

THE CIRCULATORY SYSTEM
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Types of Circulatory Systems

Living things must be capable of transporting nutrients, wastes and gases to and from cells. Single-celled organisms use their cell surface as a point of exchange with the outside environment. Multicellular organisms have developed transport and circulatory systems to deliver oxygen and food to cells and remove carbon dioxide and metabolic wastes. Sponges are the simplest animals, yet even they have a transport system. Seawater is the medium of transport and is propelled in and out of the sponge by ciliary action. Simple animals, such as the hydra and planaria (shown in Figure 1), lack specialized organs such as hearts and blood vessels, instead using their skin as an exchange point for materials. This, however, limits the size an animal can attain. To become larger, they need specialized organs and organ systems.

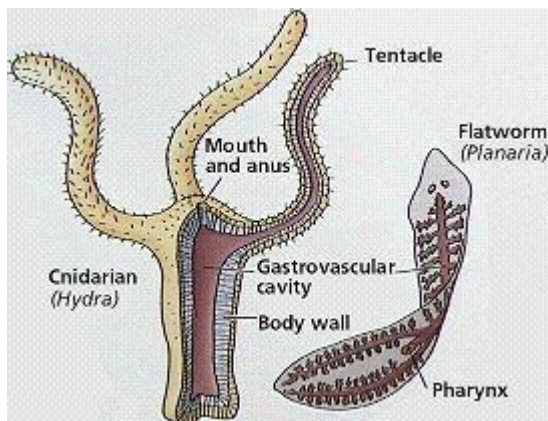


Figure 1. Structures that serve some of the functions of the circulatory system in animals that lack the system

Multicellular animals do not have most of their cells in contact with the external environment and so have developed circulatory systems to transport nutrients, oxygen, carbon dioxide and metabolic wastes. Components of the circulatory system include

blood: a connective tissue of liquid plasma and cells

heart: a muscular pump to move the blood

blood vessels: arteries, capillaries and veins that deliver blood to all tissues

There are several types of circulatory systems. The [open circulatory system](#), examples of which are diagrammed in Figure 2, is common to molluscs and arthropods. Open circulatory systems (evolved in 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. The resulting blood flow is sluggish.

Vertebrates, and a few invertebrates, have a [closed circulatory system](#), shown in Figure 2. Closed circulatory systems (evolved in echinoderms and vertebrates) 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

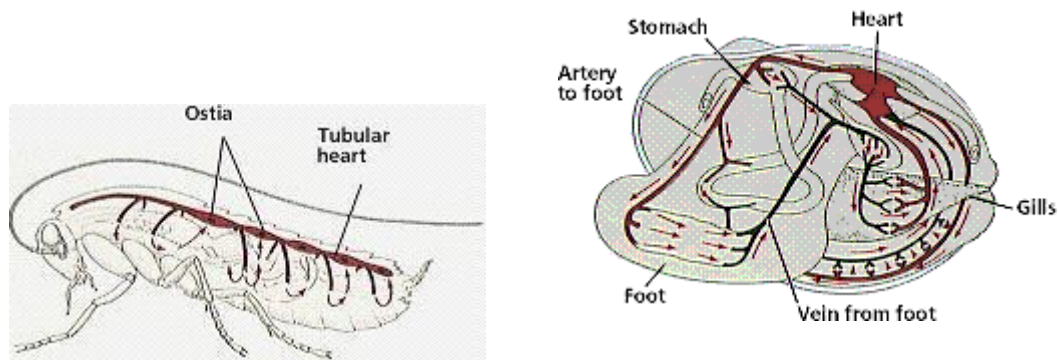


Figure 2. Circulatory systems of an insect (right) and mollusc (left)

vessels, and does not normally fill body cavities. Blood flow is not sluggish. [Hemoglobin](#) causes vertebrate blood to turn red in the presence of oxygen; but more importantly hemoglobin molecules in blood cells transport oxygen. The human closed circulatory system is sometimes called the cardiovascular system. A secondary circulatory system, the [lymphatic circulation](#), collects fluid and cells and returns them to the cardiovascular system.

Vertebrate Cardiovascular System

The vertebrate cardiovascular system includes a heart, which is a muscular pump that contracts to propel blood out to the body through arteries, and a series of blood vessels. The upper chamber of the heart, the [atrium](#) (pl. atria), is where the blood enters the heart. Passing through a valve, blood enters the lower chamber, the [ventricle](#). Contraction of the ventricle forces blood from the heart through an [artery](#). The heart muscle is composed of cardiac muscle cells.

Arteries are blood vessels that carry blood away from heart. Arterial walls are able to expand and contract. Arteries have three layers of thick walls. Smooth muscle fibers contract, another layer of connective tissue is quite elastic, allowing the arteries to carry blood under high pressure.

