Body Fluids and Circulation - Part 3

Objectives

After going through this lesson, the learners will be able to understand the following:

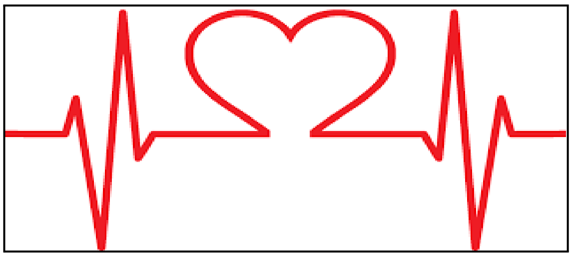
- Structure of human heart
- Circulatory system
- Cardiac cycle
- Cardiac output

Content Outline

- Introduction
- Heart in different vertebrates
- Structure of human heart:
- Circulatory system
- Cardiac cycle
- Cardiac output
- Summary

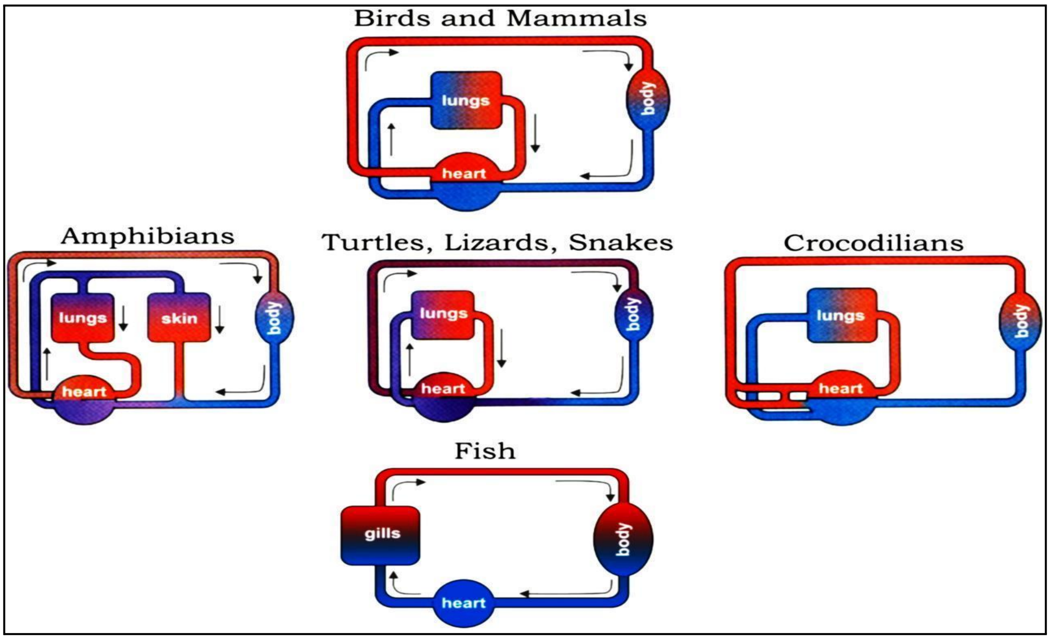
Introduction

The **heart** is a muscular organ in humans and other animals, which pumps blood through the blood vessels of the circulatory system. Blood provides the body with oxygen and nutrients, as well as. In humans, the heart is located between the lungs, in the middle compartment of the chest. The **circulatory system**, also called the **cardiovascular system** or the **vascular system**, is an organ system that permits blood to circulate and transport nutrients (such as amino acids and electrolytes), oxygen, carbon dioxide, hormones, and blood cells to and from the cells in the body to provide nourishment and help in fighting diseases, stabilize temperature and pH, maintain homeostasis and assists in the removal of metabolic wastes also. In animals there are two types of circulatory systems: open circulatory system and closed circulatory system. **Open circulatory** systems (evolved in crustaceans, insects, mollusks and other invertebrates) pump **blood** into a hemocoel with the **blood** diffusing back to the **circulatory** system between cells. **Blood** is pumped by a heart into the body cavities, where tissues are surrounded by the **blood**. Vertebrates, and a few invertebrates, have a **closed circulatory system**. **Closed circulatory systems** have the blood **closed** at all times within vessels of different size and wall thickness. In this type of **system**, blood is pumped by a heart through vessels, and does not normally fill body cavities. **Closed circulatory system** is further classified into two based on the number of times blood circulation takes place through heart i.e. single circulation (e.g. fish) and double circulation (e.g. humans). The majority of mammals utilize a **double circulatory system**.



Heart in Different Vertebrates

Heart is a thick, highly muscular, contractile and automatic pumping organ of the blood vascular system. Internally the heart is formed of a number of interconnected chambers which varies in number in different vertebrates. In most of the **fishes** the heart is two-chambered (one auricle and one ventricle) with single circulation. **Amphibians** have 3-chambered (two auricles and one un-partitioned ventricle) with double circulation. In most reptiles also, the heart is 3-chambered but the ventricle is incompletely divided by a septum. In crocodiles, alligators and gharials, the heart is 4-chambered. Birds and mammals have 4-chambered hearts (two auricles and two ventricles completely separated by interauricular and interventricular septum) they also have double circulation.



