricuspid and mitral valves. Shortly afterward, the pressure of the blood inside the ventricles rises sufficiently to force the pulmonary and aortic valves to open, and blood is ejected into the pulmonary artery and the aorta. As the ventricles relax again, blood backs up from the pulmonary artery and the aorta, closing down the pulmonary and aortic valves. The pressure in the relaxed ventricles is now lower than in the atria, the tricuspid and mitral valves open again, and the cardiac cycle starts anew.

This seemingly lengthy sequence of events in fact takes approximately a second. The familiar double throb (lub dub) of the beating heart corresponds to the two sets of synchronized contractions that occur during the cardiac cycle: The throbbing sound we hear comes not only from the snapping of the valves, but also from the accompanying vibrations of other heart structures and from the turbulence produced by the flow of blood.

HEART RATE AND CARDIAC OUTPUT

In an average adult, the pacemaker fires approximately 70 impulses a minute at rest, which means that in one minute the heart goes through a full cardiac cycle 70 times. Athletes have larger and stronger hearts that can deliver an adequate supply of blood while beating slower than the hearts of untrained individuals. Generally, the greater the physical fitness of an individual, the slower the heart rate at rest. Some well-trained athletes, for example, are known to have a pulse rate of 35 beats per minute—half the average figure for the general population. For them, the slow heart rate is efficient and does not pose a danger. For a 75-year-old untrained individual, however, a rate of 35 to 40 might be inadequate to pump sufficient blood to the brain or other vital organs. Fatigue or even fainting might result.

Because the lungs are so close to the heart and the walls of the pulmonary vessels are thinner and thus offer less resistance, the right ventricle does not have to exert nearly as much energy to do its job of supplying blood to the lungs as the left ventricle does in supplying the rest of the body.

The amount of blood pumped by the heart in one

minute is called the cardiac output. When there is a need for an increased blood supply, as during physical exertion, the heart most commonly increases its output by beating faster—for example, up to 140 or 150 beats per minute. This mechanism, however, has its limits: Above a certain rate, the heart chambers do not have time to fill properly and fail to pump efficiently.

STROKE VOLUME

The cardiac output is determined not only by the heart rate but also by the amount of blood the ventricles eject or pump out with each contraction. This amount is called the stroke volume. Usually the ventricles expel about half the blood they contain, which corresponds to about 3 ounces in an average person at rest. A decrease in the stroke volume is one of the first signs of a failing heart. While both ventricles pump out, the same amount of blood in each stroke, cardiologists usually measure only the stroke volume of the left ventricle, because it is the one that pumps blood to all of the body's organs except the lungs:

The Major Arteries

| Name | Origin | Supplies |
|-------------------|-----------------|-------------------------------------------------------------------|
| Abdominal aorta | Thoracic aorta | Stomach, liver, kidneys, intestinal tract |
| Aortic arch | Left ventricle | Head, neck, arms |
| Brachial | Base of neck | Shoulders and arms |
| Carotid, common | Aorta | Neck and head |
| Carotid, external | Common carotid | Front part of neck, face, ear and scalp |
| Carotid, internal | Common carotid | Front part of brain, eye, nose and forehead |
| Celiac | Abdominal aorta | Esophagus, stomach, duodenum, gallbladder, pancreas, spleen, etc. |
| Coronary, left | Aorta | Left atrium, left ventricle |
| Coronary, right | Aorta | Right atrium, parts of both ventricles |
| Femoral | Iliac | Lower extremities |
| Hepatic | Celiac | Liver, gallbladder, stomach, pancreas |
| Iliac | Abdominal aorta | Pelvis, legs |
| Popliteal | Femoral | Thigh, lower legs |
| Pulmonary | Right ventricle | Lungs |
| Radial | Brachial artery | Forearms, hands |
| Renal | Abdominal aorta | Kidneys, adrenal glands |
| Subclavian | Aorta | Neck, arms, brain, skull, lining of heart and lungs |
| Tibial, anterior | Popliteal | Front of leg, ankle |
| Tibial, posterior | Popliteal | Back of leg, knee, sole and back of foot |
| Ulnar | Brachial | Forearm and part of hand |

The Major Veins

| Name | Drains from | Carries blood to |
|---------------------|------------------------------|--------------------|
| Hepatic | Liver | Inferior vena cava |
| Jugular, external | Side of neck | Subclavian vein |
| Jugular, internal | Neck, face, brain | Innominate vein |
| Portal vein | Abdominal organs, intestines | Liver |
| Pulmonary | Lungs | Left atrium |
| Vena cava, inferior | Abdomen, thighs, legs | Right atrium |
| Vena cava, superior | Head, neck, chest wall, arms | Right atrium |

Note: Many veins are paired with, and have the same name as, major arteries. These veins return to the heart the blood that the arteries deliver to the tissues.