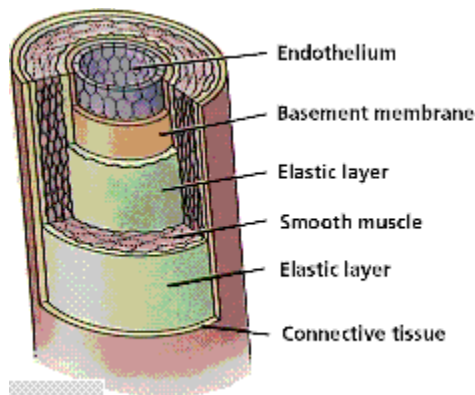


Figure 3. Structure of an artery

The [aorta](#) is the main artery leaving the heart. The [pulmonary artery](#) is the only artery that carries oxygen-poor blood. The pulmonary artery carries deoxygenated blood to the lungs. In the lungs, gas exchange occurs, carbon dioxide diffuses out, oxygen diffuses in. [Arterioles](#) are small arteries that connect larger arteries with [capillaries](#). Small arterioles branch into collections of capillaries known as capillary beds, an example of one is shown in Figure 4.

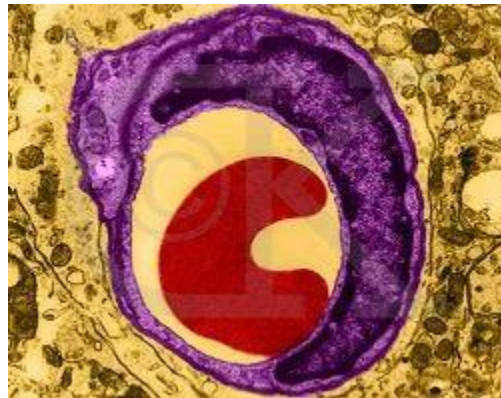
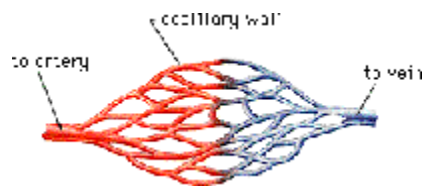


Figure 4. Structure and blood flow through a vein

Figure 5. Capillary with Red Blood Cell (TEM x32,830)

Capillaries, shown in Figures 4 and 5, are thin-walled blood vessels in which gas exchange occurs. In the capillary, the wall is only one cell layer thick. Capillaries are concentrated into [capillary beds](#). Some capillaries have small pores between the cells of the capillary wall, allowing materials to flow in and out of capillaries as well as the passage of white blood cells. Changes in blood pressure also occur in the various vessels of the circulatory system, as shown in Figure 6. Nutrients, wastes, and hormones are exchanged across the thin walls of capillaries. Capillaries are microscopic in size, although blushing is one manifestation of blood flow into capillaries. Control of blood flow into capillary beds is done by nerve-controlled sphincters.

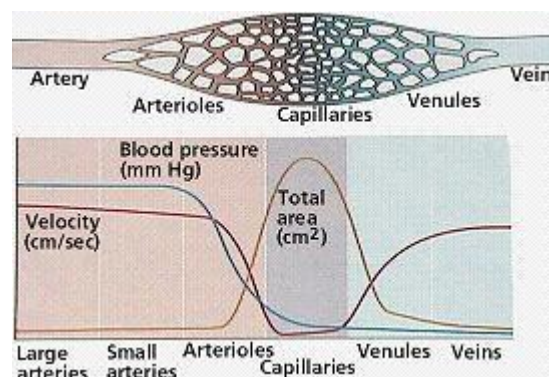


Figure 6. Changes in blood pressure, velocity, and the area of the arteries, capillaries, and veins of the circulatory system

The circulatory system functions in the delivery of oxygen, nutrient molecules, and hormones and the

removal of carbon dioxide, ammonia and other metabolic wastes. Capillaries are the points of exchange between the blood and surrounding tissues. Materials cross in and out of the capillaries by passing through or between the cells that line the capillary, as shown in Figure 7.

The extensive network of capillaries in the human body is estimated at between 50,000 and 60,000 miles long. Thoroughfare channels allow blood to bypass a capillary bed. These channels can open and close by the action of muscles that control blood flow through the channels, as shown in Figure 8.

Blood leaving the capillary beds flows into a progressively larger series of venules that in turn join to form veins. [Veins](#) carry blood from capillaries to the heart. With the exception of the [pulmonary veins](#), blood in veins is oxygen-poor. The pulmonary veins carry oxygenated blood from lungs back to the heart. [Venules](#) are smaller veins that gather blood from capillary beds into veins. Pressure in veins is low, so veins depend on nearby muscular contractions to move blood along. The veins have valves that prevent back-flow of blood, as shown in Figure 9.

