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Circulation & Gas Exchange

Every organism must exchange materials with its environment.

Exchanges ultimately occur at the cellular level by crossing the plasma membrane.

In unicellular organisms, these exchanges occur directly with the environment.

For most cells making up multicellular organisms, direct exchange with the environment is not possible.

Gills are an example of a specialized exchange system in animals.

$O_2$ diffuses from the water into blood vessels.

$CO_2$ diffuses from blood into the water.

Internal transport and gas exchange are functionally related in most animals.

Circulation ~ diffusion

Diffusion time is proportional to the square of the distance.

Diffusion is only efficient over small distances.

In small and/or thin animals, cells can exchange materials directly with the surrounding medium.

In most animals, cells exchange materials with the environment via a fluid-filled circulatory system.

Gastrovascular Cavities

Some animals lack a circulatory system.

Some cnidarians, such as jellies, have elaborate gastrovascular cavities.

A gastrovascular cavity functions in both digestion and distribution of substances throughout the body.

The body wall that encloses the gastrovascular cavity is only two cells thick.

Flatworms have a gastrovascular cavity and a large surface area to volume ratio.

A circulatory system has

A circulatory fluid.
A set of interconnecting vessels

A muscular pump, the **heart**

The circulatory system connects the fluid that surrounds cells with the organs that exchange gases, absorb nutrients, and dispose of wastes

Circulatory systems can be open or closed, and vary in the number of circuits in the body

**Open vs. Closed Circulatory Systems**

In insects, other arthropods, and most molluscs, blood bathes the organs directly in an open circulatory system

In an open circulatory system, there is no distinction between blood and interstitial fluid, and this general body fluid is called **hemolymph**

In a **closed circulatory system**, blood is confined to vessels and is distinct from the interstitial fluid

Closed systems are more efficient at transporting circulatory fluids to tissues and cells

Annelids, cephalopods, and vertebrates have closed circulatory systems

**Vertebrate C.S.'s**

Humans and other vertebrates have a closed circulatory system called the **cardiovascular system**

The three main types of blood vessels are arteries, veins, and capillaries

Blood flow is one way in these vessels

**Arteries** branch into **arterioles** and carry blood away from the heart to **capillaries**

Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid

**Venules** converge into **veins** and return blood from capillaries to the heart

Arteries and veins are distinguished by the direction of blood flow, not by O₂ content

Vertebrate hearts contain two or more chambers

Blood enters through an **atrium** and is pumped out through a **ventricle**
In reptiles and mammals, oxygen-poor blood flows through the **pulmonary circuit** to pick up oxygen through the lungs

In amphibians, oxygen-poor blood flows through a **pulmocutaneous circuit** to pick up oxygen through the lungs and skin

Oxygen-rich blood delivers oxygen through the **systemic circuit**

Double circulation maintains higher blood pressure in the organs than does single circulation

**Amphibians**

Frogs and other amphibians have a three-chambered heart: two atria and one ventricle

The ventricle pumps blood into a forked artery that splits the ventricle’s output into the pulmocutaneous circuit and the systemic circuit

When underwater, blood flow to the lungs is nearly shut off

**Reptiles (Except Birds)**

Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle

In alligators, caimans, and other crocodilians a septum divides the ventricle

Reptiles have double circulation, with a pulmonary circuit (lungs) and a systemic circuit

**Mammals & Birds**

Mammals and birds have a four-chambered heart with two atria and two ventricles

The left side of the heart pumps and receives only oxygen-rich blood, while the right side receives and pumps only oxygen-poor blood

Mammals and birds are endotherms and require more O₂ than ectotherms

Blood begins its flow with the right ventricle pumping blood to the lungs

In the lungs, the blood loads O₂ and unloads CO₂

Oxygen-rich blood from the lungs enters the heart at the left atrium and is pumped through the aorta to the body tissues by the left ventricle

The aorta provides blood to the heart through the coronary arteries

Blood returns to the heart through the superior vena cava (blood from head, neck, and forelimbs) and inferior vena cava (blood from trunk and hind limbs)
The superior vena cava and inferior vena cava flow into the right atrium

