Circulatory and Respiratory Systems

1. Gas Exchange
   a. The importance of air
      i. All oxygen in the air is a result of photosynthesis
      ii. Dry air = 78.09% N_2 + 20.95% O_2 + 0.93% argon + 0.03 CO_2
      iii. Heterotrophs obtain energy from carbon compounds in a process called cellular respiration, a process which requires oxygen and produces carbon dioxide.
      iv. The purpose of gas exchange is to obtain oxygen and get rid of carbon dioxide.
      v. Gases diffuse across cell membranes. This must occur through water so the exchange surface must be wet. Diffusion is driven by the difference in oxygen concentration between the interior of the organism and the external environment.
      vi. Gases are then distributed by the circulatory system.
   b. Evolution of complex respiratory systems
      i. Oxygen diffuses too slowly to be efficient over more than 0.5 mm, which limits the size of organisms. Protists are small enough to utilize simple diffusion but as size increases, surface area to volume ratio decreases. For organisms to be larger, a better method of getting oxygen is necessary.
      ii. Most primitive phyla possess no special respiratory organs but get oxygen by creating a water current to constantly replace water over the diffusion surface.
      iii. More advanced invertebrates and vertebrates possess respiratory organs with an increased surface area over which diffusion occurs. This system provides contact between the external environment and internal circulating fluids (like blood). A larger surface area enables organisms to get more oxygen from the environment.
      iv. Gills
         (1) Disadvantage of external gills
            (a) Difficult to constantly circulate water past the diffusion surface because the highly branched gills resist water movement.
         (2) Internal gills
            (a) Water passes through the mouth into two cavities.
            (b) Water then passes out of body after passing over the gills and through the cavity. This is a one way flow of water over the gills.
      v. Lungs
         (1) Gills are not useful for terrestrial animals because they must be kept wet at all times and the fine filaments of gills would clump together if not surrounded by water.
         (2) Terrestrial organisms constantly lose water to the atmosphere and gills would be a huge surface area for water loss.
            (a) Amphibians
               (i) The low efficiency of the simple lungs is offset by the high concentration of oxygen in the air.
               (ii) Lots of oxygen is obtained by diffusion through the skin.
               (iii) Being inactive and ectotherms decreases the O_2 demand.
            (b) Reptiles
               (i) More active so have a greater need for oxygen.
               (ii) Cannot obtain oxygen through watertight skin.
               (iii) Lungs are more developed to provide a larger surface area
            (c) Mammals - the high activity level and warm body temperature of

mammals require a large amount of oxygen.

c. Human lungs
  i. Air normally enters through the nostrils. The nostrils are lined with hairs to filter out dust. The nasal passage also warms and moistens the air.
  ii. Air enters the trachea, which branches into two bronchi - one for each lung.
  iii. Bronchi further branch into smaller and smaller tubes. The narrowest ones are called bronchioles.
  iv. The bronchioles end in clusters of tiny air sacs called alveoli
    (1) All gas exchange occurs across the walls of alveoli.
    (2) Branching and alveoli provide a huge total surface area. In humans, this is about 60-80 m^2.
  v. Air flow in the lung
    (1) Inhalation
      (a) Rib intercostal muscles contract, expanding the ribcage.
      (b) The diaphragm contracts and lowers, increasing the volume of the chest (thoracic) cavity.
      (c) The increased volume causes a decrease in pressure in the lungs so that air flows in.
    (2) Exhalation
      (a) The diaphragm and intercostal muscles relax.
      (b) The volume of the thoracic cavity and lungs decreases, increasing the pressure.
      (c) The increase in pressure forces air out.
  vi. Air volumes of human lungs
    (1) Tidal volume (TV)
      (a) Volume of air inhaled and exhaled in a single breath.
      (b) About 500 ml of air but can be increased to 3000 ml during exercise.
    (2) During normal breathing, the total lung capacity is not used.
      (a) Inspiratory reserve volume (IRV) - additional air available breathing in maximally.
      (b) Expiratory reserve volume (ERV) - additional air expelled by breathing out maximally
      (c) Vital capacity (VC) - total useable lung capacity achieved by forceful, maximum inhalation and exhalation.
      (d) VC = IRV + TV + ERV
    (3) Maximum expiration does not remove all air from the lungs; air left in lungs is the residual volume (RV).
    (4) Total lung capacity = VC + RV
    (5) Respiratory rate - number of breaths per unit time.
    (6) Respiratory rate and tidal volume determine the lung ventilation
      (a) The total amount of air moved in and out of the lungs each minute depends upon 2 factors:
        (i) Size of each breath (tidal volume)
        (ii) Number of breaths/minute (respiratory frequency)
      (b) Equals tidal volume x respiratory rate per minute
      (c) A measure of air entering and leaving the lungs per minute.
      (d) Normally 5 L/min, but can be as high as 130 L/min

2. Control of breathing.
   a. Breathing is an automatic process controlled by a part of the brain called the breathing control center.
   b. Nerve signals are sent to the diaphragm and intercostal muscles, triggering inhalation.
   c. When the signals stop, exhalation begins.
   d. The automatic control can be voluntarily overridden.
   e. When breathing stops, [CO_2] increases and is detected by the special cells in the aorta and carotid artery.
   f. They send impulses to the breathing control center to start breathing.
   g. In hyperventilation, so much CO_2 is removed from the blood that the breathing control center sends a stop breathing message.

