Circulation in Animals: Evolutionary Trends

- Every organism must exchange materials and energy with its environment, and this exchange ultimately occurs at the cellular level.
- Most animals have organ systems specialized for exchanging materials with the environment, and many have an internal transport system that conveys fluid (blood or interstitial fluid) throughout the body.
- Diffusion alone is not adequate for transporting substances over long distances in animals - for example, for moving glucose from the digestive tract and oxygen from the lungs to the brain of mammal.
- The circulatory system solves this problem by ensuring that no substance must diffuse very far to enter or leave a cell.
- The bulk transport of fluids throughout the body functionally connects the aqueous environment of the body cells to the organs that exchange gases, absorb nutrients, and dispose of wastes.
- Invertebrates have a gastrovascular cavity or a circulatory system for internal transport.
- ***Gastrovascular cavity***: cnidarians and planarians
    - serves for both digestion and for diffusion of substances throughout the body.
        - The fluid inside the cavity is continuous with the water outside through a single opening, the mouth.
        - Thus, both the inner and outer tissue layers are bathed in fluid.
- ***Circulatory systems*** – both open and closed systems have ***blood*** (circulatory fluid), ***vessels*** (tubes through which blood moves), and a ***heart*** (structure that pumps the blood).
    - **Open circulatory system**: insects, mollusks and arthropods
    - Blood bathes the organs directly.
- There is no distinction between blood and interstitial fluid, collectively called **hemolymph**.
- One or more hearts pump the hemolymph into nterconnected **sinuses** surrounding the organs, allowing exchangevbetween hemolymph and body cells.
- In a **closed circulatory system**, as found in earthworms, squid, octopuses, and vertebrates, blood is confined to vessels and is distinct from the interstitial fluid.
    - One or more hearts pump blood into large vessels that branch into smaller ones cursing through organs.
    - Materials are exchanged by diffusion between the blood and the interstitial fluid bathing the cells.
- A fish heart has two main chambers (single loop), one atrium and one ventricle.
- Blood is pumped from the ventricle to the gills (the **gill circulation**) where it picks up oxygen and disposes of carbon dioxide across the capillary walls.
- The gill capillaries converge into a vessel that carries oxygenated blood to capillary beds at the other organs (the **systemic circulation**) and back to the heart.
- Frogs and other amphibians have a three-chambered heart with two atria and one ventricle.
- This scheme, called double circulation, provides a vigorous flow of blood to the brain, muscles, and other organs because the blood is pumped a second time after it loses pressure in the capillary beds of the lung or skin.
    - Blood is under higher pressure
    - Less mixing of oxygenated and de-oxygenated blood
- In crocodilians, birds, and mammals, the ventricle is completely divided into separate right and left chambers.
- In this arrangement, the left side of the heart receives and pumps only oxygen-rich blood, while the right side handles only oxygen-poor blood.
- Double circulation restores pressure to the systemic circuit and prevents mixing of oxygen-rich and oxygen-poor blood.
- The evolution of a powerful four-chambered heart was an essential adaptation in support of the endothermic way of life characteristic of birds and mammals.
    - Endotherms use about ten times as much energy as ectotherms of the same size.
    - Therefore, the endotherm circulatory system needs to deliver about ten times as much fuel and O_2 to their tissues and remove ten times as much wastes and CO_2.