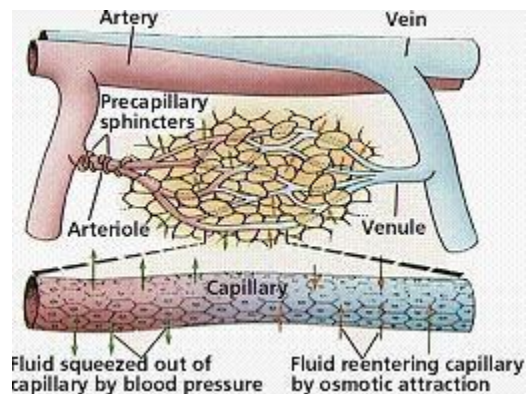


Figure 7. Capillary structure, and relationships of capillaries to arteries and veins

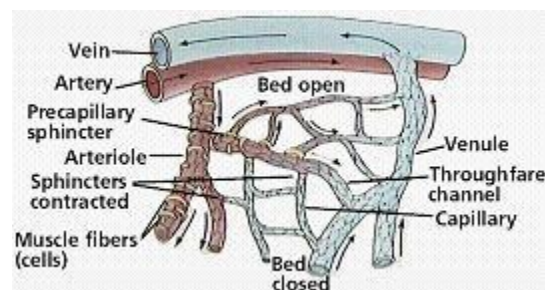


Figure 8. Capillary beds and their feeder vessels

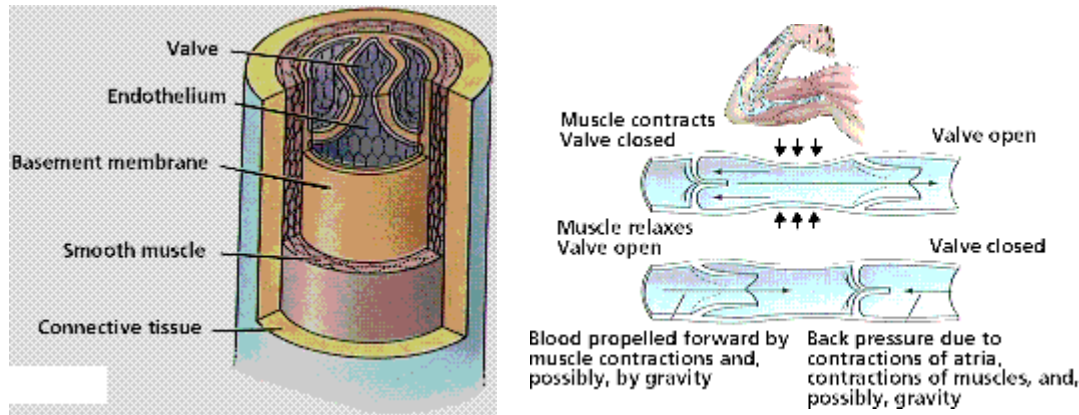


Figure 9. Structure of a vein (right) and the actions of muscles to propel blood through the veins (left)

Ventricular contraction propels blood into arteries under great pressure. Blood pressure is measured in mm of mercury; healthy young adults should have pressure of ventricular systole of 120mm, and 80 mm at ventricular diastole. Higher pressures (human 120/80 as compared to a 12/1 in lobsters) mean the volume of blood circulates faster (20 seconds in humans, 8 minutes in lobsters).

As blood gets farther from the heart, the pressure likewise decreases. Each contraction of the ventricles sends pressure through the arteries. Elasticity of lungs helps keep pulmonary pressures low.

Systemic pressure is sensed by receptors in the arteries and atria. Nerve messages from these sensors communicate conditions to the [medulla](#) in the brain. Signals from the medulla regulate blood pressure.

Vertebrate Vascular Systems

Humans, birds, and mammals have a four-chambered heart that completely separates oxygen-rich and oxygen-depleted blood, as is shown in Figure 10. Fish have a two-chambered heart in which a single-loop circulatory pattern takes blood from the heart to the gills and then to the body. Amphibians have a three-chambered heart with two atria and one ventricle. A loop from the heart goes to the pulmonary capillary beds, where gas exchange occurs. Blood then is returned to the heart. Blood exiting the ventricle is diverted, some to the [pulmonary circuit](#), some to [systemic circuit](#). The disadvantage of the three-chambered heart is the mixing of oxygenated and deoxygenated blood. Some reptiles have partial separation of the ventricle. Other reptiles, plus, all birds and mammals, have a four-chambered heart, with complete separation of both systemic and pulmonary circuits.

The Heart

The heart, shown in Figure 11, is a muscular structure that contracts in a rhythmic pattern to pump blood. Hearts have a variety of forms: chambered hearts in mollusks and vertebrates, tubular hearts of arthropods, and aortic arches of annelids. Accessory hearts are used by insects to boost or supplement the main heart's actions. Fish, reptiles, and amphibians have [lymph hearts](#) that help pump [lymph](#) back into veins.