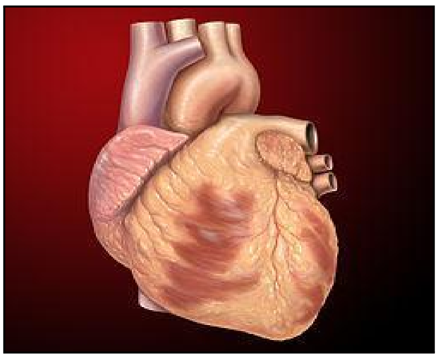
Structure of Human Heart

Position and shape:

The human heart is reddish brown about the size of a person's closed fist i.e., 12 cm (5 in) in length, 8 cm (3.5 in) wide, and 6 cm (2.5 in) in thickness and weighs approx. 250-350 grams, the weight in females being about 25% lesser than the males. Well-trained athletes can have much larger hearts due to the effects of exercise on the heart muscle, similar to the response of skeletal muscle. It is a hollow, highly muscular, cone-shaped structure located in the thoracic cavity above the diaphragm in between the two lungs. Its broader side, called base, is forwarded and upward and the pointed side, called apex, is backward and downward. It is protected by a rib cage. The narrow end of the triangular heart is pointed about 9 cm to the left of the median axis, during working this end gives a feeling of the heart being on the left side.

The heart wall:

The heart is surrounded by two layered tissue membranes called pericardium. Three layers of tissue form the heart wall. The outer visceral layer of the heart wall forms the epicardium, the middle layer is the myocardium, and the inner layer is the endocardium. The space between the two layers is filled with fluid called pericardial fluid. This fluid protects the heart from external pressure, push, shock and reduces friction during the heart beat and facilitates free heart contraction.



The heart consists of three layers:

- **Pericardium or outer covering layer:**

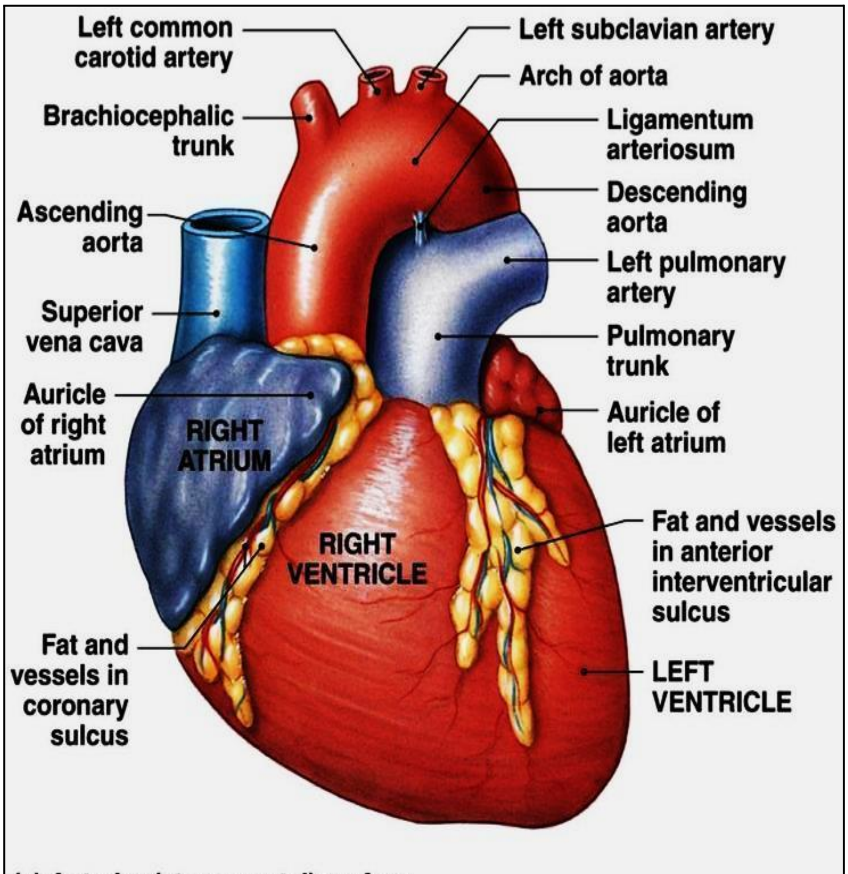
The heart lies in a double membranous sac of pericardium with serous fluid between the two layers. This is known as pericardial fluid. By its lubricating action, the heart can move freely or contract and expand without any injury. So it allows the easy movement of the heart. It keeps the heart moist and absorbs external shock, push and pressure.

