University of Anbar
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Lectures of human physiology

Lec. 5

Blood, Heart, and Circulation

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FUNCTIONS AND COMPONENTS OF THE CIRCULATORY SYSTEM

Blood serves numerous functions, including the transport of respiratory gases, nutritive molecules, metabolic wastes, and hormones. Blood travels through the body in a system of vessels leading from and returning to the heart.

Functions of the Circulatory System

The functions of the circulatory system can be divided into three broad areas: transportation, regulation, and protection.

1. Transportation. All of the substances essential for cellular metabolism are transported by the circulatory system.These substances can be categorized as follows:

a. *Respiratory.* Red blood cells, or *erythrocytes,* transport oxygen to the cells. In the lungs, oxygen from the inhaled air attaches to hemoglobin molecules within the erythrocytes and is transported to the cells for aerobic respiration. Carbon dioxide produced by cell respiration is carried by the blood to the lungs for elimination in the exhaled air.

b. *Nutritive.* The digestive system is responsible for the mechanical and chemical breakdown of food so that it can be absorbed through the intestinal wall into the blood and lymphatic vessels. The blood then carries these absorbed products of digestion through the liver to the cells of the body.

c. *Excretory.* Metabolic wastes (such as urea), excess water and ions, and other molecules not needed by the body are carried by the blood to the kidneys and excreted in the urine.

2. Regulation. The circulatory system contributes to both hormonal and temperature regulation.

a. *Hormonal.* The blood carries hormones from their site of origin to distant target tissues where they perform a variety of regulatory functions.

b. *Temperature.* Temperature regulation is aided by the diversion of blood from deeper to more superficial cutaneous vessels or vice versa. When the ambient temperature is high, diversion of blood from deep to

superficial vessels helps cool the body; when the ambient temperature is low, the diversion of blood from superficial to deeper vessels helps keep the body warm.

3. Protection. The circulatory system protects against blood loss from injury and against pathogens, including foreign microbes and toxins introduced into the body.

a. *Clotting.* The clotting mechanism protects against blood loss when vessels are damaged.

b. *Immune.* The immune function of the blood is performed by the *leukocytes* (white blood cells) that protect against many disease-causing agents (pathogens).

Major Components of the Circulatory System

The **circulatory system** consists of two subdivisions: the cardiovascular system and the lymphatic system. The **cardiovascular system** consists of the heart and blood vessels, and the **lymphatic system,** which includes lymphatic vessels and lymphoid tissues within the spleen, thymus, tonsils, and lymph nodes.

The **heart** is a four-chambered double pump. Its pumping action creates the pressure head needed to push blood through the vessels to the lungs and body cells. At rest, the heart of an adult pumps about 5 liters of blood per minute. At this rate, it takes about 1 minute for blood to be circulated to the most distal extremity and back to the heart.

Blood vessels form a tubular network that permits blood to flow from the heart to all the living cells of the body and then back to the heart. *Arteries* carry blood away from the heart, whereas *veins* return blood to the heart. Arteries and veins are continuous with each other through smaller blood vessels. Arteries branch extensively to form a "tree" of progressively smaller vessels. The smallest of the arteries are called *arterioles.* Blood passes from the arterial to the venous system in microscopic *capillaries,* which are the thinnest and most numerous of the blood vessels. All exchanges of fluid, nutrients, and wastes between the blood and tissues occur across the walls of capillaries. Blood flows

through capillaries into microscopic veins called *venules,* which deliver blood into progressively larger veins that eventually return the blood to the heart.

As blood *plasma* (the fluid portion of the blood) passes through capillaries, the hydrostatic pressure of the blood forces some of this fluid out of the capillary walls. Fluid derived from plasma that passes out of capillary walls into the surrounding tissues is called *tissue fluid,* or *interstitial fluid.* Some of this fluid returns directly to capillaries, and some enters into **lymphatic vessels** located in the connective tissues around the blood vessels. Fluid in lymphatic vessels is called *lymph.* This fluid is returned to the venous blood at specific sites. **Lymph nodes,** positioned along the way, cleanse the lymph prior to its return to the venous blood.

COMPOSITION OF THE BLOOD

Blood consists of formed elements that are suspended and carried in a fluid called plasma. The formed elements—erythrocytes, leukocytes, and platelets—function respectively in oxygen transport, immune defense, and blood clotting.