- Humans have a closed circulatory system called the ***cardiovascular system.***
  - The heart has ***atria***; chambers that receive blood returning to the heart) and ***ventricles***; chambers that pump blood out of the heart.
- The main types of blood vessels in humans are the ***arteries***, ***veins***, and ***capillaries***.
  - Arteries carry blood away from the heart and branch into smaller arterioles.
  - Then capillaries network to form capillary beds.
  - These capillary beds converge into venules, which converge into veins, which carry the blood back to the heart.
- To trace the double circulation pattern of the mammalian cardiovascular system, we'll start with the pulmonary (lung) circuit.
- The pulmonary circuit carries blood from the heart to the lungs and back again.
  - (1) The right ventricle pumps blood to the lungs via (2) the pulmonary arteries.
  - As blood flows through (3) capillary beds in the right and left lungs, it loads O_2 and unloads CO_2.
  - Oxygen-rich blood returns from the lungs via the pulmonary veins to (4) the left atrium of the heart.
  - Next, the oxygen-rich blood blows to (5) the left ventricle, as the ventricle opens and the atrium contracts.
- The left ventricle pumps oxygen-rich blood out to the body tissues through the systemic circulation.
  - Blood leaves the left ventricle via (6) the aorta, which conveys blood to arteries leading throughout the body.
    - The first branches from the aorta are the coronary arteries, which supply blood to the heart muscle.
  - The next branches lead to capillary beds (7) in the head and arms.
  - The aorta continues in a posterior direction, supplying oxygen-rich blood to arteries leading to (8) arterioles and capillary beds in the abdominal organs and legs.
    - Within the capillaries, blood gives up much of its O_2 and picks up CO_2 produced by cellular respiration.
- Venous return to the right side of the heart begins as capillaries rejoin to form venules and then veins.
  - Oxygen-poor blood from the head, neck, and forelimbs is channeled into a large vein called (9) the anterior (or superior)
    vena cava.
  - Another large vein called the (10) posterior (or inferior) vena cava drains blood from the trunk and hind limbs.
  - The two venae cavae empty their blood into (11) the right atrium, from which the oxygen-poor blood flows into the right ventricle.
- A **cardiac cycle** is one complete sequence of pumping, as the heart contracts, and filling, as it relaxes and its chambers fill with blood.
  - The contraction phase is called **systole**, and the relaxation phase is called **diastole**.
- For a human at rest with a pulse of about 75 beat per minute, one complete cardiac cycle takes about 0.8 sec.
  (1) During the relaxation phase (atria and ventricles in diastole) lasting about 0.4 sec, blood returning from the large veins flows into atria and ventricles.
  (2) A brief period (about 0.1 sec) of atrial systole forces all the remaining blood out of the atria and into the ventricles.
  (3) During the remaining 0.3 sec of the cycle, ventricular systole pumps blood into the large arteries.
- Cardiac output depends on two factors: the rate of contraction or **heart rate** (number of beats per second) and **stroke volume**, the amount of blood pumped by the left ventricle in each contraction.
  - The average stroke volume for a human is about 75 mL.
  - The typical resting cardiac output, about 5.25 L / min, is about equivalent to the total volume of blood in the human body.
  - Cardiac output can increase about fivefold during heavy exercise.
  - Heart rate can be measured indirectly by measuring your **pulse -** the rhythmic stretching of arteries caused by the pressure of blood pumped by the ventricles.
- Four valves in the heart, each consisting of flaps of connective tissue, prevent backflow and keep blood moving in the correct direction.
  - Between each atrium and ventricle is an **atrioventricular** (**AV**) **valve** which keeps blood from flowing back into the atria when the ventricles contract.
  - Two sets of **semilunar valves**, one between the left ventricle and the aorta and the other between the right ventricle and the pulmonary artery, prevent backflow from these vessels into the ventricles while they are relaxing.

- The heart sounds we can hear with a stethoscope are caused by the closing of the valves; the sound pattern is “lub-dup, lub-dup.”
  - The first heart sound (“lub”) is created by the recoil of blood against the closed AV valves.
  - The second sound (“dup”) is the recoil of blood against the semilunar valves.
- Because the timely delivery of oxygen to the body’s organs is critical for survival, several mechanisms have evolved that assure the continuity and control of heartbeat.
- Certain cells of vertebrate cardiac muscle are self-excitable, meaning they contract without any signal from the nervous system.
  - Each cell has its own intrinsic contraction rhythm.
  - However, these cells are synchronized by the **sinoatrial** (**SA**) **node**, or **pacemaker**, which sets the rate and timing at which all cardiac muscle cells contract.
  - The SA node is located in the wall of the right atrium.
- The cardiac cycle is regulated by electrical impulses that radiate throughout the heart.

  (1) The SA node generates electrical impulses, much like those produced by nerves that spread rapidly (2) through the wall of the atria, making them contract in unison. The impulse from the SA node is delayed by about 0.1 sec at the **atrioventricular** (**AV**) **node**, the relay point to the ventricle, allowing the atria to empty completely before the ventricles contract.