The basic vertebrate heart, such as occurs in fish, has two chambers. An [auricle](#) is the chamber of the heart where blood is received from the body. A ventricle pumps the blood it gets through a valve from the auricle out to the gills through an artery.

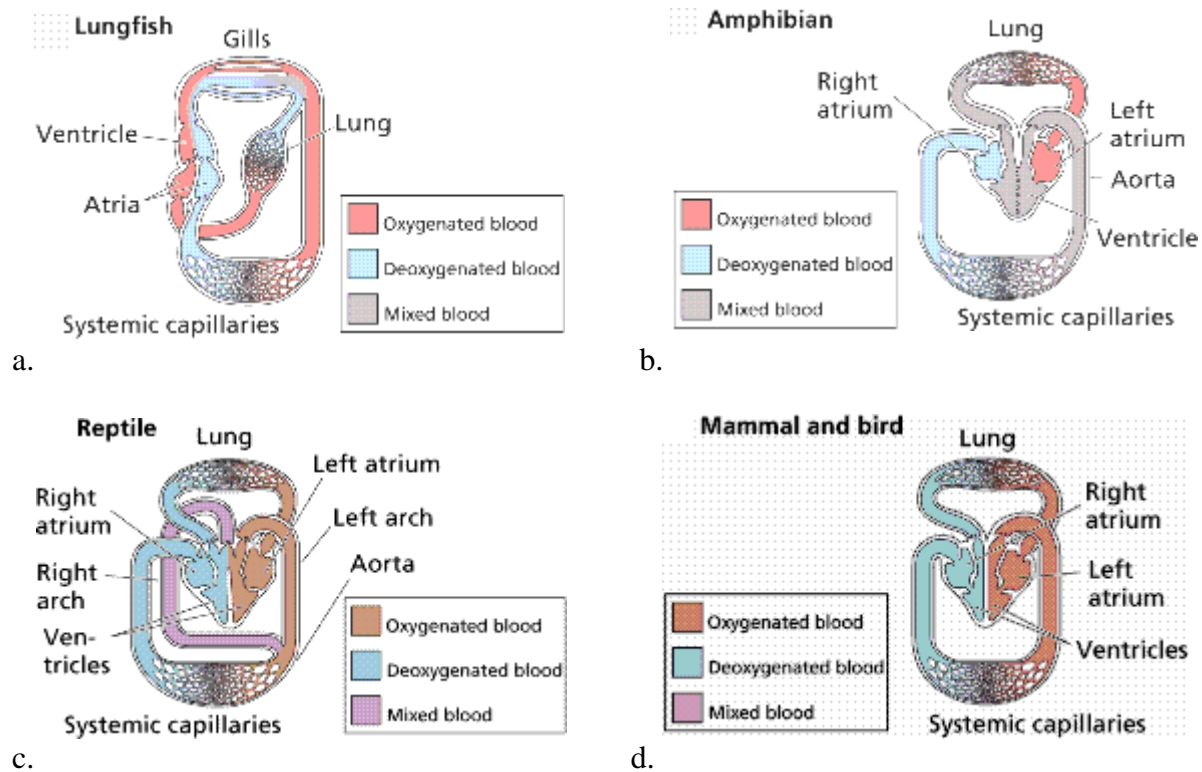


Figure 10. Circulatory systems of several vertebrates showing the progressive evolution of the four-chambered heart and pulmonary and systemic circulatory circuits

Amphibians have a three-chambered heart: two atria emptying into a single common ventricle. Some species have a partial separation of the ventricle to reduce the mixing of oxygenated (coming back from the lungs) and deoxygenated blood (coming in from the body). Two sided or two chambered hearts permit pumping at higher pressures and the addition of the pulmonary loop permits blood to go to the lungs at lower pressure yet still go to the systemic loop at higher pressures.

Establishment of the four-chambered heart, along with the pulmonary and systemic circuits, completely separates oxygenated from deoxygenated blood. This allows higher the metabolic rates needed by warm-blooded birds and mammals.

The human heart, as seen in Figure 11, is a two-sided, four-chambered structure with muscular walls. An [atrioventricular \(AV\) valve](#) separates each auricle from ventricle. A [semilunar \(also known as arterial\) valve](#) separates each ventricle from its connecting artery.