The total blood volume in the average-size adult is about 5 liters, constituting about 8% of the total body weight. Blood leaving the heart is referred to as *arterial blood.* Arterial blood, with the exception of that going to the lungs, is bright red because of a high concentration of oxyhemoglobin (the combination of oxygen and hemoglobin) in the red blood cells. *Venous blood* is blood returning to the heart. Except for the venous blood from the lungs, it contains less oxygen and is therefore a darker red than the oxygen-rich arterial blood.

Blood is composed of a cellular portion, called *formed elements,* and a fluid portion, called *plasma.* When a blood sample is centrifuged, the heavier formed elements are packed into the bottom of the tube, leaving plasma at the top (fig.1). The formed elements constitute approximately 45% of the total blood volume, and the plasma accounts for the

remaining 55%. Red blood cells compose most of the formed elements; the percentage of red blood cell volume to total blood volume in a centrifuged blood sample (a measurement called the *hematocrit)* is 36% to 46% in women and 41% to 53% in men.

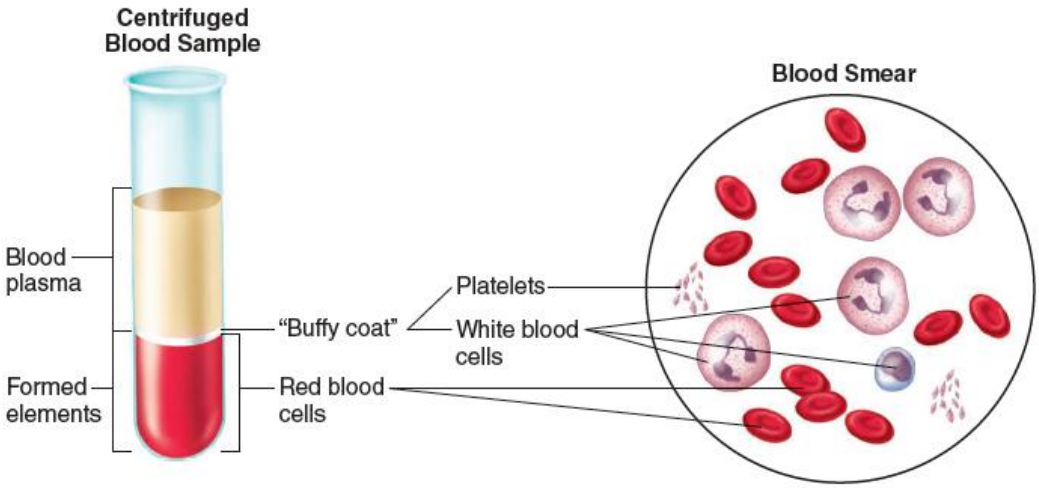

Figure 1 The constituents of blood

Plasma

Plasma is a straw-colored liquid consisting of water and dissolved solutes. The major solute of the plasma in terms of its concentration is Na^{+1}. In addition to Na^{+1}, plasma contains many other ions, as well as organic molecules such as metabolites, hormones, enzymes, antibodies, and other proteins.

Plasma Proteins

Plasma proteins constitute 7% to 9% of the plasma. The three types of proteins are albumins, globulins, and fibrinogen. **Albumins** account for most (60% to 80%) of the plasma proteins and are the smallest in size. They are produced by the liver and provide the osmotic pressure needed to draw water from the surrounding tissue fluid into the capillaries. This action is needed to maintain blood volume and pressure. **Globulins** are

grouped into three subtypes: **alpha globulins, beta globulins,** and **gamma globulins.** The alpha and beta globulins are produced by the liver and function in transporting lipids and fat-soluble vitamins. Gamma globulins are antibodies produced by lymphocytes (one of the formed elements found in blood and lymphoid tissues) and function in immunity. **Fibrinogen,** which accounts for only about 4% of the total plasma proteins, is an important clotting factor produced by the liver. During the process of clot formation, fibrinogen is converted into insoluble threads of *fibrin.* Thus, the fluid from clotted blood, called **serum,** does not contain fibrinogen but is otherwise identical to plasma.