- **The Myocardium:**

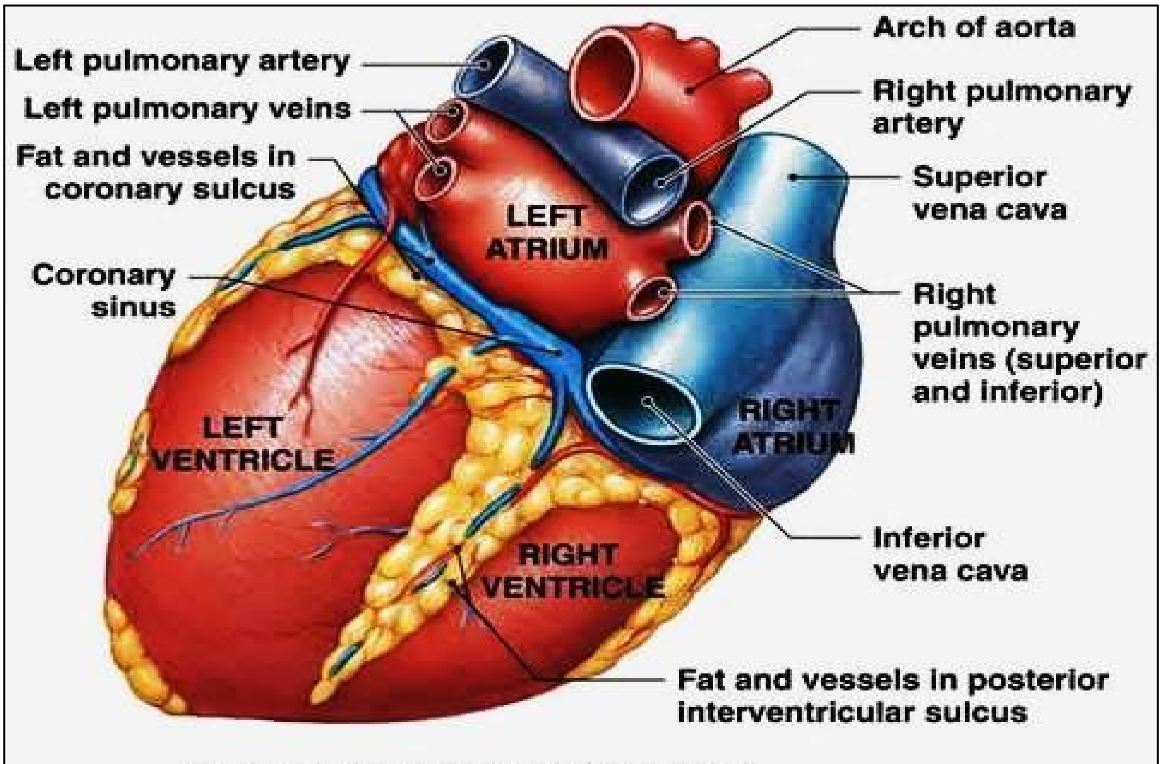
This is the middle muscular layer. The thickness of the heart wall is composed of a network of heart muscle fibers which is known as myocardium. The muscular walls of the heart vary in thickness. The ventricles have the thickest walls. The walls of the left ventricles are thicker than those of the right ventricle because the force of contraction of the left ventricle is much greater. The walls of the auricle are composed of thinner muscles.

- **The Endocardium:**

This is the inner layer of the heart. The heart is lined by an endothelium layer which is known as Endocardium. The valves attached to the heart are the thickened portions of this membrane.



(a) Anterior (sternocostal) surface



(b) Posterior (diaphragmatic) surface

Heart chambers

The heart has four chambers, two upper atria, the **receiving chambers**, and two lower ventricles, the **discharging chambers**. The atria open into the ventricles via the atrioventricular valves, present in the atrioventricular septum. There is an ear-shaped structure in the upper right atrium called the right atrial appendage, or auricle, and another in the upper left atrium, the left atrial appendage. The right atrium and the right ventricle together are sometimes referred to as the *right heart*. Similarly, the left atrium and the left ventricle together are sometimes referred to as the *left heart*. The ventricles are separated from each other by the interventricular septum, visible on the surface of the heart as the anterior longitudinal sulcus and the posterior interventricular sulcus.

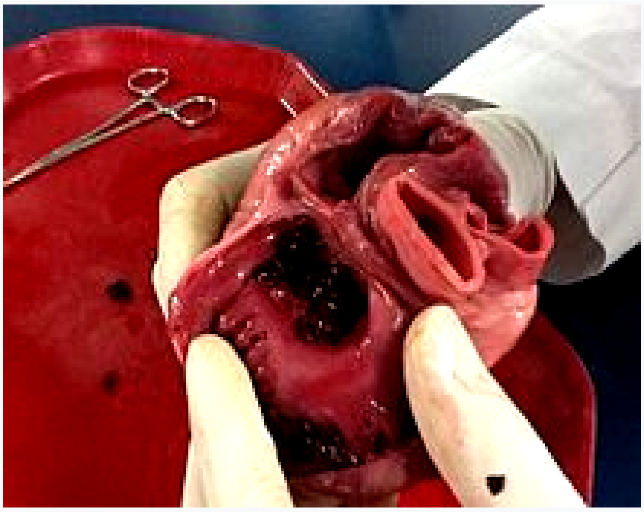


Fig.: Heart being dissected showing right and left ventricles, from above

The cardiac skeleton is made of dense connective tissue and this gives structure to the heart. It forms the atrioventricular septum which separates the atria from the ventricles, and the fibrous rings which serve as bases for the four heart valves. The cardiac skeleton also provides an important boundary in the heart's electrical conduction system since collagen cannot conduct electricity. The interatrial septum separates the atria and the interventricular septum separates the ventricles. The interventricular septum is much thicker than the interatrial septum, since the ventricles need to generate greater pressure when they contract.