The heart contracts and relaxes in a rhythmic cycle called the **cardiac cycle**

The contraction, or pumping, phase is called **systole**

The relaxation, or filling, phase is called **diastole**

The **heart rate**, also called the pulse, is the number of beats per minute

The **stroke volume** is the amount of blood pumped in a single contraction

The **cardiac output** is the volume of blood pumped into the systemic circulation per minute and depends on both the heart rate and stroke volume

Four valves prevent backflow of blood in the heart

The **atrioventricular (AV) valves** separate each atrium and ventricle

The **semilunar valves** control blood flow to the aorta and the pulmonary artery

Some cardiac muscle cells are self-excitable, meaning they contract without any signal from the nervous system

The **sinoatrial (SA) node**, or pacemaker, sets the rate and timing at which cardiac muscle cells contract

Impulses that travel during the cardiac cycle can be recorded as an **electrocardiogram** (ECG or EKG)

**Vessel Structure & Function**

A vessel’s cavity is called the central lumen

The epithelial layer that lines blood vessels is called the **endothelium**

The endothelium is smooth and minimizes resistance

Capillaries have thin walls, the endothelium plus its basal lamina, to facilitate the exchange of materials

Arteries and veins have an endothelium, smooth muscle, and connective tissue

Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart

In the thinner-walled veins, blood flows back to the heart mainly as a result of muscle action
Blood Flow Velocity

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

Velocity of blood flow is slowest in the capillary beds, as a result of the high resistance and large total cross-sectional area.

Blood flow in capillaries is necessarily slow for exchange of materials.

Pressure

Blood flows from areas of higher pressure to areas of lower pressure.

Blood pressure is the pressure that blood exerts against the wall of a vessel.

In rigid vessels blood pressure is maintained; less rigid vessels deform and blood pressure is lost.

**Systolic pressure** is the pressure in the arteries during ventricular systole; it is the highest pressure in the arteries.

**Diastolic pressure** is the pressure in the arteries during diastole; it is lower than systolic pressure.

A **pulse** is the rhythmic bulging of artery walls with each heartbeat.

Pressure Regulation

Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles.

**Vasoconstriction** is the contraction of smooth muscle in arteriole walls; it increases blood pressure.

**Vasodilation** is the relaxation of smooth muscles in the arterioles; it causes blood pressure to fall.

Vasoconstriction and vasodilation help maintain adequate blood flow as the body’s demands change.

Nitric oxide is a major inducer of vasodilation.

The peptide endothelin is an important inducer of vasoconstriction.

Blood pressure is generally measured for an artery in the arm at the same height as the heart.
Blood pressure for a healthy 20 year old at rest is 120 mm Hg at systole and 70 mm Hg at diastole

Capillary Function

Blood flows through only 5–10% of the body’s capillaries at a time

Capillaries in major organs are usually filled to capacity

Blood supply varies in many other sites

Two mechanisms regulate distribution of blood in capillary beds

Contraction of the smooth muscle layer in the wall of an arteriole constricts the vessel

Precapillary sphincters control flow of blood between arterioles and venules

Blood flow is regulated by nerve impulses, hormones, and other chemicals

Fluid return – Lymphatic System

The **lymphatic system** returns fluid that leaks out from the capillary beds

Fluid, called **lymph**, reenters the circulation directly at the venous end of the capillary bed and indirectly through the lymphatic system

The lymphatic system drains into veins in the neck

Valves in lymph vessels prevent the backflow of fluid

**Lymph nodes** are organs that filter lymph and play an important role in the body’s defense

Edema is swelling caused by disruptions in the flow of lymph

Blood Composition

With open circulation, the fluid that is pumped comes into direct contact with all cells

The closed circulatory systems of vertebrates contain blood, a specialized connective tissue

Blood consists of several kinds of cells suspended in a liquid matrix called **plasma**

The cellular elements occupy about 45% of the volume of blood

Blood Plasma

Blood plasma is about 90% water
Among its solutes are inorganic salts in the form of dissolved ions, sometimes called electrolytes.

Another important class of solutes is the plasma proteins, which influence blood pH, osmotic pressure, and viscosity.