The Formed Elements of Blood

The **formed elements** of blood include two types of blood cells: *erythrocytes,* or *red blood cells,* and *leukocytes,* or *white blood cells.* Erythrocytes are by far the more numerous of the two. A cubic millimeter of blood normally contains 5.1 million to 5.8 million erythrocytes in males and 4.3 million to 5.2 million erythrocytes in females. By contrast, the same volume of blood contains only 5,000 to 9,000 leukocytes.

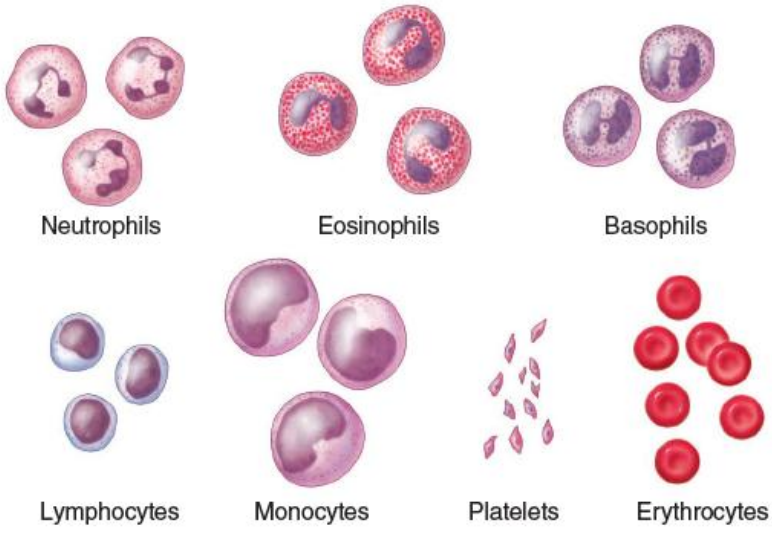

Figure 2. The blood cells and platelets

Hematopoiesis

Blood cells are constantly formed through a process called hematopoiesis (also called hemopoiesis). The hematopoietic stem cells —those that give

rise to blood cells—originate in the yolk sac of the human embryo and then migrate in sequence to regions around the aorta, to the placenta, and then to the liver of a fetus. The liver is the major hematopoietic organ of the fetus, but then the stem cells migrate to the bone marrow and the liver ceases to be a source of blood cell production shortly after birth. Scientists estimate that the hematopoietic tissue of the bone marrow produces about 500 billion cells each day. The hematopoietic stem cells form a population of relatively undifferentiated, multipotent adult stem cells that give rise to all of the specialized blood cells. The hematopoietic stem cells are self-renewing, duplicating themselves by mitosis so that the parent stem cell population will not become depleted as individual stem cells differentiate into the mature blood cells.

The term **erythropoiesis** refers to the formation of erythrocytes, and **leukopoiesis** to the formation of leukocytes. These processes occur in two classes of tissues after birth, myeloid and lymphoid. **Myeloid tissue** is the red bone marrow of the long bones, ribs, sternum, pelvis, bodies of the vertebrae, and portions of the skull. **Lymphoid tissue** includes the lymph nodes, tonsils, spleen, and thymus. The bone marrow produces all of the different types of blood cells; the lymphoid tissue produces lymphocytes derived from cells that originated in the bone marrow.

Red Blood Cell Antigens and Blood Typing

There are certain molecules on the surfaces of all cells in the body that can be recognized as foreign by the immune system of another individual. These molecules are known as *antigens.* As part of the immune response, particular lymphocytes secrete a class of proteins called *antibodies* that bond in a specific fashion with antigens. The specificity of antibodies for antigens is analogous to the specificity of enzymes for their substrates.

ABO System

The distinguishing antigens on other cells are far more varied than the antigens on red blood cells. Red blood cell antigens, however, are of

extreme clinical importance because their types must be matched between donors and recipients for blood transfusions. There are several groups of red blood cell antigens, but the major group is known as the **ABO system.** In terms of the antigens present on the red blood cell surface, a person may be *type A* (with only A antigens), *type B* (with only B antigens), *type AB* (with both A and B antigens), or *type O* (with neither A nor B antigens).