Heart Valves

The heart has four valves, which separate its chambers. One valve lies between each atrium and ventricle, and one valve rests at the exit of each ventricle.

The valves between the atria and ventricles are called the atrioventricular valves. Between the right atrium and the right ventricle is the **tricuspid valve**. The tricuspid valve has three cusps, which connect to chordae tendineae and three papillary muscles named the anterior, posterior, and septal muscles, after their relative positions. The **mitral valve** lies between the left atrium and left ventricle. It is also known as the **bicuspid valve** due to its having two cusps, an anterior and a posterior cusp. These cusps are also attached via chordae tendineae to two papillary muscles projecting from the ventricular wall.

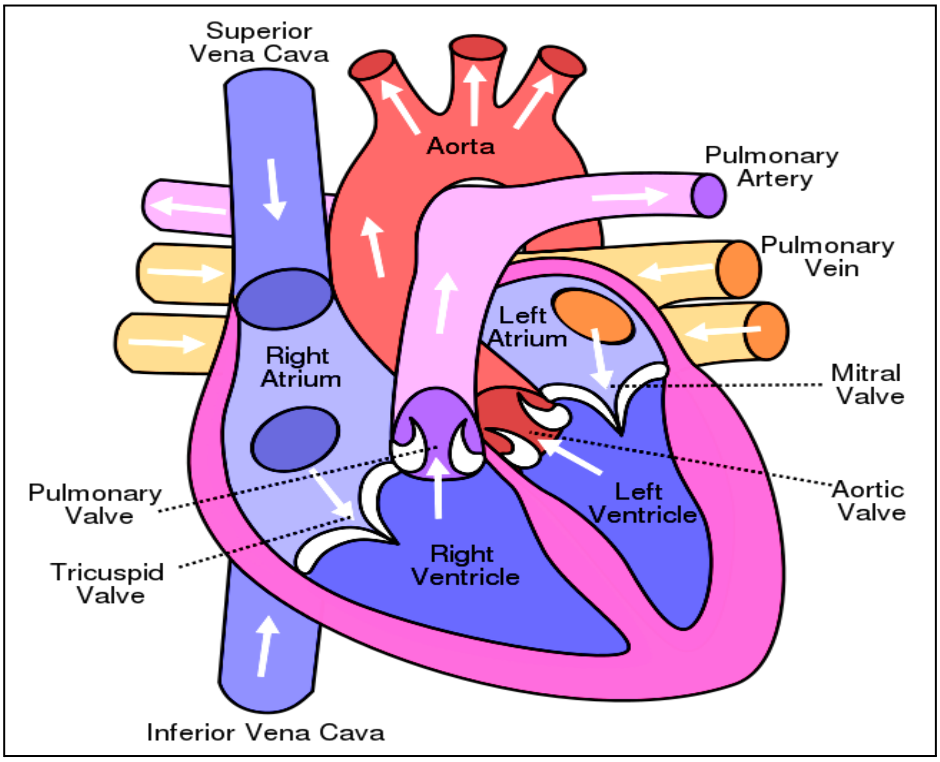


Fig.: he heart, showing valves, arteries and veins.

The papillary muscles extend from the walls of the heart to valves by cartilaginous connections called chordae tendineae. These muscles prevent the valves from falling too far back when they close. During the relaxation phase of the cardiac cycle, the papillary muscles are also relaxed and the tension on the chordae tendinae is slight. As the heart chambers contract, so do the papillary muscles. This creates tension on the chordae tendineae, helping to hold the cusps of the atrioventricular valves in place and preventing them from being blown back into the atria.

Two additional semilunar valves sit at the exit of each of the ventricles. The pulmonary valve is located at the base of the pulmonary artery. This has three cusps which are not attached to any papillary muscles. When the ventricle relaxes blood flows back into the ventricle from the artery and this flow of blood fills the pocket-like valve, pressing against the cusps which close to seal the valve. The **semilunar aortic valve** is at the base of the aorta and also is not attached to papillary muscles. This too has three cusps which close with the pressure of the blood flowing back from the aorta.

Right heart

The right heart consists of two chambers, the right atrium and the right ventricle, separated by a valve, the tricuspid valve. The right atrium receives blood almost continuously from the body's two major veins, the superior and inferior vena cavae. A small amount of blood from the coronary circulation also drains into the right atrium via the coronary sinus, which is immediately above and to the middle of the opening of the inferior vena cava. In the wall of the right atrium is an oval-shaped depression known as the fossa ovalis, which is a remnant of an opening in the fetal heart known as the foramen ovale.

The right atrium is connected to the right ventricle by the valve. The right ventricle tapers into the pulmonary trunk, into which it ejects blood when contracting. The pulmonary trunk branches into the left and right pulmonary arteries that carry the blood to each lung. The pulmonary valve lies between the right heart and the pulmonary trunk.