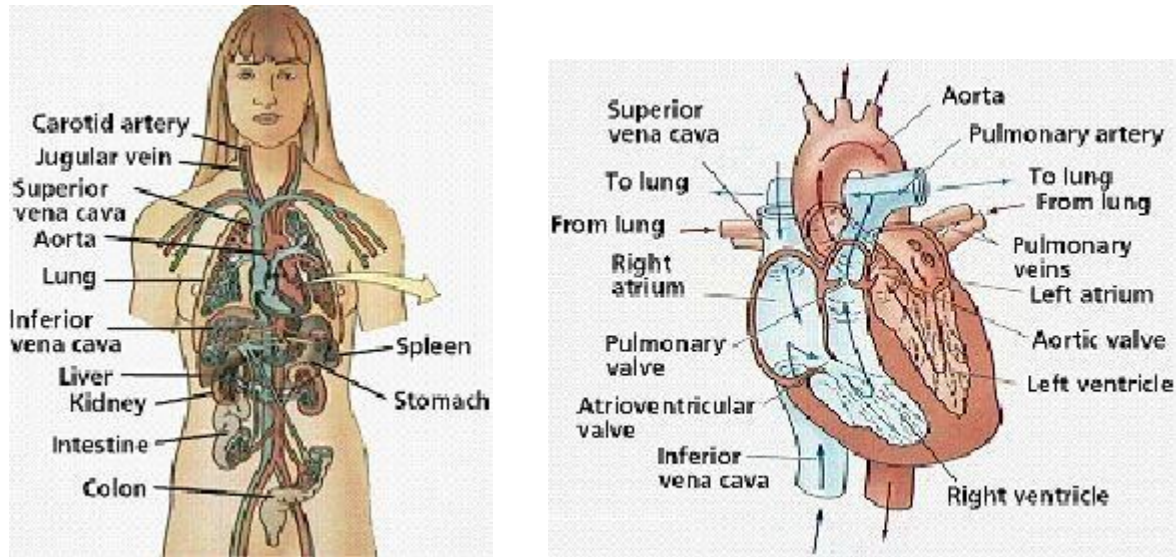


Figure 11. The relationship of the heart and circulatory system to major visceral organs. Right: the structure of the heart

The heart beats or contracts approximately 70 times per minute. The human heart will undergo over 3 billion contraction cycles, as shown in Figure 12, during a normal lifetime. The [cardiac cycle](#) consists of two parts: [systole](#) (contraction of the heart muscle) and [diastole](#) (relaxation of the heart muscle). Atria contract while ventricles relax. The pulse is a wave of contraction transmitted along the arteries. Valves in the heart open and close during the cardiac cycle. Heart muscle contraction is due to the presence of nodal tissue in two regions of the heart. The [SA node \(sinoatrial node\)](#) initiates heartbeat. The [AV node \(atrioventricular node\)](#) causes ventricles to contract. The AV node is sometimes called the pacemaker since it keeps heartbeat regular. Heartbeat is also controlled by nerve messages originating from the autonomic nervous system.

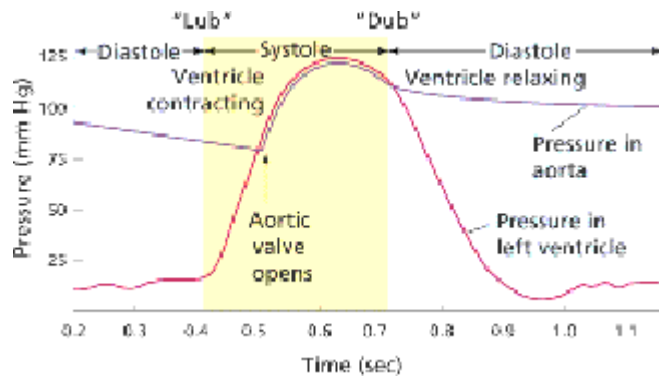


Figure 12. The cardiac cycle

Blood flows through the heart from veins to atria to ventricles out by arteries. Heart valves limit flow to a single direction. One heartbeat, or cardiac cycle, includes atrial contraction and relaxation, ventricular contraction and relaxation, and a short pause. Normal cardiac cycles (at rest) take 0.8 seconds. Blood from the body flows into the vena cava, which empties into the right atrium. At the same time, oxygenated blood from the lungs flows from the pulmonary vein into the left atrium. The

muscles of both atria contract, forcing blood downward through each AV valve into each ventricle. Diastole is the filling of the ventricles with blood. Ventricular systole opens the SL valves, forcing blood out of the ventricles through the pulmonary artery or aorta. The sound of the heart contracting and the valves opening and closing produces a characteristic "lub-dub" sound. Lub is associated with closure of the AV valves, dub is the closing of the SL valves.

Human heartbeats originate from the sinoatrial node (SA node) near the right atrium. Modified muscle cells contract, sending a signal to other muscle cells in the heart to contract. The signal spreads to the atrioventricular node (AV node). Signals carried from the AV node, slightly delayed, through bundle of His fibers and Purkinje fibers cause the ventricles to contract simultaneously. Figure 13 illustrates several aspects of this.