Rh Factor

Another group of antigens found on the red blood cells of most people is the **Rh factor** (named for the rhesus monkey, in which these antigens were first discovered). There are a number of different antigens in this group, but one stands out because of its medical significance. This Rh antigen is termed D, and is often indicated as Rho(D). If this Rh antigen is present on a person's red blood cells, the person is **Rh positive;** if it is absent, the person is **Rh negative.** The Rh-positive condition is by far the more common (with a frequency of 85% in the Caucasian population, for example).

Blood Clotting

When a blood vessel is injured, a number of physiological mechanisms are activated that promote **hemostasis,** or the cessation of bleeding. Breakage of the endothelial lining of a vessel exposes collagen proteins from the subendothelial connective tissue to the blood. This initiates three separate, but overlapping, hemostatic mechanisms: (1) vasoconstriction, (2) the formation of a platelet plug, and (3) the production of a web of fibrin proteins that penetrates and surrounds the platelet plug.

Platelets and Blood Vessel Walls

Platelets contain secretory granules; when platelets stick to collagen, they degranulate as the secretory granules release their products. These products include adenosine diphosphate (ADP), serotonin, and a prostaglandin called thromboxane A2. This event is known as the platelet release reaction. The ADP and thromboxane A2 released from activated platelets recruits new platelets to the vicinity and makes them "sticky," so that they adhere to those stuck on the collagen (fig. 2 b). The second layer of platelets, in turn, undergoes a platelet release reaction, and the ADP and thromboxane A2 that are secreted cause additional platelets to aggregate at the site of the injury. This produces a platelet plug (fig. 2 c) in the damaged vessel. The activated platelets also help to activate plasma clotting factors, leading to the conversion of a soluble plasma protein known as fibrinogen into an insoluble fibrous protein, fibrin.

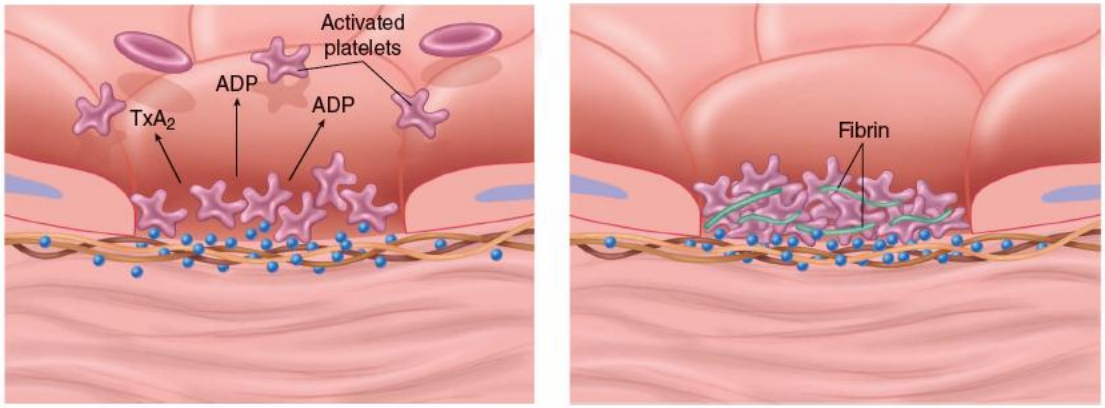

Figure 2 Platelet aggregation.

Clotting Factors: Formation of Fibrin

The platelet plug is strengthened by a meshwork of insoluble protein fibers known as **fibrin**. Blood clots therefore are composed of platelets and fibrin, and they usually contain trapped red blood cells that give the clot a red color (clots formed in arteries, where the blood flow is more rapid, generally lack red blood cells and thus appear gray). Finally,

contraction of the platelet mass in the process of *clot retraction* forms a more compact and effective plug**.** The conversion of fibrinogen into fibrin may occur via either of two pathways. Blood left in a test tube will clot without the addition of any external chemicals. Because all of the components are present in the blood, this clotting pathway is called the **intrinsic pathway.** Damaged tissues, however, release a chemical that initiates a "shortcut" to the formation of fibrin. Because this chemical is not part of blood, the shorter pathway is called the **extrinsic pathway.**

Dissolution of Clots

As the damaged blood vessel wall is repaired, activated factor XII promotes the conversion of an inactive molecule in plasma into the active form called *kallikrein.* Kallikrein, in turn, catalyzes the conversion of inactive *plasminogen* into the active molecule **plasmin.** Plasmin is an enzyme that digests fibrin into "split products," thus promoting dissolution of the clot.