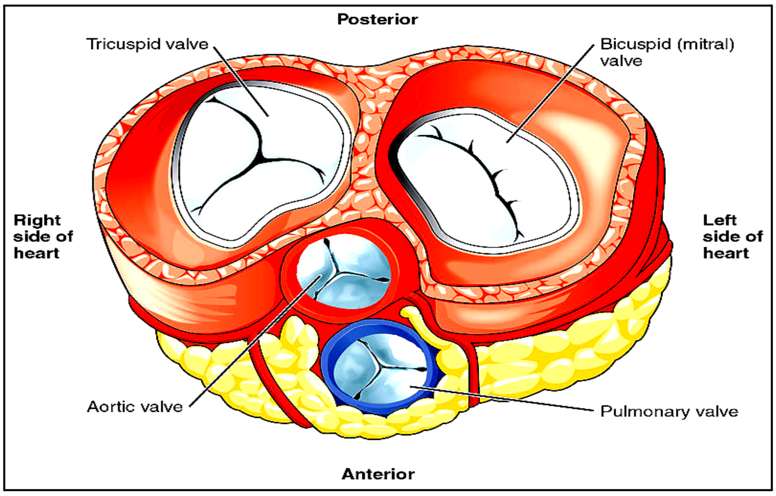


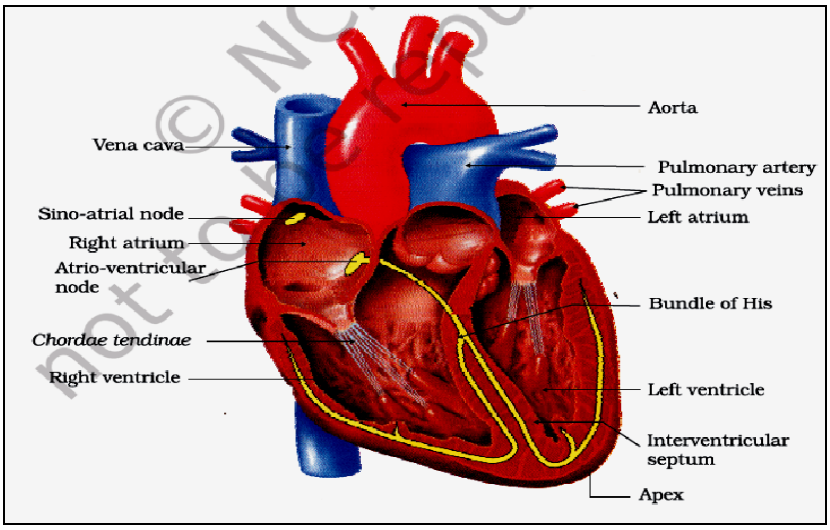
Fig.: With the atria and major vessels removed, all four valves

Left heart

The left heart has two chambers: the left atrium, and the left ventricle, separated by the mitral valve.

The left atrium receives oxygenated blood back from the lungs via one of the four pulmonary veins. The left atrium has an outpouching called the left atrial appendage. Like the right atrium, the left atrium is lined by pectinate muscles. The left atrium is connected to the left ventricle by the mitral valve.

The left ventricle is much thicker as compared with the right, due to the greater force needed to pump blood to the entire body. The left ventricle pumps blood to the body through the aortic valve and into the aorta. Two small openings above the aortic valve carry blood to the heart itself, the left main coronary artery and the right coronary artery.



Circulatory System

Blood flow (Blood circulation)

The heart functions as a pump in the circulatory system to provide a continuous flow of blood throughout the body. This circulation consists of the systemic circulation to and from the body and the pulmonary circulation to and from the lungs. Blood in the pulmonary circulation exchanges carbon dioxide for oxygen in the lungs through the process of respiration. The systemic circulation then transports oxygen to the body and returns carbon dioxide and relatively deoxygenated blood to the heart for transfer to the lungs.

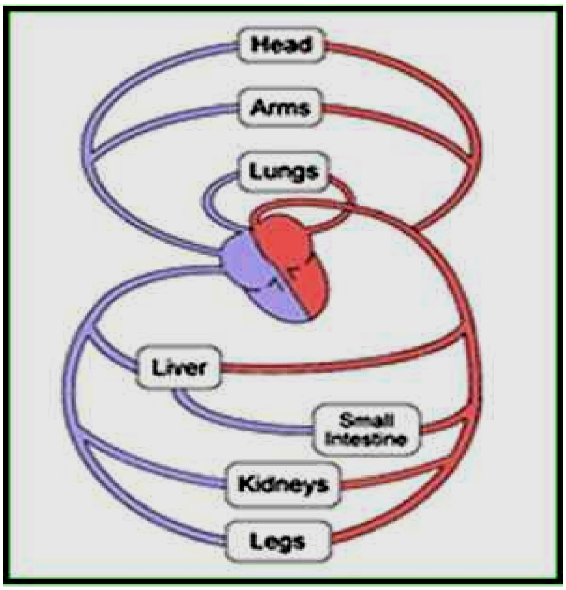


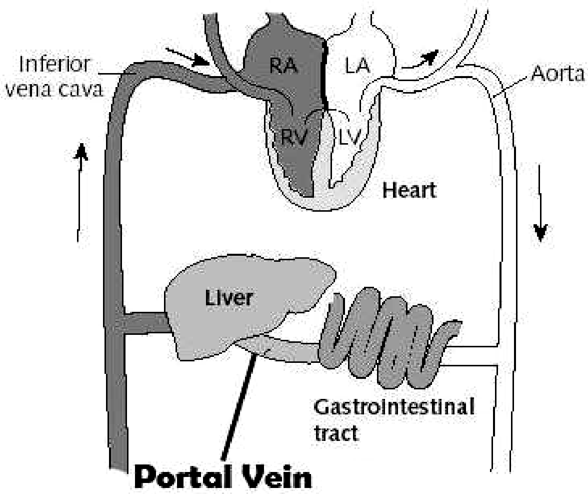
Fig.: Systemic (Greater) Circulation

Portal circulation:

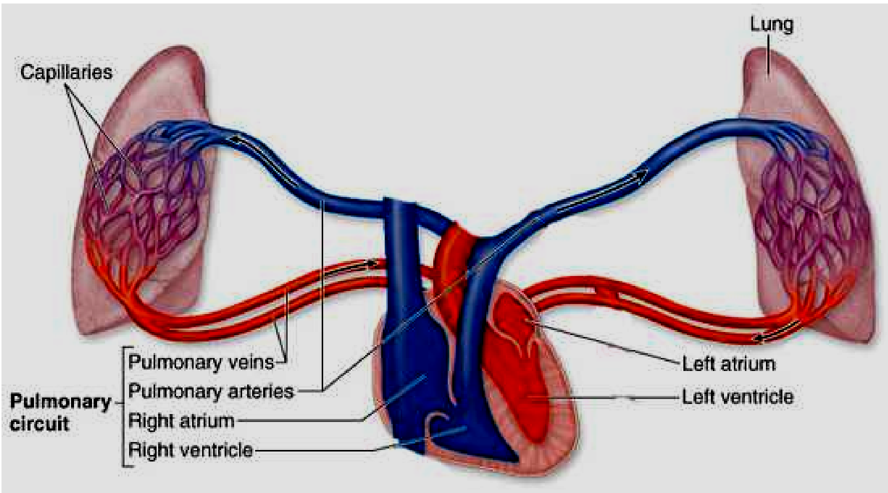
It is a part of systemic circulation, which has the following characteristics.

i. The blood passes through two sets of capillaries before draining into a systemic vein.

ii. The vein draining the first capillary network is known as *portal vein* which branches like an artery to form the second set of capillaries or sinusoids. Examples: hepatic portal circulation and renal portal circulation.



The **right heart** collects deoxygenated blood from two large veins, the superior and inferior vena cavae. Blood collects in the right and left atrium continuously. The superior vena cava drains blood from above the diaphragm and empties into the upper back part of the right atrium. The inferior vena cava drains the blood from below the diaphragm and empties into the back part of the atrium below the opening for the superior vena cava. Immediately above and to the middle of the opening of the inferior vena cava is the opening of the thin-walled coronary sinus. Additionally, the coronary sinus returns deoxygenated blood from the myocardium to the right atrium. The blood collects in the right atrium. When the right atrium contracts, the blood is pumped through the tricuspid valve into the right ventricle. As the right ventricle contracts, the tricuspid valve closes and the blood is pumped into the pulmonary trunk through the pulmonary valve. The pulmonary trunk divides into pulmonary arteries and progressively smaller arteries throughout the lungs, until it reaches capillaries. As these pass by alveoli carbon dioxide is exchanged for oxygen. This happens through the passive process of diffusion.