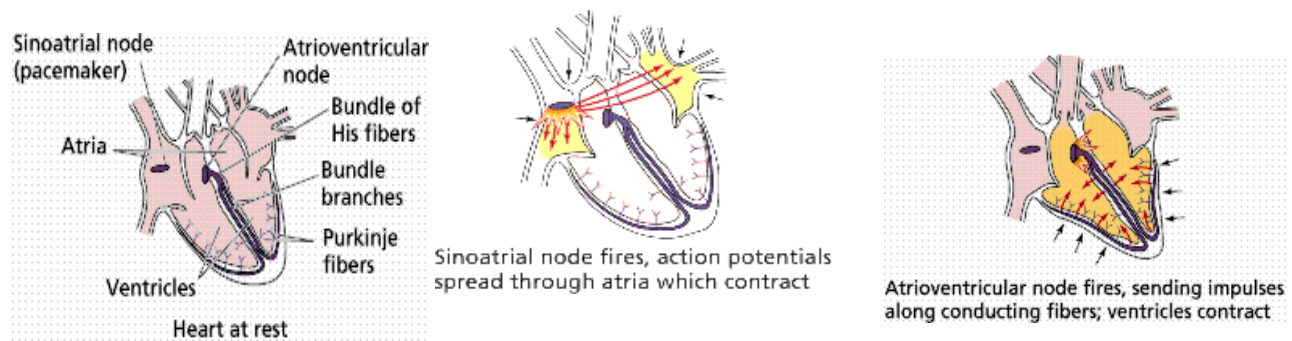


Figure 13. The contraction of the heart and the action of the nerve nodes located on the heart

Heartbeats are coordinated contractions of heart cardiac cells, shown in an animate GIF image in Figure 14. When two or more of such cells are in proximity to each other their contractions synch up and they beat as one.

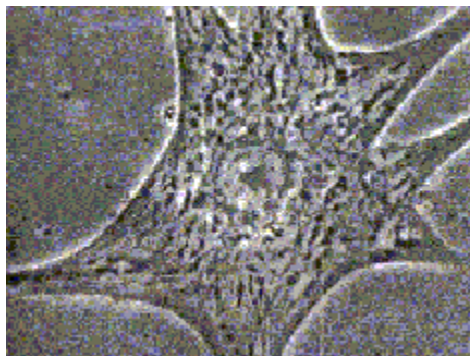


Figure 14. GIF image of a single human heart muscle cell beating

An electrocardiogram (ECG) measures changes in electrical potential across the heart, and can detect the contraction pulses that pass over the surface of the heart. There are three slow, negative changes, known as P, R, and T as shown in Figure 15. Positive deflections are the Q and S waves. The P wave represents the contraction impulse of the atria, the T wave the ventricular contraction. ECGs are useful in diagnosing heart abnormalities.

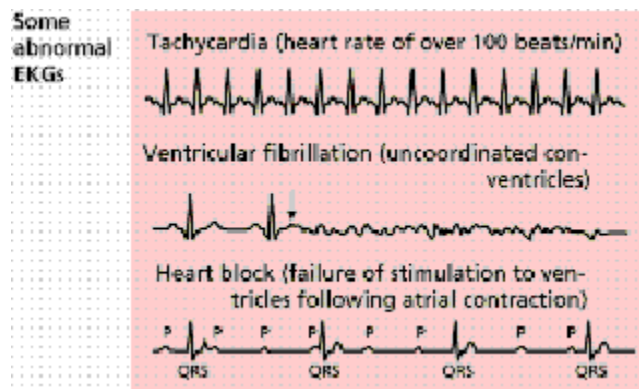
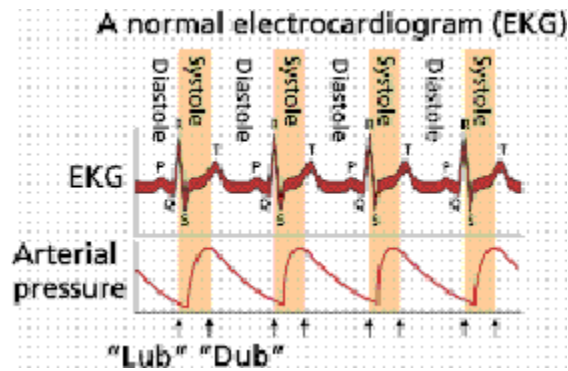


Figure 15. Normal cardiac pattern (top) and some abnormal patterns (bottom)

Diseases of the Heart and Cardiovascular System

Cardiac muscle cells are serviced by a system of [coronary arteries](#). During exercise the flow through these arteries is up to five times normal flow. Blocked flow in coronary arteries can result in death of heart muscle, leading to a heart attack.

Blockage of coronary arteries, shown in Figure 16, is usually the result of gradual buildup of lipids and cholesterol in the inner wall of the coronary artery. Occasional chest pain, angina pectoralis, can result during periods of stress or physical exertion. [Angina](#) indicates oxygen demands are greater than capacity to deliver it and that a heart attack may occur in the future. Heart muscle cells that die are not replaced since heart muscle cells do not divide. Heart disease and coronary artery disease are the leading causes of death in the United States.