STRUCTURE OF THE HEART

The heart contains four chambers: two atria, which receive venous blood, and two ventricles, which eject blood into arteries. The right ventricle pumps blood to the lungs where the blood becomes oxygenated; the left ventricle pumps oxygenated blood to the entire body.

About the size of a fist, the hollow, cone-shaped **heart** is divided into four chambers. The right and left **atria** (singular, *atrium)* receive blood from the venous system; the right and left **ventricles** pump blood into the arterial system. The right atrium and ventricle (sometimes called the *right pump)* are separated from the left atrium and ventricle (the *left pump)* by a muscular wall, or *septum.* This septum normally prevents mixture of the blood from the two sides of the heart. Between the atria and ventricles, there is a layer of dense connective tissue known as the **fibrous skeleton** of the heart. Bundles of myocardial cells in the atria attach to the upper margin of this fibrous skeleton and form a single functioning unit, or *myocardium.* The myocardial cell bundles of the ventricles attach to the

lower margin and form a different myocardium. As a result, the myocardia of the atria and ventricles are structurally and functionally separated from each other, and special conducting tissue is needed to carry action potentials from the atria to the ventricles. The connective tissue of the fibrous skeleton also forms rings, called *annuli fibrosi*, around the four heart valves, providing a foundation for the support of the valve flaps.

Pulmonary and Systemic Circulations

Blood whose oxygen content has become partially depleted and whose carbon dioxide content has increased as a result of tissue metabolism returns to the right atrium. This blood then enters the right ventricle, which pumps it into the pulmonary trunk and pulmonary arteries. The pulmonary arteries branch to transport blood to the lungs, where gas exchange occurs between the lung capillaries and the air sacs (alveoli) of the lungs. Oxygen diffuses from the air to the capillary blood, while carbon dioxide diffuses in the opposite direction.

The blood that returns to the left atrium by way of the pulmonary veins is therefore enriched in oxygen and partially depleted of carbon dioxide. The path of blood from the heart (right ventricle), through the lungs, and back to the heart (left atrium) completes one circuit: the pulmonary circulation. Oxygen-rich blood in the left atrium enters the left ventricle and is pumped into a very large, elastic artery—the aorta.

The aorta ascends for a short distance, makes a U-turn, and then descends through the thoracic (chest) and abdominal cavities. Arterial branches from the aorta supply oxygen-rich blood to all of the organ systems and are thus part of the systemic circulation.

As a result of cellular respiration, the oxygen concentration is lower and the carbon dioxide concentration is higher in the tissues than in the capillary blood. Blood that drains from the tissues into the systemic veins is thus partially depleted of oxygen and increased in carbon dioxide content. These veins ultimately empty into two large veins—the *superior* and *inferior venae cavae* —that return the oxygen-poor blood to the right atrium. This completes the systemic circulation: from the heart (left

ventricle), through the organ systems, and back to the heart (right atrium). The systemic and pulmonary circulations are illustrated in figure 3.

