Circulation and Gas Exchange

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Circulation in Animals

Transport systems functionally connect the organs of exchange with the body cells: an overview

- **Diffusion**: Diffusion rate is proportional to the square of the distance the chemical will travel.
  - Diffusion is too slow, which need the circulation system to improve:

Most invertebrates have a gastrovascular cavity of a circulatory system for internal transport

Gastrovascular cavity: hydra and planarian.

Open and close circulatory system

- **Open circulatory system**: mollusks (except cephalopods), arthropods, etc.
  - (**Hemo**)**sinus** and **Hemolymph**:
- **Close circulatory system**: earthworm, octopus, vertebrates, etc.
  - Blood is confined to vessels including capillaries.

Vertebrate phylogeny is reflected in adaptations of the cardiovascular system

- Internal transport is accomplished by the **cardiovascular system:** heart (**atrium** and **ventricle**), blood vessels (**artery**, **arteriole**, **vein**, **venule**, and **capillary**), and blood.
- **Double circulation** (**pulmocutaneous** or **pulmonary circuit** and **systemic circuit**) in two atria animals:
  - **Pulmocutaneous** or **pulmonary circuit** leads to the gas exchange tissues.
  - **Systemic circuit** carries oxygen-rich blood to all body organs.

Double circulation in mammals depends on the anatomy and pumping cycle of the heart

The mammalian heart: a closer look

- **Atria**: function as collection chambers for blood returning to the heart.
- **Ventricle**s have thicker walls and are much more powerful than the atria. Especially the left ventricle must pump blood through the systemic circuit.

- **Heart valve**s: keeping blood from flowing back into the atria or ventricles
  - **Atrioventricular valve**: between each atrium and ventricle
  - **Semilunar valve** locates at the two exits of the heart: aorta-left ventricle and pulmonary-right ventricle.
- **Heart sound**s: "lub-dupp" can be heard with a stethoscope:
  - The sound of "lub" creates by the forceful contraction of the ventricles and the closing of the **atrioventricular valve**s.
  - The sound of "dupp" causes by the closing of the **semilunar valve**s.

- **Cardiac cycle** takes about 0.8 second (about 75 beats per minute)
  - **Systole**: The heart muscle contracts, which refers to only the contraction of the ventricles, but we shall include atrial contraction in systole.
  - **Diastole**: The relaxation phase of heart muscle

	(0.1 sec)	(0.3 sec)	(0.4 sec)
atria	systole →	diastole →	diastole
ventricles	diastole →	systole →	diastole
AV valves	open →	closed →	open
semilunar valves	closed →	open →	closed

- **Cardiac output** depends on two factors: heart rate and stroke volume
  - **Heart rate** (**pulse**) and size show an inverse relationship in mammals: 70 beats per minute in human
  - **Stroke volume**: 75 ml per beat in human

Maintaining the heart's rhythmic beat

- Cardiac muscle is self-excitable: without any signal from the nervous system.
  - Each separated cardiac muscle cells pulsate at irregular intervals.

- **Sinoatrial** (**SA**) **node** (**pacemaker**) is located in the wall of the right atrium, near the point where the **superior vena cava** enters the heart.
  - When the SA node contracts, it generates electrical impulses like those found in nerve, which spreads rapidly causing the two atria contract in unison.
  - Pacemaker is controlled by two sets of nerves, hormones, exercise, or body temperature (1℃ increases the heart rate by about 10 to 20 beats/min).
- **Atrioventricular** (**AV**) **node**: between the right atrium and right ventricle.
  - When the wave of excitation reaches the AV node, it is delayed for about 0.1 second. The delay ensures that atria contract first and empty completely before ventricle contract. The signal is then conducted quickly down **AV bundle** to **bundle branch**es and on to **Purkinje fiber**s, which terminate on ventricular cells.

- **Electrocardiogram** (**EKG** or **ECG**):
  - The impulses that travel through cardiac muscle during the heart cycle produce electoral currents that are conducted through body to the body surface, and can be detected and recorded by electrodes placed on the skin.

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

- The wall of an artery or vein has three layers:
  1. Outer layer: connective tissue with elastic fiber.
  2. Middle layer: smooth muscle and more elastic fiber (thicker in the artery).
  3. Liner: **endothelium**.
     - The thin walls of capillaries consist only of the endothelium.

