**BLY 122**
**Chapter 44 Gas Exchange and Circulation**

I. Gas exchange between the mitochondria and the environment relies on diffusion.
  A. Gas exchange in all animals involves a three-part sequence. (**Fig. 44.1**)
    1. Ventilation—air or water moving through the gas-exchange organ
    2. Circulation—the transportation of dissolved gases to the animal's cells
    3. Respiration—the exchange of gases between the blood or interstitial fluid and the mitochondria

  B. The exchange of $O_2$ and $CO_2$ differs depending on whether air or water is the respiratory medium.
    1. How do oxygen and carbon dioxide behave in the air?
      a. Oxygen content is 21% no matter what the altitude.
      b. However, the air at higher altitudes is less dense, so less $O_2$ is available.
      c. The partial pressure of oxygen indicates how much oxygen is present, taking into account the density of the air at any given altitude. (**Fig. 44.2**)
        (1) The partial pressure of $O_2$ at sea level is 160 mm Hg.
        (2) The partial pressure of $O_2$ on Mt. Everest is 53 mm Hg.
      d. In both air and water, gases move from a region of high partial pressure to one of lower partial pressure.
    2 How do oxygen and carbon dioxide behave in water?
      a. Water contains far less oxygen than air does.
      b. Water is far denser than air, so more energy is required to ventilate a gas exchange surface with water than with air.
      c. The diffusion of gases in aquatic habitats is dependent on several factors:
        (1) Water solubility of the gas
        (2) Water temperature
        (3) Presence of other solutes in the water
        (4) Partial pressure of the gas in contact with the water
        (5) Surface area of the water
          (*a*) Waterfalls and whitewater have higher oxygen content. (**Fig. 4.3a**)
          (*b*) Bogs and stagnant water have lower oxygen content. (**Fig. 44.3b**)

II. Organs for Gas Exchange

  A. Fick's Law of Diffusion
    1. Fick's law states that the rate of diffusion depends on five parameters: (**Fig. 44.4**)
      a. Solubility of the gas
      b. Temperature
      c. Surface area available for gas exchange
      d. Partial pressure gradient across that surface
      e. Thickness of the gas exchange surface
    2. This law states that oxygen and carbon dioxide diffuse in the largest amounts when three conditions are met:
      a. The surface area of the gas exchange surface is large.
      b. The respiratory surface is very thin.
      c. The partial pressure gradient is large.

  B. Most aquatic animals rely on gills for gas exchange.
    1. The gill structure allows for a large surface area for gas exchange.
    2. Invertebrate gills vary in structure.
      a. Some invertebrates have gills that project from the body surface and contact surrounding water directly. (**Fig. 44.5a**)
      b. In other invertebrates, gills are internal, so water must be driven over them. (**Fig. 44.5b**)
    3. The gills of all bony fishes are similar.
      a. Gills are located on both sides of the head. (**Fig. 44.6a**)
      b. A flap of skin, the operculum, is moved to bring water over the gills.
      c. Fast-swimming fish also move water over their gills by swimming with their mouths open.

4. The flow of blood through the gill runs countercurrent to the flow of water, maintaining a partial pressure gradient for gas exchange across the entire surface. (**Fig. 44.6b**)

C. The insect tracheal system transports air directly to respiring cells.
   1. Openings, called spiracles, regulate the rate of gas exchange to minimize water loss.
   2. In flying insects, contraction of the flight muscles helps to ventilate the trachea. (**Fig. 44.7**)

D. Lungs occur in amphibians, lizards, birds, and mammals.
   1. Most mammals draw air in through both the mouth and nose.
      a. The air enters the lungs via the trachea and is carried through bronchi into the bronchioles. (**Fig. 44.8a**)
      b. Bronchioles end in millions of tiny sacs called alveoli. (**Fig. 44.8b**)
         (1) Alveoli increase the respiratory surface area.
         (2) Alveoli are very thin, maximizing gas exchange. (**Fig. 44.8c**)
   2. Ventilation of mammalian lungs is accomplished through contraction and relaxation cycles of the muscles of respiration.
      a. In contrast to frogs that push air into their lungs, mammals draw air into their lungs via negative pressure ventilation.
      b. When the diaphragm contracts, lung volume increases, creating negative pressure inside the lung and drawing air in. (**Fig. 44.9a**)
      c. Exhalation is driven by the elastic recoil of the lung when the diaphragm relaxes. (**Fig. 44.9b**)
         (1) The elasticity of the lungs exists because a thin layer of fluid coats the inside surface of the alveoli.
         (2) The surface tension of that fluid generates tension, causing the elastic recoil that in turn causes the lung to return to its original size during exhalation. (**Fig. 44.10**)
         (3) This surface tension is so strong that it must be reduced a bit to allow breathing to occur.
         (4) Surfactants relieve the surface tension enough to allow the lungs to expand.
         (5) Babies born prematurely do not yet make these surfactants, and can experience respiratory distress. (**Box 44.1**)
   3. Ventilation of bird lungs is constant, allowing for vigorous exercise at high altitudes.
      a. The bird trachea is connected to air sacs, which branch into airways called parabronchi.
      b. The parabronchi pass through the lungs and terminate in more air sacs. (**Fig. 44.11a**)
      c. With this unidirectional ventilation system, oxygenated air is moved over the respiratory surface during both inhalation and exhalation. (**Fig. 44.11b**)