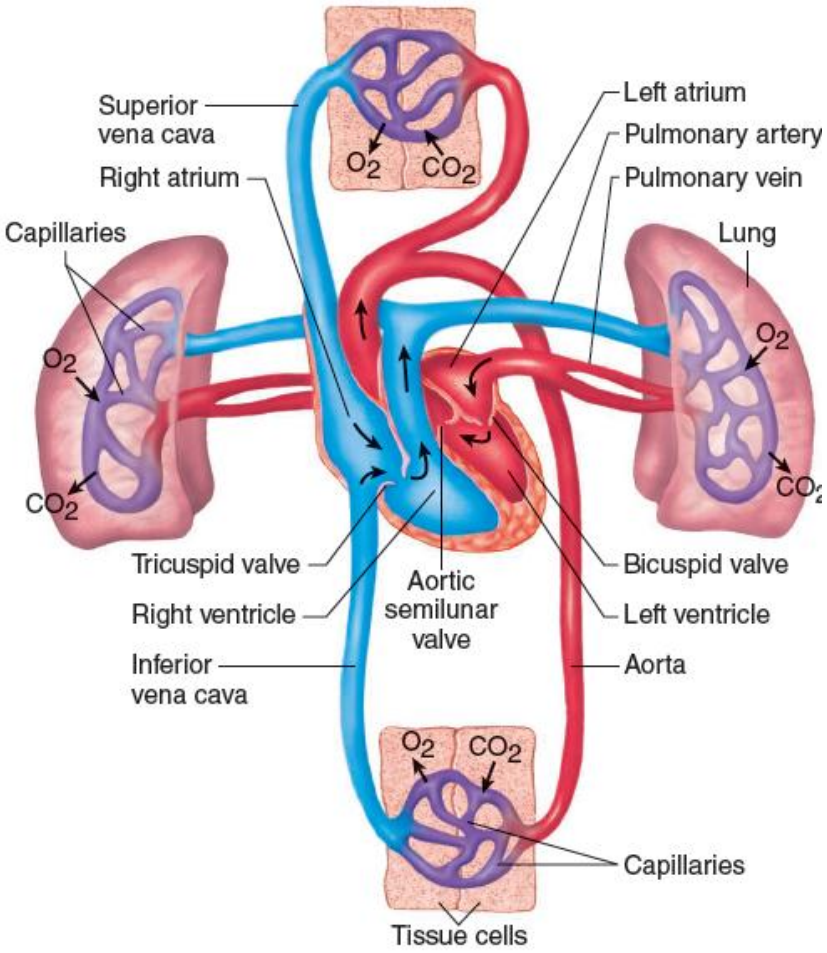

Figure 3 A diagram of the circulatory system

The numerous small muscular arteries and arterioles of the systemic circulation present greater resistance to blood flow than that in the pulmonary circulation. Despite the difference in resistance, the rate of blood flow through the systemic circulation must be matched to the flow rate of the pulmonary circulation. Because the amount of work performed by the left ventricle is greater (by a factor of 5 to 7) than that performed by the right ventricle, it is not surprising that the muscular wall of the left ventricle is thicker (8 to 10 mm) than that of the right ventricle (2 to 3 mm).

Atrioventricular and Semilunar Valves

Although adjacent myocardial cells are joined together mechanically and electrically by intercalated discs, the atria and ventricles are separated into two functional units by a sheet of connective tissue—the fibrous skeleton previously mentioned. Embedded within this sheet of tissue are one-way atrioventricular (AV) valves. The AV valve located between the right atrium and right ventricle has three flaps, and is therefore called the tricuspid valve. The AV valve between the left atrium and left ventricle has two flaps and is thus called the bicuspid valve, or, alternatively, the mitral valve (fig. 4).

The AV valves allow blood to flow from the atria to the ventricles, but they normally prevent the backflow of blood into the atria. Opening and closing of these valves occur as a result of pressure differences between the atria and ventricles. When the ventricles are relaxed, the venous return of blood to the atria causes the pressure in the atria to exceed that in the ventricles. The AV valves therefore open, allowing blood to enter the ventricles. As the ventricles contract, the intraventricular pressure rises above the pressure in the atria and pushes the AV valves closed.

There is a danger, however, that the high pressure produced by contraction of the ventricles could push the valve flaps too much and evert them. This is normally prevented by contraction of the papillary muscles within the ventricles, which are connected to the AV valve flaps by strong tendinous cords called the chordae tendineae (fig. 4). Contraction of the papillary muscles occurs at the same time as contraction of the muscular walls of the ventricles and serves to keep the valve flaps tightly closed.