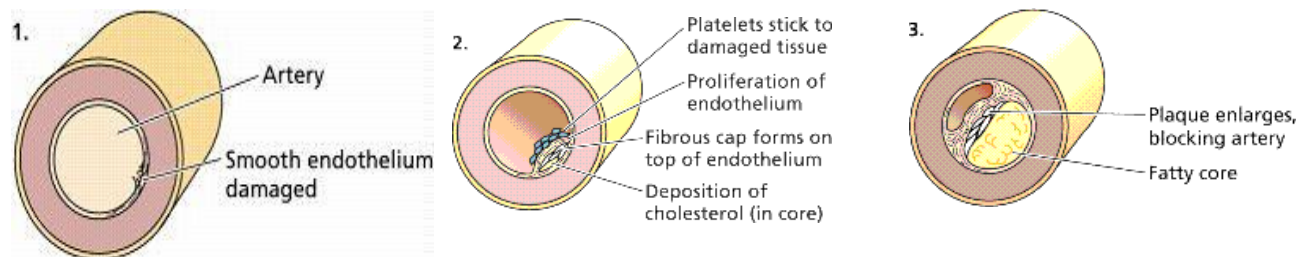


Figure 16. Development of arterial plaque

[Hypertension](#), high blood pressure (the silent killer), occurs when blood pressure is consistently above 140/90. Causes in most cases are unknown, although stress, obesity, high salt intake, and smoking can add to a genetic predisposition. Luckily, when diagnosed, the condition is usually treatable with medicines and diet/exercise.

The Vascular System

Two main routes for circulation are the pulmonary (to and from the lungs) and the systemic (to and from the body). Pulmonary arteries carry blood from the heart to the lungs. In the lungs gas exchange occurs. Pulmonary veins carry blood from lungs to heart. The aorta is the main artery of systemic circuit. The vena cavae are the main veins of the systemic circuit. [Coronary arteries](#) deliver oxygenated blood, food, etc. to the heart. Animals often have a [portal system](#), which begins and ends in capillaries, such as between the digestive tract and the liver.

Fish pump blood from the heart to their gills, where gas exchange occurs, and then on to the rest of the body. Mammals pump blood to the lungs for gas exchange, then back to the heart for pumping out to the systemic circulation. Blood flows in only one direction.

Blood

[Plasma](#) is the liquid component of the blood. Mammalian blood consists of a liquid (plasma) and a number of cellular and cell fragment components as shown in Figure 21. Plasma is about 60 % of a volume of blood; cells and fragments are 40%. Plasma has 90% water and 10% dissolved materials including proteins, glucose, ions, hormones, and gases. It acts as a buffer, maintaining pH near 7.4. Plasma contains nutrients, wastes, salts, proteins, etc. Proteins in the blood aid in transport of large molecules such as cholesterol.

[Red blood cells](#), also known as [erythrocytes](#), are flattened, doubly concave cells about 7 μm in diameter that carry oxygen associated in the cell's hemoglobin. Mature erythrocytes lack a nucleus. They are small, 4 to 6 million cells per cubic millimeter of blood, and have 200 million hemoglobin molecules per cell. Humans have a total of 25 trillion red blood cells (about 1/3 of all the cells in the body). Red blood cells are continuously manufactured in red marrow of long bones, ribs, skull, and vertebrae. Life-span of an erythrocyte is only 120 days, after which they are destroyed in liver and spleen. Iron from hemoglobin is recovered and reused by red marrow. The liver degrades the heme units and secretes them as pigment in the bile, responsible for the color of feces. Each second two million red blood cells are produced to replace those thus taken out of circulation.

[White blood cells](#), also known as [leukocytes](#), are larger than erythrocytes, have a nucleus, and lack hemoglobin. They function in the cellular immune response. White blood cells (leukocytes) are less than 1% of the blood's volume. They are made from stem cells in bone marrow. There are five types of leukocytes, important components of the immune system. Neutrophils enter the tissue fluid by squeezing through capillary walls and phagocytosing foreign substances. [Macrophages](#) release white blood cell growth factors, causing a population increase for white blood cells. [Lymphocytes](#) fight infection. [T-cells](#) attack cells containing viruses. [B-cells](#) produce [antibodies](#). Antigen-antibody complexes are phagocytized by a macrophage. White blood cells can squeeze through pores in the capillaries and fight infectious diseases in interstitial areas.

Platelets result from cell fragmentation and are involved with clotting, as is shown by Figures 17 and 18. Platelets are cell fragments that bud off megakaryocytes in bone marrow. They carry chemicals essential to blood clotting. Platelets survive for 10 days before being removed by the liver and spleen. There are 150,000 to 300,000 platelets in each milliliter of blood. Platelets stick and adhere to tears in blood vessels; they also release clotting factors. A hemophiliac's blood cannot clot. Providing correct proteins (clotting factors) has been a common method of treating hemophiliacs. It has also led to HIV transmission due to the use of transfusions and use of contaminated blood products.