   4. Homeostatic control of ventilation
      a. Resting breathing rate is established by the medullary respiratory center (MRC) in the brain.
      b. During exercise, active muscles take up more oxygen and give off more carbon dioxide.
         (1) This decreases the partial pressure of oxygen in the blood and increases the partial pressure of carbon dioxide in the blood.
         (2) This carbon dioxide diffuses into the cerebrospinal fluid (CSF) and combines with water to make carbonic acid, which then dissociates to form bicarbonate and a free proton.
         (3) This reduces the pH of blood and of CSF, which is sensed by a popu-lation of nerve cells that signal the MRC to increase breathing rate.

III. Blood is a fluid tissue composed of plasma and formed elements.

A. Blood is composed of watery plasma and cellular formed elements including platelets, white blood cells and red blood cells.
   1. Platelets are cell fragments that are essential in blood clotting.
   2. White blood cells are part of the immune system and fight infections.
   3. Red blood cells transport oxygen from the lungs to the tissues.

B. The respiratory pigment hemoglobin binds four $O_2$ molecules at the respiratory surface for delivery to respiring tissues.
   1. Hemoglobin consists of four polypeptide chains, each with an iron-containing heme group that can carry one oxygen molecule.

2. There is a sigmoidal relationship between the degree of $O_2$ saturation of hemoglobin and the $PO_2$ of the surrounding environment.
3. The Bohr effect describes how the affinity of hemoglobin for $O_2$ decreases with increasing $CO_2$ levels, releasing more $O_2$ to the tissues.
    a. Dissociation curves show there is only a 25% change in saturation as hemoglobin unloads oxygen into the tissue. (**Fig. 44.12a**)
    b. The binding of one oxygen molecule to hemoglobin makes it easier to bind successive oxygen molecules; this is known as cooperative binding.
        (1) If binding were not cooperative, the four subunits of hemoglobin would load and unload oxygen independently of one another. (**Fig. 44.12b**)
        (2) Cooperative binding means that hemoglobin will become saturated with oxygen even at a small partial-pressure gradient.
    c. However, during exercise hemoglobin unloads 60% of its oxygen.
        (1) Hemoglobin is sensitive to pH.
        (2) As blood pH drops when active tissues give off oxygen, hemoglobin changes shape and releases oxygen more readily. (**Fig. 44.12c**)

C. $CO_2$ is transported to the lungs for elimination, primarily in the form of bicarbonate.
1. Red blood cells contain carbonic anhydrase, which catalyzes the formation of carbonic acid that dissociates into bicarbonate and a hydrogen ion.
    a. This keeps the concentration of carbon dioxide low in the red blood cells, favoring diffusion of carbon dioxide out of tissues and into red blood cells. (**Fig. 44.13**)
    b. The hydrogen ions bind to hemoglobin, preventing a change in pH.
    c. When bicarbonate is transferred to the lungs, the reaction is reversed and $CO_2$ is released to the environment.
2. $CO_2$ that is not transported as bicarbonate is either bound to amino groups on proteins or dissolved as a gas.

D. Homeostatic Control of Oxygen-Carrying Capacity
1. The body regulates the total oxygen-carrying capacity of the blood by regulating the total mass of red blood cells.
2. Total red blood cell mass increases in people who need more oxygen on a regular basis.
3. Cells in the kidney can sense blood oxygen levels and release a hormone called erythropoietin when oxygen levels are low.
4. Erythropoietin stimulates the bone marrow to produce more red blood cells. (**Box 44.2**)

IV. Circulatory systems move blood or hemolymph throughout body using pumps.

A. Open circulatory systems are low-pressure systems. (**Fig. 44.14**)
1. The extracellular fluid is all in one compartment called the hemolymph.
2. Low pressure of this system means that rate of flow is very low, and there is no mechanism for redirecting flow to specific tissues.