Physical laws governing the movement of fluids through pipes affect blood flow and blood pressure

- Blood flow velocity: Blood does not flow through the circulatory system at a uniform speed
- **Law of continuity**: a rule governs the flow of fluids through pipes.
  - The volume of flow per second must be constant through the entire pipe:
  - Although an individual capillary is very narrow, the total diameter is much greater in capillary beds than in any other part of the circulatory system.

- **Blood pressure**: the hydrostatic force of blood exerts against the wall of a vessel, which is related to **cardiac output** and **peripheral resistance** to blood flow due to the **arteriole**s.
  - The surge of pressure is partly due to the **narrow openings of arteriole**s impeding the exit of blood from the arteries.
- **Measurement of blood pressure**: Blood pressure is recorded as two numbers separated by a slash -- systolic pressure/diastolic pressure.
  - By the time blood reaches the veins, its pressure has dropped to near zero. Two ways to help blood returning to the heart:
    1. Veins are sandwiched in between skeletal muscles:
    2. One-way valves within large veins:

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

- At any given time, only about 5% to 10% of the body's capillaries have blood flowing through them.
  - Capillaries in the brain, heart, kidneys, and liver are usually filled with blood. The blood supply in other sites varies from time to time: e.g., after a meal or during exercise.

- Two mechanisms regulate the distribution of blood in capillary beds.
  1. Contraction of the smooth muscle layer in the wall of arterioles constricts the arteriole, decreasing blood flow through it to a capillary bed.
  2. **Precapillary sphincter**s of smooth muscle control the flow of blood between arterioles and venules.

- Capillary exchange:
  - Capillary is the main place to exchange substances between blood and the interstitial fluid.
  - In addition blood cells suspended in blood and most proteins dissolved in blood are too large to pass through the endothelium, most small molecules like nutrients and gases can diffuse or be endocytosed across the membrane of endothelium.

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

- **Lymph**: its composition is about the same as that of interstitial fluid.
  - About 15% of the fluid lost from capillaries is eventually returned to the blood by the vessels of the lymphatic system.
  - Like veins, lymph vessels have valves to prevent back flow of fluid, and depend mainly on the movement of skeletal muscles to squeeze fluid.

- **Lymph node**: some specialized swellings along a lymph vessel.
  - Lymph node on the body's defense: by filtering the lymph and attacking viruses and bacteria. When the body is fighting an infection, these cells multiply rapidly, and the lymph nodes becomes swollen and tender.

- **Edema**: Interstitial fluid accumulates, and cannot return to blood.

Blood is a connective tissue with cells suspended in plasma

- blood cells - clotting factors

blood ---------- **plasma** ---------- **serum**

(100%) (55%)

Plasma: 90% of water

- Blood electrolytes: inorganic salts - osmotic balance.
  - Some of the ions help buffer the blood: pH of 7.4 in humans.
  - The kidney maintains plasma electrolytes at precise concentrations.
  - The ability of muscles and nerves to function normally depends on the concentration of key ions (Na^+, K^+, Ca^{++}, and Mg^{++}) in the interstitial fluid.
- Immunoglobulins & clotting factors

Cellular elements

- **Red blood cell**s (**RBC**s, **erythrocyte**s): the most numerous blood cells – 5 X 10^6 RBCs / mm^3 of human blood
  - RBCs in vertebrates have nuclei except in mammals. All RBCs lack mitochondria and generate their ATP exclusively by anaerobic metabolism.
  - The major function of erythrocytes is to carry oxygen.
    1. The biconcave shape of the RBCs adds to its surface area.
    2. The smaller the cells, the greater the total area of plasma membrane.
    3. Each RBC contains about 250 X 10^6 molecules of **hemoglobin**, which composed four peptides (**heme**s). Each heme contains one iron molecule that is the oxygen-binding site.

- **White blood cell**s (**WBC**s, **leukocyte**s): **basophil**s, **eosinophil**s, **neutrophil**s (polymorphonuclear leukocyte, **PMN**), **lymphocyte**s (T lymphocyte and B-lymphocyte), and **monocyte**s (**macrophage**).
  - 5,000 to 10,000 WBCs / mm^3 of human blood

- **Platelet**s: **no nuclei** and originate as pinched off cytoplasmic fragments of large cells in the bone marrow.