THE CIRCULATION

The circulatory system is an intricate network of vessels that supplies blood to all body organs and tissues. The part of the network that delivers blood to all parts of the body except the lungs is called the systemic circulation, while the flow of blood through the lungs is referred to as the pulmonary circulation. Placed end to end, all the blood vessels of the body would stretch some 60,000 miles in length.

THE SYSTEMIC CIRCULATION: THE ARTERIES AND CAPILLARIES

Blood that has been oxygenated in the lungs—bright red in color—is pumped out of the heart through the aorta, the body's largest artery, which measures approximately 1 inch in diameter. The coronary arteries, which provide the heart's own blood supply, branch out from the aorta just above the aortic valve. The aorta arches upward from the left ventricle to the upper chest, then runs down the chest into the abdomen. It forms the main trunk of the arterial part of the circulation, which branches off into numerous arteries that deliver oxygen-rich blood to various tissues. (See box, "The Major Arteries.")

The arteries are further subdivided into smaller tubes, the arterioles, which in turn branch off into even smaller vessels, the capillaries. While the walls of larger and medium-sized blood vessels are made of a layer of connective tissue and muscle cells with a very thin inner lining called the endothelium (see color atlas, #6), the walls of the capillaries consist of endothelium alone.

Most capillary walls are only one cell thick, and

sometimes the blood flow through these vessels consists of a single red blood cell at a time. It is in the capillaries that the exchange of substances between the blood and the tissues takes place. Through the walls of the capillaries, the blood gives off its oxygen and nutrients and picks up carbon dioxide and waste products.

A large part of the waste is extracted from blood as it flows through the kidneys, where the plasma—the fluid component of blood—seeps through the capillary walls of the kidneys excreting mechanism. Most of the fluid is reabsorbed into the bloodstream; a fraction of a percent, together with the waste, is removed from the body as urine, which accumulates at a rate of about a quart a day in a healthy adult.

The blood pressure on the arterial side of the circulatory system is relatively high, but it decreases as the arteries branch off into arterioles and capillaries. On the venous side, the blood pressure is relatively low. The difference in pressure contributes to the driving force that propels the blood through the circulatory system.

THE VEINS

The capillaries carrying blood that now has a lower oxygen content merge to form the venules, which in turn converge into successively larger veins. (See box, "The Major Veins.") Venous blood, sometimes referred to as blue, is in fact a purplish or dark red color.

Venous blood enters the right atrium through two major vessels: the superior vena cava, which brings blood from the upper part of the body, including the brain; and the inferior vena cava, which brings blood from the lower part. Since the pressure in the veins is normally significantly lower than in the arteries,

the walls of the veins are considerably thinner than arterial walls.

The larger veins have a system of internal one-way valves that prevents the blood from flowing downward under the pull of gravity when an individual stands up. When he or she moves, the veins are squeezed by the surrounding muscle, which helps propel more blood toward the heart. Without valves in the veins, blood would pool in the legs, which would then be perpetually swollen.

THE PULMONARY CIRCULATION

The main function of the pulmonary circulation is to deliver oxygen to the blood and free it of carbon dioxide. This goal is accomplished as the blood flows through the lungs. The pressure in this part of the system is only about one-sixth as great as in the systemic circulation, and the walls of pulmonary arteries and veins are significantly thinner than the walls of corresponding vessels in the rest of the body.

In the pulmonary circulation, the roles of arteries and veins are the opposite of what they are in the systemic circulation: Blood in the arteries has less oxygen, while blood in the veins is oxygen-rich. The circuit starts with the pulmonary artery, which extends from the right ventricle and carries blood with a low oxygen content to the lungs. In the lungs, it branches off into the two arteries, one for each lung, and then into arterioles and capillaries.

The gas exchange between the air we breathe in and the blood takes place in the pulmonary capillaries. Their walls act like filters by allowing molecules of gas but not molecules of fluid to pass through. The total surface area of the capillaries in the lungs ranges from 500 to 1,000 square feet.

The carbon dioxide and waste products are removed from the blood in the pulmonary arteries across capillary walls and leave the body through the mouth and nose. The blood that has picked up oxygen returns to the heart through four pulmonary veins and into the left atrium.