  (3) Specialized muscle fibers called bundle branches conduct the signals to the apex of the heart and (4) throughout the ventricular walls. This stimulates the ventricles to contract from the apex toward the atria, driving blood into the large arteries.
- The impulses generated during the heart cycle produce electrical currents that are conducted through body fluids to the skin.
- Here, the currents can be detected by electrodes and recorded as an **electrocardiogram** (**ECG** or **EKG**).
- While the SA node sets the tempo for the entire heat, it is influenced by a variety of physiological cues.
  - Two sets of nerves affect heart rate with one set speeding up the pacemaker and the other set slowing it down.
    - Heart rate is a compromise regulated by the opposing actions of these two sets of nerves.
  - The pacemaker is also influenced by hormones.
    - For example, epinephrine from the adrenal glands increases heart rate.
  - The rate of impulse generation by the pacemaker increases in response to increases in body temperature and with exercise.

Structural differences of arteries, veins, and capillaries correlate with their different functions

- All blood vessels are built of similar tissues.
- The walls of both arteries and veins have three similar layers.
  - On the outside, a layer of connective tissue with elastic fibers allows the vessel to stretch and recoil.
  - A middle layer has smooth muscle and more elastic fibers.
  - Lining the lumen of all blood vessels, including capillaries, is an **endothelium**, a single layer of flattened cells that minimizes resistance to blood flow.
- Structural differences correlate with the different functions of arteries, veins, and capillaries.
  - Capillaries lack the two outer layers and their very thin walls consist of only endothelium and its basement membrane, thus enhancing exchange.
- Arteries have thicker middle and outer layers than veins.
  - The thicker walls of arteries provide strength to accommodate blood pumped rapidly and at high pressure by the heart.
  - Their elasticity (elastic recoil) helps maintain blood pressure even when the heart relaxes.
- The thinner-walled veins convey blood back to the heart at low velocity and pressure.
  - Blood flows mostly as a result of skeletal muscle contractions when we move that squeeze blood in veins.
  - Within larger veins, flaps of tissues act as one-way valves that allow blood to flow only toward the heart.

Transfer of substances between the blood and the interstitial fluid occurs across the thin walls of capillaries

- At any given time, only about 5-10% of the body's capillaries have blood flowing through them.
  - Capillaries in the brain, heart, kidneys, and liver are usually filled to capacity, but in many other sites, the blood supply varies over times as blood is diverted.
    - After a meal blood supply to the digestive tract increases.
- The exchange of substances between the blood and the interstitial fluid that bathes the cells takes place across the thin endothelial walls of the capillaries.
  - Some substances are carried across endothelial cells in vesicles that form by endocytosis on one side and then release their contents by exocytosis on the other side.
  - Others simply diffuse between the blood and the interstitial fluid across cells or through the clefts between adjoining cells.
- Transport through these clefts occurs mainly by bulk flow due to fluid pressure.
  - Blood pressure within the capillary pushes fluid, containing water and small solutes, through the capillary clefts.
    - This causes a net loss of fluid at the upstream of the capillary.
- Blood cells and most proteins in the blood are too large to pass through and remain in the capillaries.
- As blood proceeds along the capillary, blood pressure continues to drop and the capillary becomes hyperosmotic compared to the interstitial fluids.
  - The resulting osmotic gradient pulls water into the capillary by osmosis near the downstream end.
  - About 85% of the fluid that leaves the blood at the arterial end of the capillary bed reenters from the interstitial fluid at the venous end.
  - The remaining 15% is eventually returned to the blood by the vessels of the lymphatic system.

The lymphatic system returns fluid to the blood and aids in body defense

- Fluids and some blood proteins that leak from the capillaries into the interstitial fluid are returned to the blood via the **lymphatic system**.
  - Fluid enters this system by diffusing into tiny lymph capillaries intermingled among capillaries of the cardiovascular system.
  - Once inside the lymphatic system, the fluid is called **lymph**, with a composition similar to the interstitial fluid.
  - The lymphatic system drains into the circulatory system near the junction of the venae cavae with the right atrium.
- Lymph vessels, like veins, have valves that prevent the backflow of fluid toward the capillaries.
  - Rhythmic contraction of the vessel walls help draw fluid into lymphatic capillaries.
  - Also like veins, lymph vessels depend mainly on the movement of skeletal muscle to squeeze fluid toward the heart.
- Along a lymph vessels are organs called **lymph nodes**.
  - The lymph nodes filter the lymph and attack viruses and bacteria.
  - Inside a lymph node is a honeycomb of connective tissue with spaces filled with white blood cells specialized for defense.
    - When the body is fighting an infection, these cells multiply, and the lymph nodes become swollen.