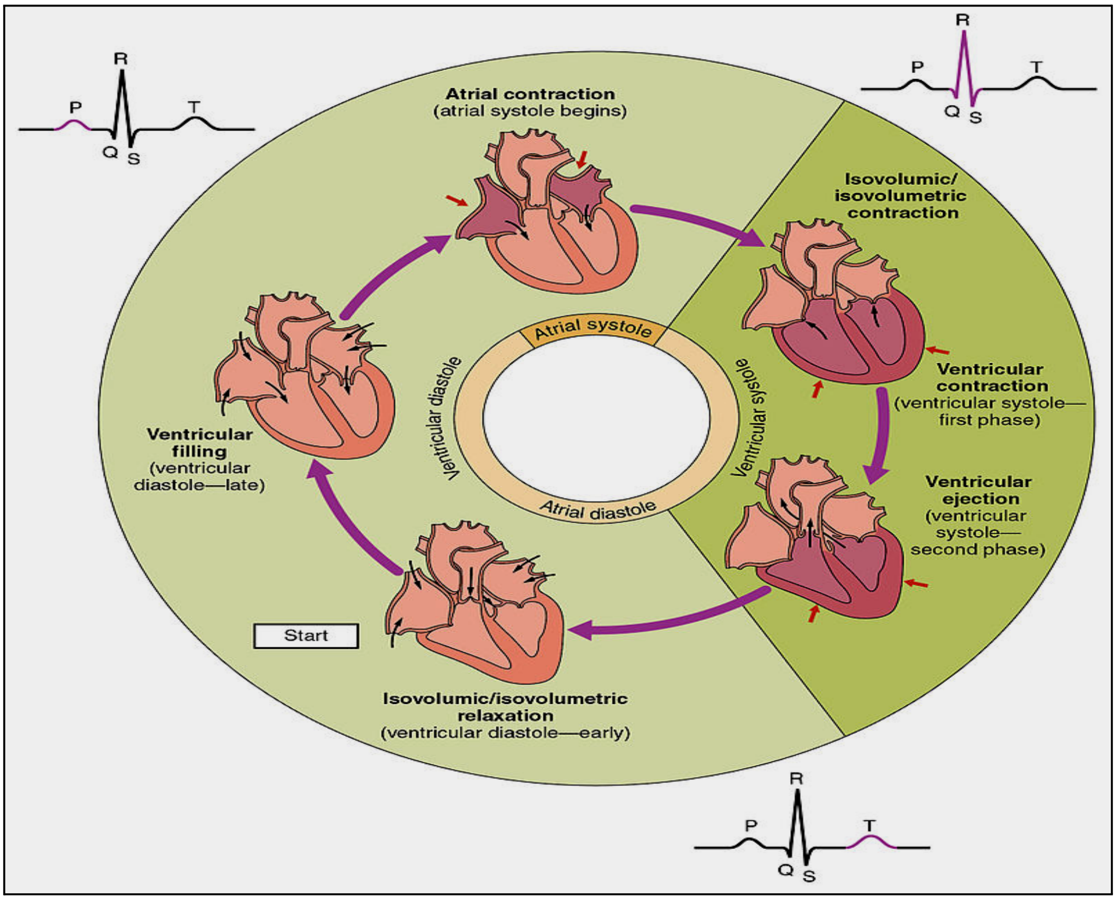
Pulmonary (Lesser) Circulation

In the **left heart**, oxygenated blood is returned to the left atrium via the pulmonary veins. It is then pumped into the left ventricle through the mitral valve and into the aorta through the aortic valve for systemic circulation. The aorta is a large artery that branches into many smaller arteries, arterioles, and ultimately capillaries. In the capillaries, oxygen and nutrients from blood are supplied to body cells for metabolism, and exchanged for carbon dioxide and waste products. Capillary blood, now deoxygenated, travels into venules and veins that ultimately collect in the superior and inferior vena cavae, and into the right heart.

Cardiac Cycle

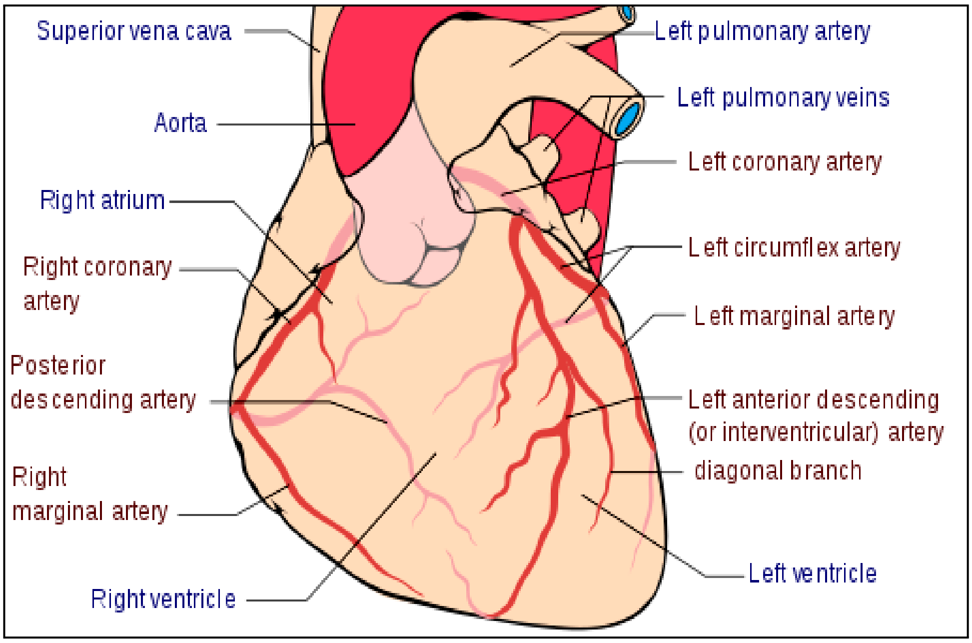
The cardiac cycle is formed by sequential events in the heart which are cyclically repeated and is called the cardiac cycle. A healthy person shows 72 such cycles per minute. How does our heart function? Let us take a look. To begin with, all the four chambers of the heart are in a relaxed state, i.e., they are in joint diastole. As the tricuspid and bicuspid valves are open, blood from the pulmonary veins and vena cava flows into the left and the right ventricle respectively through the left and right atria. The semilunar valves are closed at this stage.

The SAN now generates an action potential which stimulates both the atria to undergo a simultaneous contraction – the atrial systole. This increases the flow of blood into the ventricles by about 30 per cent. The action potential is conducted to the ventricular side by the AVN and AV bundle from where the bundle of His transmits it through the entire ventricular musculature. This causes the ventricular muscles to contract, (ventricular systole), the atria undergoes relaxation (diastole), coinciding with the ventricular systole. Ventricular systole increases the ventricular pressure causing the closure of tricuspid and bicuspid valves due to attempted backflow of blood into the atria.



As the ventricular pressure increases further, the semilunar valves guarding the pulmonary artery (right side) and the aorta (left side) are forced open, allowing the blood in the ventricles to flow through these vessels into the circulatory pathways. The ventricles now relax (ventricular diastole) and the ventricular pressure falls causing the closure of semilunar valves which prevents the backflow of blood into the ventricles.