Various plasma proteins function in lipid transport, immunity, and blood clotting.

Erythrocytes

Red blood cells, or erythrocytes, are by far the most numerous blood cells. They contain hemoglobin, the iron-containing protein that transports O₂.

Each molecule of hemoglobin binds up to four molecules of O₂.

In mammals, mature erythrocytes lack nuclei and mitochondria.

Leukocytes

There are five major types of white blood cells, or leukocytes: monocytes, neutrophils, basophils, eosinophils, and lymphocytes.

They function in defense by phagocytizing bacteria and debris or by producing antibodies.

They are found both in and outside of the circulatory system.

Platelets & Clotting

Platelets are fragments of cells and function in blood clotting.

Coagulation is the formation of a solid clot from liquid blood.

A cascade of complex reactions converts inactive fibrinogen to fibrin, forming a clot.

A blood clot formed within a blood vessel is called a thrombus and can block blood flow.

Cardiovascular Disease

Cardiovascular diseases are disorders of the heart and the blood vessels.

Cardiovascular diseases account for more than half the deaths in the United States.

Cholesterol, a steroid, helps maintain membrane fluidity.

**Low-density lipoprotein (LDL)** delivers cholesterol to cells for membrane production.

**High-density lipoprotein (HDL)** scavenges cholesterol for return to the liver.
Risk for heart disease increases with a high LDL to HDL ratio

Inflammation is also a factor in cardiovascular disease

Gas Exchange

**Gas exchange** supplies $O_2$ for cellular respiration and disposes of $CO_2$

A gas diffuses from a region of higher partial pressure to a region of lower partial pressure

**Partial pressure** is the pressure exerted by a particular gas in a mixture of gases

Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure

Respiratory Surfaces

Animals require large, moist respiratory surfaces for exchange of gases between their cells and the respiratory medium, either air or water

Gas exchange across respiratory surfaces takes place by diffusion

Respiratory surfaces vary by animal and can include the outer surface, skin, gills, tracheae, and lungs

**Ventilation** moves the respiratory medium over the respiratory surface

Aquatic animals move through water or move water over their gills for ventilation

Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills; blood is always less saturated with $O_2$ than the water it meets

Insects

The **tracheal system** of insects consists of tiny branching tubes that penetrate the body

The tracheal tubes supply $O_2$ directly to body cells

The respiratory and circulatory systems are separate

Larger insects must ventilate their tracheal system to meet $O_2$ demands

Mammals

A system of branching ducts conveys air to the lungs
Air inhaled through the nostrils is warmed, humidified, and sampled for odors.

The pharynx directs air to the lungs and food to the stomach.

Swallowing tips the epiglottis over the glottis in the pharynx to prevent food from entering the **trachea**.

Air passes through the pharynx, **larynx**, trachea, **bronchi**, and **bronchioles** to the alveoli, where gas exchange occurs.

Exhaled air passes over the vocal cords in the larynx to create sounds.

Cilia and mucus line the epithelium of the air ducts and move particles up to the pharynx.

This “mucus escalator” cleans the respiratory system and allows particles to be swallowed into the esophagus.

Gas exchange takes place in **alveoli**, air sacs at the tips of bronchioles.

Oxygen diffuses through the moist film of the epithelium and into capillaries.

Carbon dioxide diffuses from the capillaries across the epithelium and into the air space.

Alveoli lack cilia and are susceptible to contamination.

Secretions called **surfactants** coat the surface of the alveoli.

Preterm babies lack surfactant and are vulnerable to respiratory distress syndrome; treatment is provided by artificial surfactants.

The maximum tidal volume is the **vital capacity**.

After exhalation, a **residual volume** of air remains in the lungs.

**Respiratory Pigments**

A single hemoglobin molecule can carry four molecules of O₂, one molecule for each iron containing heme group.

The hemoglobin dissociation curve shows that a small change in the partial pressure of oxygen can result in a large change in delivery of O₂.

CO₂ produced during cellular respiration lowers blood pH and decreases the affinity of hemoglobin for O₂; this is called the **Bohr shift**.