Stem cells and the replacement of cellular elements

- RBCs, leukocytes all develop from **pluripotent stem cell**s in the red marrow of bones, particularly the ribs, vertebrae, breastbone, and pelvis.
  - Those stem cells maybe use to treat certain human diseases, like **leukemia**.
- When the tissues do not receive enough oxygen, the kidney produces **erythropoietin** to stimulate production of RBCs in the bone marrow.
- RBCs circulate for about 3 to 4 months before being destroyed by phagocytic cells located mainly in the liver and spleen.

Blood clotting

- The clotting mechanism begins with release of clotting factors from platelets and involves a complex chain of reactions that ultimately transforms **fibrinogen** (inactive form) to **fibrin** (active form).
- **Hemophilia**: an inherited defect in any step of the clotting process
- **Thrombus**: a clot formed by platelet clump and fibrin coagulation within a blood vessel block the flow of blood in a key artery.
- Anticlotting: mosquito and leech

Cardiovascular Diseases are the leading cause of death in the United State and most other developed nations

- **Heart attack**: the death of cardiac muscle tissues resulting from prolonged blockage of **coronary arteries**.
- **Stroke** causes the death of nervous tissue in the brain.
- The healthy arteries have smooth linings: When plaques develop, the risk of blood clot plugging an artery greatly increases. Also, the rougher lining of an artery encourages the adhesion of platelets, which trigger the clotting process.

- **Atherosclerosis** is causes by **plaque**s developing and **lipid infiltration** on the inner walls of the arteries.
  - If a coronary artery is partially blocked by atherosclerosis, a person may feel occasional **chest pain** (**angina pectoris**), which is a signal that part of the heart is not receiving sufficient supply of oxygen.
- **Arteriosclerosis**: hardening of the arteries caused by **calcium deposit**

- **Cardiopulmonary resuscitation** (**CPR**) can restore the heartbeat.

- **Hypertension** (high blood pressure):
  - Diastolic pressure above 90 mmHg may be cause for concern:
  - To some extent, the tendency for hypertension and atherosclerosis is **inherited**. But smoking, lack of exercise, and diet rich in animal fats and cholesterol are among the factors that have been correlated with an increased risk of cardiovascular disease.

- **Cholesterol**: An abnormally high concentration of cholesterol in blood plasma is one of the most important correlates of potential atherosclerosis.
  - Cholesterol travels in the blood plasma mainly in the form of particles made up of thousands of cholesterol molecules and other lipids bound to a protien.
    - **LDL**s (low-density lipoproteins): the main form of cholesterol travelling in the blood.
      - Cells of the liver and other organs remove LDLs from blood when the particles bind to membrane receptors and enter the cells by endocytosis.
    - **HDL**s (high-density lipoproteins): reducing deposit of cholesterol in arterial plaques.
  - Many researchers realize that the ratio of LDL/HDL is more reliable than total plasma cholesterol as an indicator of impending cardiovascular disease.
  - Exercise tends to increase HDL concentration, while smoking has the opposite effect on the LDL/HDL ratio.

Gas Exchange in Animals

Gas exchange supplies oxygen for cellular respiration and disposes of carbon dioxide: an overview

- One of major function of circulatory system – to enhance gas transportation.
- **Respiratory medium**: Air and water.
  - The warmer and saltier the water, the less dissolved oxygen it holds.
- **Respiratory surface**:
  - The respiratory surface of a lung, gill, or other respiratory organ is a thin, moist epithelium, usually with a rich blood supply.
    - Small animals have long or flat shape: high ratio of surface to volume.
    - Most of animals lack sufficient body surface to exchange gases for the whole body: folded or branched a localized region of body surface.
    - O_2 and CO_2 have to dissolve in the water and diffuse through membranes.

Gills are respiratory adaptations of most aquatic animals

- Gills are external and vulnerable to physical damage or to attack from other organisms: shell of clam and shrimp, or **operculum** of fish.
- **Ventilation**:
  - Shrimp: pleopods as paddles are used to beat a current of water over the gills
  - Shark: non-stop swimming to force water pass through their gills
- **Countercurrent exchange**:

Tracheal systems and lungs are respiratory adaptations of terrestrial animals

Tracheal system: spiracles → tracheae → tracheoles → cells

- Some larger insects ventilate their tracheal systems with rhythmic body movements that compress and expand the air tubes like **bellows**.