B. Closed circulatory systems are high-pressure systems that can maintain high flow rate.
1. In closed systems, blood is pumped from the heart into a large artery called the aorta.
    a. The walls of the aorta have elastic fibers, allowing the aorta to stretch when blood is pumped from the heart at high pressure.
    b. When pumping ends, the diameter of the aorta returns to its original size, propelling the blood away from the heart.
2. Small arteries, called arterioles, have sphincters so that blood can be redirected from one tissue to another based on changes in $O_2$ demand.
    a. Diving Baikal seals redirect blood flow from the digestive organs to the heart and brain. (**Fig. 44.24**)
    b. Constriction of a tissue's blood vessels reduces flow, while dilation increases flow to that organ.
3. Capillaries are vessels that allow for gas and nutrient exchange in the tissues.
    a. The walls are only one cell layer thick.
    b. The diameter is equal to the diameter of one red blood cell. (**Fig. 44.15a**)
4. Veins carry deoxygenated blood back to the heart. (**Fig. 44.15b**)

a. Blood pressure drops as blood passes through capillaries, and is very low by the time the blood reaches the veins.
b. Veins have valves that keep the blood moving back toward the heart.
c. Veins are embedded in skeletal muscle, and contractions in those muscles help propel the blood to the heart.

5. Extracellular fluid is divided into blood plasma and interstitial compartments between cells.
a. The thin walls of capillaries allow a constant exchange between plasma and interstitial fluid.
b. Two forces affect this flow: (**Fig. 44.16**)
(1) The force created by the pressure of the blood in the capillary forces fluid out of the capillary.
(2) There is more solute (due to large proteins such as albumin) in the blood than in the interstitial fluid, causing water to return to the capillary.
(3) This results in fluid and ions exiting the capillary at the arteriole end, and fluid returning on the venous end.

6. The lymphatic system returns excess interstitial fluid to circulation.

C. Hearts are divided into chambers called atria and ventricles.

1. Atria receive blood returning from circulation; ventricles force blood out of the heart and back into circulation.
a. The number of heart chambers differs among vertebrate groups. (**Fig. 44.17**)
b. Increased number of chambers allows for two separate circuits, one supplying the organ(s) of gas exchange and the other supplying remaining tissues.

2. The human circulatory system consists of one four-chambered heart and separate pulmonary and systemic circuits.
a. One half of the heart pumps blood to the lungs to pick up oxygen, while the other half of the heart pumps blood to the body to give away oxygen.
b. This ensures that blood is delivered to both the lungs and the body tissues at high pressure.

3. The route of blood through the heart (**Fig. 44.18**)
a. Deoxygenated blood from the body returns to the right atrium via the venae cavae.
b. When the atria contract, blood is pumped from the right atrium to the right ventricle.
(1) Blood flows through the heart in only one direction, due to valves between the atria and ventricles.
(2) When these valves are not effective, blood can flow back into the atria from the ventricles, causing a heart murmur.
c. After ventricular contraction, the deoxygenated blood leaves the right ventricle and travels through the pulmonary artery to the lungs.
d. Oxygenated blood from the lungs returns to the left atrium of the heart via the pulmonary vein. (**Fig. 44.19**)
e. Oxygenated blood is the pumped to the left ventricle, and ultimately through the aorta to the body. (**Fig. 44.19**)

4. One cardiac cycle consists of a contraction phase, systole, and a relaxation phase called diastole. (**Fig. 44.20**)
a. Diastole phase allows for filling of the atria and ventricles with blood.
b. Systole phase creates the pressures needed to eject blood into the pulmonary and systemic circuits.
c. Blood pressure is reported as systolic/diastolic. High blood pressure, or hypertension, can be a dangerous health condition. (**Box 44.3**)
d. Pacemaker cells located in the sinoatrial node produce electrical impulses that coordinate systole and diastole. (**Fig. 44.21**)
(1) The cells of the atria are intercalated disks.
(2) These cells are electrically continuous because they are connected via gap junctions.
(3) Once the electrical signal has swept through the atria, it arrives at the atrioventricular node, a set of specialized atrial cells.
(4) The atrioventricular node regenerates the signal and causes a delay before passing the signal to the ventricles.
(5) The delay ensures that the ventricles contract after the atria.
(6) An electrocardiogram is a recording of these events. (**Fig. 44.22**)

D. Blood pressure is the force that blood exerts on the vessel walls.

1. Blood pressure drops as blood progresses from the arteries to the capillaries and on to the veins. (**Fig. 44.23**)
    a. Increased total cross-sectional area of the capillaries causes a large drop in blood pressure.
    b. Changes in blood pressure corresponding to systole and diastole can be observed in the elastic arteries.
2. Maintaining blood pressure within a normal range is critical to the health of an individual; changes are detected by baroreceptors (pressure receptors).
    a. A drop in blood pressure will trigger an increase in heart rate, stroke volume, and constriction of blood vessels—changes that will help return blood pressure to normal.
    b. A rise in blood pressure will trigger a decrease in heart rate, stroke volume, and dilation of blood vessels—changes that will help return blood pressure to normal.
3. Heart rate, stroke volume, and respiratory rate respond to changes in blood chemistry as sensed by chemoreceptors.
    a. A decrease in $PCO_2$ and increases in $PO_2$ and pH trigger decreases in heart rate, stroke volume, and respiratory rate.
    b. An increase in $PCO_2$ and decrease in $PO_2$ and pH trigger increases in heart rate, stroke volume, and respiratory rate.