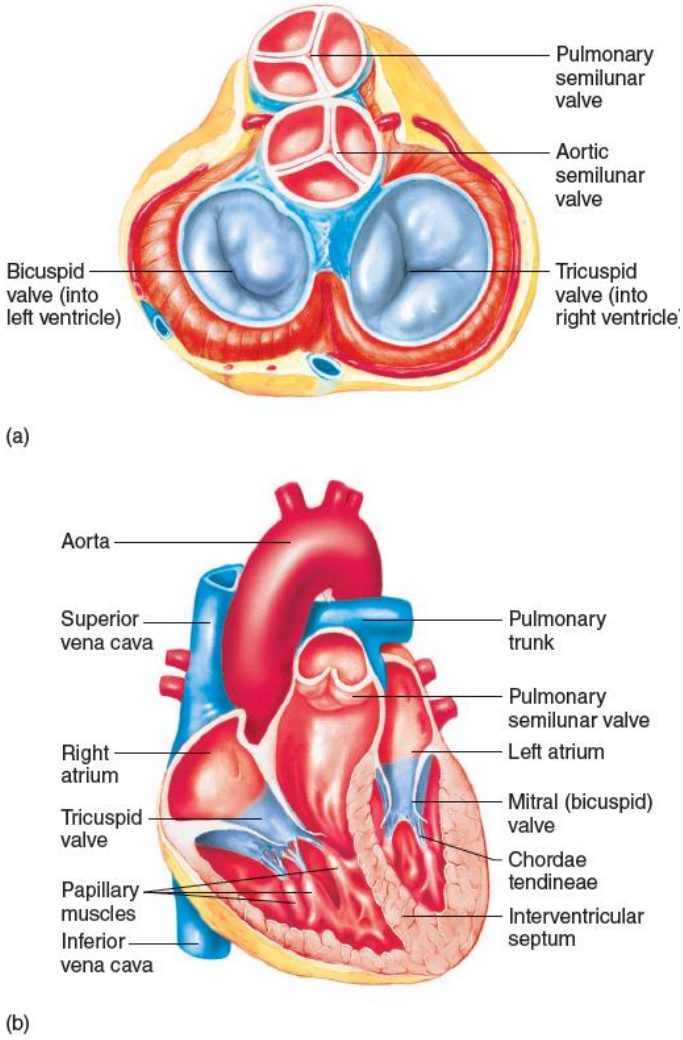

Figure 4 The heart valves

CARDIAC CYCLE

The two atria fill with blood and then contract simultaneously. This is followed by simultaneous contraction of both ventricles, which sends blood through the pulmonary and systemic circulations. Pressure changes in the atria and ventricles as they go through the cardiac cycle are responsible for the flow of blood through the heart chambers and out into the arteries.

The **cardiac cycle** refers to the repeating pattern of contraction and relaxation of the heart. The phase of contraction is called **systole,** and the phase of relaxation is called **diastole.** When these terms are used without reference to specific chambers, they refer to contraction and relaxation of

the ventricles. It should be noted, however, that the atria also contract and relax. There is an atrial systole and diastole. Atrial contraction occurs toward the end of diastole, when the ventricles are relaxed; when the ventricles contract during systole, the atria are relaxed. The heart thus has a two-step pumping action. The right and left atria contract almost simultaneously, followed by contraction of the right and left ventricles 0.1 to 0.2 second later. During the time when both the atria and ventricles are relaxed, the venous return of blood fills the atria. The buildup of pressure that results causes the AV valves to open and blood to flow from atria to ventricles.

It has been estimated that the ventricles are about 80% filled with blood even before the atria contract. Contraction of the atria adds the final 20% to the *end-diastolic volume,* which is the total volume of blood in the ventricles at the end of diastole. Contraction of the ventricles in systole ejects about two thirds of the blood they contain—an amount called the *stroke volume* —leaving one-third of the initial amount left in the ventricles as the *end-systolic volume.* The ventricles then fill with blood during the next cycle. At an average *cardiac rate* of 75 beats per minute, each cycle lasts 0.8 second; 0.5 second is spent in diastole, and systole takes 0.3 second.

Pressure Changes During the Cardiac Cycle

When the heart is in diastole, the pressure in the systemic arteries averages about 80 mmHg (millimeters of mercury). These events in the cardiac cycle then occur (fig. 5):

1. As the ventricles begin their contraction, the intraventricular pressure rises, causing the AV valves to snap shut and produce the first heart sound. At this time, the ventricles are neither being filled with blood (because the AV valves are closed) nor ejecting blood (because the intraventricular pressure has not risen sufficiently to open the semilunar valves). This is the phase of *isovolumetric contraction.*

2. When the pressure in the left ventricle becomes greater than the pressure in the aorta, the phase of *ejection* begins as the semilunar valves

open. The pressure in the left ventricle and aorta rises to about 120 mmHg (fig. 5) when ejection begins and the ventricular volume decreases.