As the ventricular pressure declines further, the tricuspid and bicuspid valves are pushed open by the pressure in the atria exerted by the blood which was being emptied into them by the veins. The blood now once again moves freely to the ventricles. The ventricles and atria are now again in a relaxed (joint diastole) state, as earlier. Soon the SAN generates a new action potential and the events described above are repeated in that sequence and the process continues. This sequential event in the heart which is cyclically repeated is called the cardiac cycle and it consists of systole and diastole of both the atria and ventricles. As mentioned earlier, the heart beats 72 times per minute, i.e., that many cardiac cycles are performed per minute. From this it could be deduced that the duration of a cardiac cycle is 0.8 seconds. During a cardiac cycle, each ventricle pumps out approximately 70 mL of blood which is called the stroke volume. The stroke volume multiplied by the heart rate (no. of beats per min.) gives the cardiac output. Therefore, the cardiac output can be defined as the volume of blood pumped out by each ventricle per minute and averages 5000 mL or 5 litres in a healthy individual.

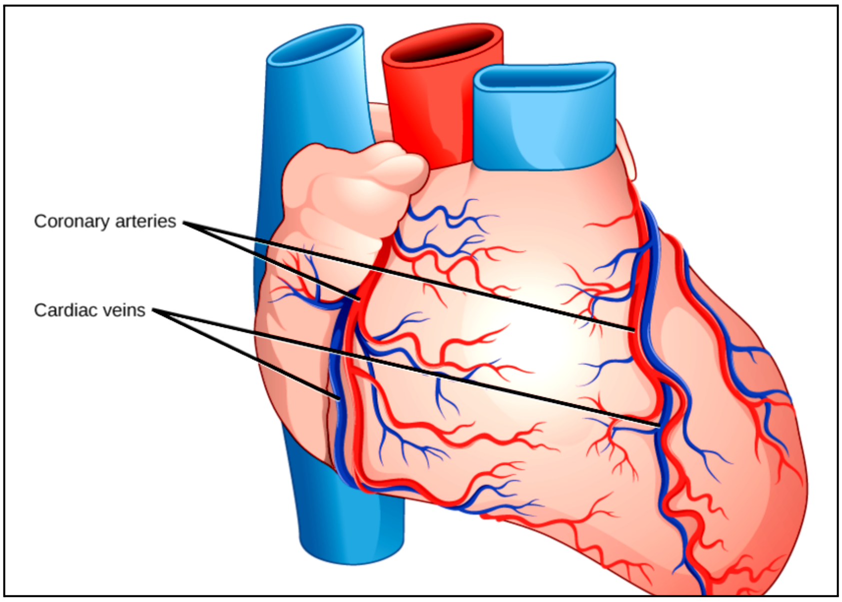


The body has the ability to alter the stroke volume as well as the heart rate and thereby the cardiac output. For example, the cardiac output of an athlete will be much higher than that of an ordinary man. During each cardiac cycle two prominent sounds are produced which can be easily heard through a stethoscope. The first heart sound (lub) is associated with the closure of the tricuspid and bicuspid valves whereas the second heart sound (dub) is associated with the closure of the semilunar valves. These sounds are of clinical diagnostic significance.

Cardiac Output

Cardiac output (CO) is a measurement of the amount of blood pumped by each ventricle (stroke volume) in one minute. This is calculated by multiplying the stroke volume (SV) by the beats per minute of the heart rate (HR). So that: CO = SV x HR. The cardiac output is normalized to body size through body surface area and is called the cardiac index.

The average cardiac output, using an average stroke volume of about 70mL, is 5.25 L/min, with a normal range of 4.0-8.0 L/min. The stroke volume is normally measured using an echocardiogram and can be influenced by the size of the heart, physical and mental condition of the individual, sex, contractility, duration of contraction, preload and afterload.



Preload refers to the filling pressure of the atria at the end of diastole, when they are at their fullest. A main factor is how long it takes the ventricles to fill — if the ventricles contract faster, then there is less time to fill and the preload will be less. Preload can also be affected by a person's blood volume. The force of each contraction of the heart muscle is directly proportional to the initial length of muscle fiber, meaning a ventricle will contract more forcefully, the more it is stretched.

Afterload, or how much pressure the heart must generate to eject blood at systole, is influenced by vascular resistance. It can be influenced by narrowing of the heart valves or contraction or relaxation of the peripheral blood vessels. The strength of heart muscle contractions controls the stroke volume.

Summary

All vertebrates and a few invertebrates have a closed circulatory system. Our circulatory system consists of a muscular pumping organ, heart, a network of vessels and a fluid, blood. Heart has two atria and two ventricles. Sino-atrial node (SAN) generates the maximum number of action potentials per minute (70-75/min) and therefore, it sets the pace of the activities of the heart. Hence, it is called the Pacemaker. The action potential causes the atria and then the ventricles to undergo contraction (systole) followed by their relaxation (diastole). The systole forces the blood to move from the atria to the ventricles and to the pulmonary artery and the aorta. About 70 mL of blood is pumped out by each ventricle during a cardiac cycle and it is called the stroke or beat volume. Volume of blood pumped out by each ventricle of the heart per minute is called the cardiac output and it is equal to the product of stroke volume and heart rate (approx 5 litres).