Blood is a connective tissue with cells suspended in plasma

- In invertebrates with open circulation, blood (hemolymph) is not different from interstitial fluid.
- However, blood in the closed circulatory systems of vertebrates is a specialized connective tissue consisting of several kinds of cells suspended in a liquid matrix called **plasma**.
- The plasma includes the cellular elements (cells and cell fragments), which occupy about 45% of the blood volume, and the transparent, straw-colored plasma.
- The plasma, about 55% of the blood volume, consists of water, ions, various plasma proteins, nutrients, waste products, respiratory gases, and hormones, while the cellular elements include red and white blood cells and platelets.
- Blood plasma is about 90% water.
- Dissolved in the plasma are a variety of ions, sometimes referred to as blood electrolytes.
    - These are important in maintaining osmotic balance of the blood and help buffer the blood.
    - Also, proper functioning of muscles and nerves depends on the concentrations of key ions in the interstitial fluid, which reflects concentrations in the plasma.
- Plasma carries a wide variety of substances in transit from one part of the body to another, including nutrients, metabolic wastes, respiratory gases, and hormones.
- The plasma proteins have many functions.
    - Collectively, they acts as buffers against pH changes, help maintain osmotic balance, and contribute to the blood's viscosity.
    - Some specific proteins transport otherwise-insoluble lipids in the blood.
    - Other proteins, the immunoglobins or antibodies, help combat viruses and other foreign agents that invade the body.
    - Fibrinogen proteins help plug leaks when blood vessels are injured.
        - Blood plasma with clotting factors removed is called serum.
- Suspended in blood plasma are two classes of cells: **red blood cells** which transport oxygen, and **white blood cells**, which function in defense.
- A third cellular element, **platelets**, are pieces of cells that are involved in clotting.
- Red blood cells, or **erythrocytes**, are by far the most numerous blood cells.
- The main function of red blood cells, oxygen transport, depends on rapid diffusion of oxygen across the red cell's plasma membranes.
    - Human erythrocytes are small biconcave disks, presenting a great surface area.
    - Mammalian erythrocytes lack nuclei, an unusual characteristic that leaves more space in the tiny cells for **hemoglobin**, the iron-containing protein that transports oxygen.
    - Red blood cells also lack mitochondria and generate their ATP exclusively by anaerobic metabolism.
- An erythrocyte contains about 250 million molecules of **hemoglobin**.
    - Each hemoglobin molecule binds up to four molecules of O_2.
- There are five major types of white blood cells, or **leukocytes**: monocytes, neutrophils, basophils, eosinophils, and lymphocytes.
- Their collective function is to fight infection.
    - White blood cells spend most of their time outside the circulatory system, patrolling through interstitial fluid and the lymphatic system, fighting pathogens.
- The third cellular element of blood, **platelets**, are fragments of cells about 2 to 3 microns in diameter.
    - They have no nuclei and originate as pinched-off cytoplasmic fragments of large cells in the bone marrow.
    - Platelets function in blood clotting.
- Erythrocytes, leukocytes, and platelets all develop from a single population of cells, **pluripotent stem cells**, in the red marrow of bones, particularly the ribs, vertebrae, breastbone, and pelvis.
    - "Pluripotent" means that these cells have the potential to differentiate into any type of blood cells or cells that produce platelets.
    - This population renews itself while replenishing the blood with cellular elements.

- Blood contains a self-sealing material that plugs leaks from cuts and scrapes.
  - A clot forms when the inactive form of the plasma protein **fibrinogen** is converted to **fibrin**, which aggregates into threads that form the framework of the clot.
  - The clotting mechanism begins with the release of clotting factors from platelets.

  (1) The clotting process begins when the endothelium of a vessel is damaged and connective tissue in the wall is exposed to blood.

  - Platelets adhere to collagen fibers and release a substance that makes nearby platelets sticky.

  (2) The platelets form a plug.

  (3) The seal is reinforced by a clot of fibrin when vessel damage is severe.
- Anticlotting factors in the blood normally prevent spontaneous clotting in the absence of injury.