3. As the pressure in the ventricles falls below the pressure in the arteries, the back pressure causes the semilunar valves to snap shut and produce the second heart sound. The pressure in the aorta falls to 80 mmHg, while pressure in the left ventricle falls to 0 mmHg. During *isovolumetric relaxation,* the AV and semilunar valves are closed. This phase lasts until the pressure in the ventricles falls below the pressure in the atria.

4. When the pressure in the ventricles falls below the pressure in the atria, the AV valves open and a phase of *rapid filling* of the ventricles occurs.

5. *Atrial contraction (atrial systole)* delivers the final amount of blood into the ventricles immediately prior to the next phase of isovolumetric contraction of the ventricles.

Similar events occur in the right ventricle and pulmonary circulation, but the pressures are lower. The maximum pressure produced at systole in the right ventricle is 25 mmHg, which falls to a low of 8 mmHg at diastole.

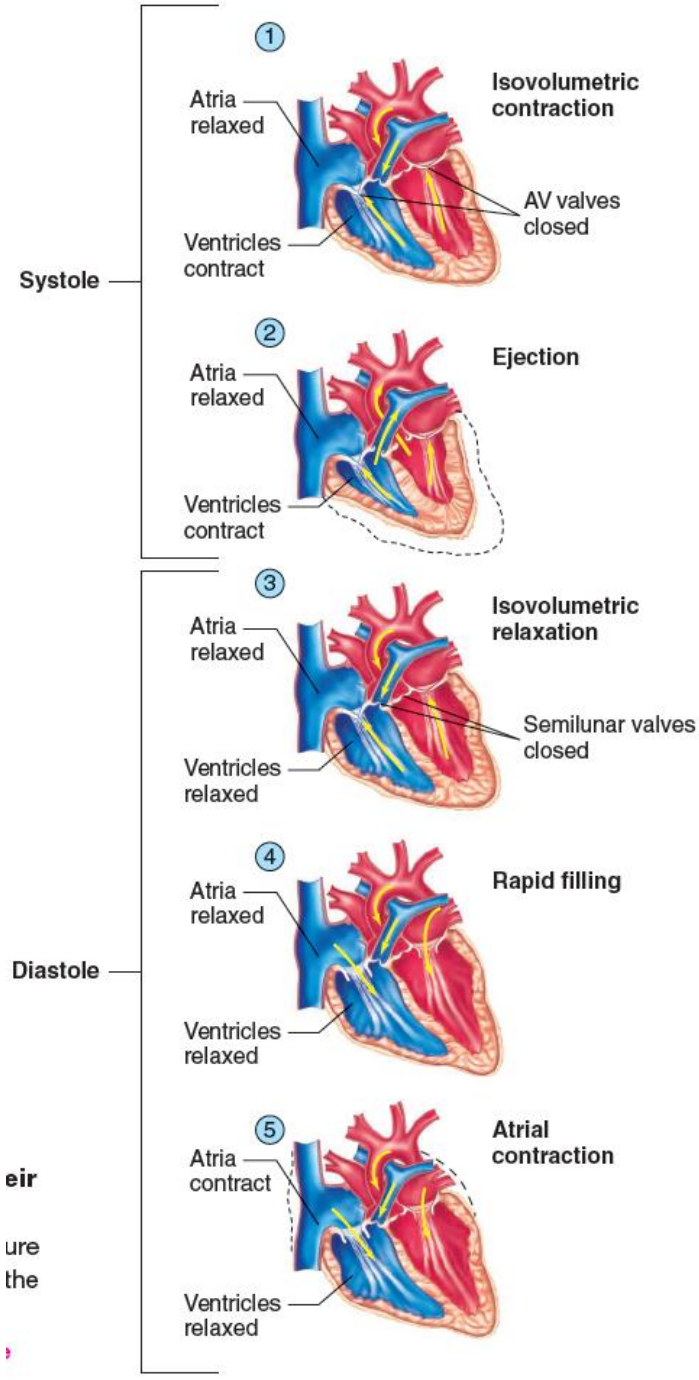

Figure 5 Pressure changes in the left ventricle and their effects during the cardiac cycle

-Reference

Fox, S. I. (2014). Fox Human Physiology.