Lungs: respiratory adaptation of terrestrial vertebrates

- The lungs of mammals have a spongy texture and are honeycombed: In human, the total lung area is as large as a tennis court.
- The passageways connecting the lungs to the outside air are narrow: loss of water by evaporation is minimized.
- Other modification: vascularized mantle in land snails; book lungs in spiders; balloon like lungs and moist outer skin in frogs.

Mammalian respiratory system: a closer look

air → nostril → nasal cavity → pharynx → glottis → larynx

↓

alveoli ← bronchiole ← bronchus ← trachea

- Air enters through the nostrils and is then filtered by hairs, warmed, humidified, and sampled for odors as it flows through the nasal cavity.

- **Larynx** (Adam's apple): as voice box in humans and many other mammals.
  - As air is exhaled through the chamber, a pair of vocal cords vibrates and produces sounds. Pitch is controlled by changing the tension of the cords.

- The epithelial lining of the **trachea** is covered by a thin film of mucus:
- **Alveolus** (alveoli): the bronchioles dead-end, multi-lobed air sacs.

Ventilating the lungs

- Vertebrates ventilate their lungs by breathing: the alternate inhalation and exhalation of air.
  - **Positive pressure breathing**: The lungs ventilate like a pressure pump.
    - Frog: The nostrils and mouth are closed, and the floor of its mouth is raised, which forces air down the trachea.

- **Negative pressure breathing**: The lungs ventilate like a suction pump.
  - During vigorous exercise, we use the rib muscles to pull the ribs upward from their normal position, which expands the rib cage.
  - Shallow breathing: When we are at rest, **diaphragm** rather than rib muscle is used. Air is exhaled when the diaphragm relaxes to its dome shape.

- Birds have eight or nine **air sac**s besides their lungs:
  - The lungs of a bird have tiny channels, **parabronchi**, through which air can flow continuously in one direction.

- **Tidal volume** of air: an animal inhales and exhales with each breath.
- **Vital capacity**: The maximum volume of air that can be inhaled and exhaled during forced breathing.
  - The lungs actually hold more air than the vital capacity, but since it is impossible to completely collapse the alveoli, a **residual volume** of air remains in the lungs even we forcefully blow out as much air as we can.
  - As lungs lose their resilience as a result of aging or disease:

Control centers in the brain regulate the rate and depth of breathing

- The control center of our breathing is located in the **medulla**:
  - As inhalation deepens, stretch sensors in the lung tissue send nervous impulses that inhibit the breathing center.
  - The breathing center also monitors the pH of the blood: the amount of carbon dioxide in the blood.
  - Oxygen has little affect on the breathing center: Oxygen sensors in key arteries send alarm signals to the breathing center when O_2 level is too low.

Gases diffuse down pressure gradients in the lungs and other organs

- The concentration of gases (in air or in water) is measured as partial pressure.

Respiratory pigments transport gases and help buffer the blood

Oxygen transport

- Since very little oxygen is transported in blood in the form of dissolved O_2, **respiratory pigment**s such as **hemoglobin** are required as transporters.
  - In some animals, such as earthworm, the hemoglobin is dissolved directly in the blood plasma rather than being located in the cells.
  - **Hemocyanin** has copper as its oxygen-binding component: blue blood.
- **Allosteric effect**:

Carbon dioxide transport:

- About 7% of the carbon dioxide is transported as dissolved CO_2 in blood plasma; another 23% binds to the multiple amino groups of hemoglobin; about 70% is transported in the blood in the form of bicarbonate ions.
  - Carbon dioxide first reacts with water to form carbonic acid, which then dissociate into a hydrogen ion and a bicarbonate ion.
  - Most of the hydrogen ions produced as a by-product of this reaction attach to various sites on hemoglobin and other proteins: hemoglobin acts as a buffer.

Deep-diving mammals stockpile oxygen and consume it slowly

- Ability to store oxygen: Compared to humans, the seals store about twice as much oxygen per kilogram of body weight, mostly in the blood and muscles.
  - Human: 36% of total oxygen in lungs, 51% in blood, and 13% in muscle
  - Seal: 5% in lungs, 70 % in blood, and 25% in muscle
    1. Huge spleen: store about 24 L of blood
    2. Higher concentration of **myoglobin** (one of oxygen-storing protein) in their muscles than most other mammals.
    3. Regulatory mechanisms affecting peripheral resistance route most blood to the brain, spinal cord, eyes, adrenal glands, and placenta (in pregnant seals). Blood supply to the muscles is restricted.