THE BLOOD

Blood is a life-sustaining fluid that helps maintain an optimum environment within the body by providing a constant supply of nutrients from the outside world

and removing waste products from the tissues. Its cells are produced in the marrow of bones, primarily the flat bones such as the ribs and the breastbone. The volume of blood in an average adult amounts to approximately 10.5 pints.

TYPES OF BLOOD CELLS

The blood has two main components: cells of several types and a solution called plasma, in which the cells are suspended. The vast majority of blood cells are erythrocytes, or red blood cells, which outnumber white blood cells by about 700 to 1 in the healthy adult. The major function of the red blood cells, of which there are about 25 trillion, is to transport oxygen. They contain the red pigment hemoglobin, a complex protein arranged around iron that carries oxygen and releases it whenever needed. Red cells are smaller than white cells and live three to four months. They are created at a rate of approximately 8 million a second to keep the supply constant.

The white blood cells are called leukocytes. There are several types, which vary in size and shape, but all share the function of defending the body against a wide variety of invading organisms. They are produced in increased amounts in response to infection.

The platelets are plate-shaped disks that, together with special substances in the plasma, trigger the blood-clotting mechanism and prevent an uncontrollable loss of blood when the vessels are damaged.

THE PLASMA

Plasma is a yellowish fluid that consists of 90 percent water and various salts, glucose, cholesterol, proteins, etc. Proteins in the plasma perform a wide variety of functions, from transporting molecules of nutrients to acting as antibodies in the immune response.

CONTROL OF CARDIO-VASCULAR FUNCTION

The cardiovascular system plays an important role in maintaining homeostasis—that is, a stable environment—inside the body. It can carry out, or signal other systems to carry out, rapid short-term adjust-

ments in response to demands placed on the body by various human activities and changing external conditions. For example, when blood supply to one area is increased, the flow to other organs must be reduced, or else the cardiac output has to be increased. Throughout these adaptations, blood pressure must remain constant to maintain the vital functions of all body tissues.

To perform the adjustments, the cardiovascular system communicates with other organs through a complex network of monitoring and signaling mechanisms. It sends out signals about its condition and, in turn, receives messages that control its performance. The two main regulatory centers of cardiovascular function are the nervous system and the kidneys.

THE NERVOUS SYSTEM

The brain and other parts of the nervous system constantly monitor and control the heart and circulation. They receive information about the cardiovascular system through numerous receptors that generate coded impulses describing the body's internal environment. Different kinds of receptors transmit information about the stretching of the arterial walls and the resulting changes in blood pressure or about the stretching of the heart chambers and the chemical composition of blood. Little receptors in the carotid arteries in the neck, for example, help to adjust heart rate and the size of blood vessels in response to certain activities. When we stand up suddenly and blood pressure begins to decrease, these receptors sense a lack of pressure and send out signals to the heart to beat faster and the blood vessels to constrict and narrow down so that adequate blood pressure can be maintained.

In response to changes, the nervous system issues adjustment commands. Thus, if the receptors detect a decrease in oxygen and an increase in carbon dioxide in the blood, the brain sends a command to the respiratory center to increase the rate of respiration, which delivers more oxygen to the lungs. At the same time, the brain issues impulses that accelerate the heart rate and constrict the veins. This brings more blood to the lungs to be purified. As a result, an adequate supply of oxygen to body tissues is ensured.

Messages between the nervous and cardiovascular systems are relayed by chemicals called neurotransmitters. These are chemicals that travel between cells and can provoke a response in the target tissue. The neurotransmitter norepinephrine, an adrenaline-like substance, can increase the heart rate and force of contractions, as well as constrict the blood vessels. Thus, if we become frightened, more adrenaline is released, more blood is pumped out by the heart to muscles, and we become better able to run or react if necessary. (This is called the "flight or fight" reaction.) In contrast, other neurotransmitters, such as acetylcholine, slow down the heart.

THE KIDNEYS

The kidneys play an important role in regulating blood pressure. Because they influence the volume of fluids in the body, they can affect the pressure by changing the volume of circulating blood. They also release an enzyme called renin, which is converted into a powerful blood-pressure-elevating substance that constricts blood vessels and induces sodium and water retention. Delicate mechanisms allow the kidneys to adjust under a wide variety of situations. If we are deprived of water, for example, the kidneys stop putting out urine; if we eat a lot of salt, the kidneys respond by putting out more urine.