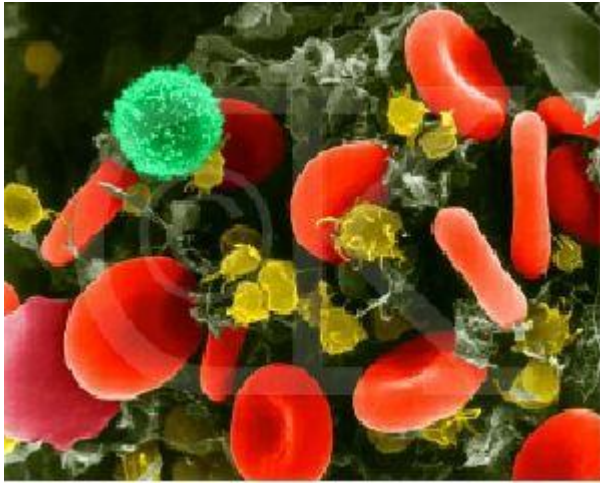


Figure 17. Human Red Blood Cells, Platelets and T-lymphocyte (erythrocytes = red; platelets = yellow; T-lymphocyte = light green) (SEM x 9,900)

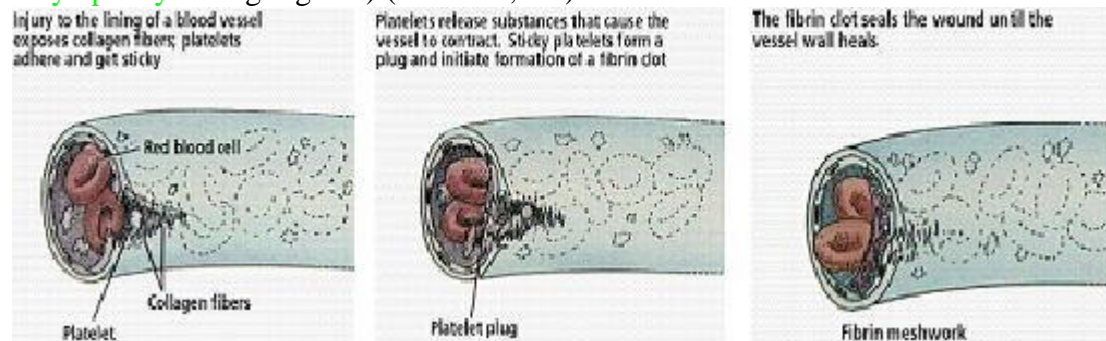
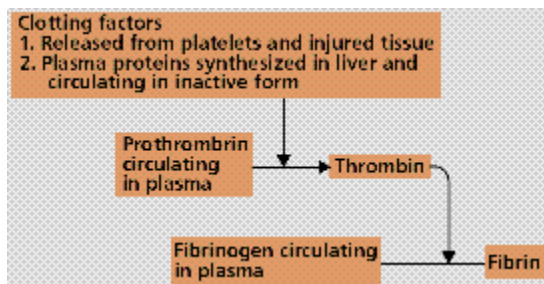


Figure 18. The formation and actions of blood clots



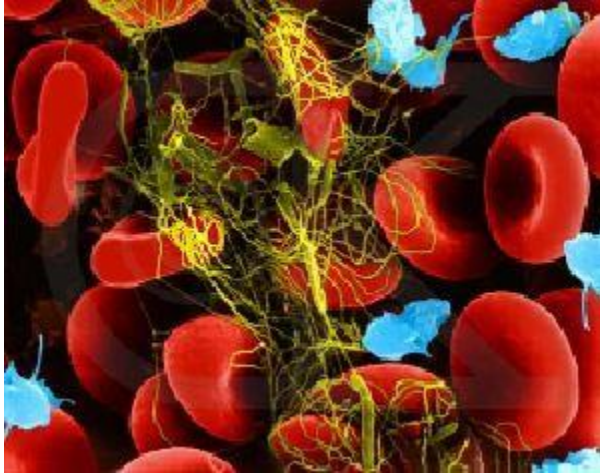


Figure 19. Blood Clot Formation (blood cells, platelets, fibrin clot) (SEM x10,980)

The Lymphatic System

Water and plasma are forced from the capillaries into intracellular spaces. This interstitial fluid transports materials between cells. Most of this fluid is collected in the capillaries of a secondary circulatory system, the lymphatic system. Fluid in this system is known as lymph.

Lymph flows from small lymph capillaries into lymph vessels that are similar to veins in having valves that prevent backflow. Lymph vessels connect to lymph nodes, lymph organs, or to the cardiovascular system at the thoracic duct and right lymphatic duct.

Lymph nodes are small irregularly shaped masses through which lymph vessels flow. Clusters of nodes occur in the armpits, groin, and neck. Cells of the [immune system](#) line channels through the nodes and attack bacteria and viruses traveling in the lymph.