3. Breathing disorders
   a. Allergens trigger the release of histamine which constricts muscles to narrower the diameter of the bronchioles. This results in lower air flow.
   b. Bronchitis
      i. An inflammation of the airways that causes mucous to accumulate. The normal cleansing activity of cilia is reduced and not sufficient to remove the mucous. Coughing attempts to clear the mucus.
      ii. Smoking and other irritants increase mucus secretion and diminish cilia function.
   c. Emphysema
      i. Emphysema occurs when the alveolar walls become less flexible. Damage to the walls also reduces the amount of surface area available for gas exchange.
      ii. Emphysema is associated with environmental conditions, diet, infections, and genetics. It can result from chronic bronchitis when the airways become clogged with mucous and air becomes trapped within the alveoli.
   d. Effects of cigarette smoke
      i. Cigarette smoke prevents the cilia from beating and stimulates mucus secretion.
      ii. Coughing expels excess mucous but contributes to bronchitis and emphysema.
      iii. Cigarette smoke contains compounds that are modified in the body to form carcinogens. Smoking causes 80% of lung cancer deaths.

4. Circulation
   a. Evolution of complex circulatory systems
      i. All organisms must transport materials to each cell and in large organisms diffusion is insufficient to do so.
      ii. In simple organisms, the body cavity is filled with fluid which helps to distribute materials.
      iii. Types of circulatory systems
         (1) Open system
            (a) There is no distinction between the circulating fluid and body fluid.
            (b) A muscular tube in the body cavity pumps fluid through a network of channels.
            (c) Fluid drains back into the central cavity.
         (2) Closed system
            (a) Blood is enclosed within vessels.
            (b) The circulating fluid does not mix with other body fluids
            (c) Materials pass from one to the other by diffusion through the walls

of vessels.

(d) Movement of fluid in vessels is accomplished by muscle contraction (*i.e.*, a heart).

(3) The advantage of a closed system is being able to change the diameter of individual blood vessels to direct blood as needed and regulate fluid flow in specific parts of body independently.

b. The functions of vertebrate circulatory systems

i. Nutrient and waste transport

(1) Nutrients enter the blood through the wall of the small intestine.

(2) Those nutrients are carried to all body cells.

(3) Cells release wastes into the blood. These are carried to the liver and kidney.

ii. Oxygen and carbon dioxide transport

(1) Oxygen (O_2) transport

(a) Oxygen diffuses into blood through gills or lungs and is picked up by a protein called hemoglobin in red blood cells. It must be delivered to all cells of the body.

(b) Blood plasma holds a maximum of 3 ml O_2/L while whole blood is able to carry 200 ml O_2/L

(c) Hemoglobin makes the difference.

(i) This protein carries oxygen in the blood of most animals.

(ii) Hemoglobin picks up oxygen in lungs and becomes bright red in color

(iii) Hemoglobin releases oxygen at tissues and becomes dark red in color. It looks blue under the skin because of the way light passes through the skin.

(d) The fluid surrounding tissues and cells has a lower [O_2] than blood so oxygen diffuses from the blood into the fluid surrounding the tissues. This diffusion occurs in the capillaries.

(e) At rest, only about 20% of the oxygen in blood is unloaded. When it's needed (like during exercise) the rest of the oxygen can be unloaded.

(f) Blood contains reserves for 4-5 minutes without breathing. After that time, cells begin to die.

(2) Anemia

(a) Hemoglobin requires iron to function properly.

(b) A lack of iron means less hemoglobin so less oxygen can be carried.

(c) Oxygen is needed for cells to make energy so the person will feel tired.

(3) Carbon monoxide (CO)

(a) Hemoglobin binds to carbon monoxide (CO) but the binding is not easily reversible.

(b) In the presence of CO, hemoglobin is less able to carry oxygen and suffocation results.

(4) Carbon dioxide (CO_2) transport

(a) Carbon dioxide, the waste from cellular respiration, is released by cells into the blood. This is carried back to the gills or lungs and released.

(b) The lower [CO_2] in the alveoli causes CO_2 to diffuses into the alveoli and it is exhaled.

iii. Temperature regulation

(1) For most vertebrates, body temperature varies with environmental temperature. Mammals and birds are exceptions in that they maintain constant body temperature.

(2) Heat is distributed by circulating blood and temperature can be adjusted by directing flow to the body interior or to the extremities.

(3) Body temperature can be decreased by dissipating heat to the environment.

(4) Heat can be conserved by directing blood from the extremities to the interior of the body.

iv. Hormone circulation - Body activities are coordinated by hormones produced in endocrine glands and circulated throughout the body in blood.

v. Immune system - several types of cells and proteins in the immune system are transported in the blood.

c. Blood vessels

i. Arteries

(1) Muscular layers allow them to withstand high pressure.

(2) Carry blood away from heart.

(3) Arteries are elastic to allow them to expand and recoil when receiving blood from heart.

ii. Arterioles

(1) Form a large network of smaller vessels, leading away from the heart.

(2) They are also elastic.

(3) Have muscles that control their diameters.

iii. Capillaries

(1) The smallest blood vessels, these are typically less than 1 mm long.

(2) The diameter is so small that red blood cells travel single file.

(3) The very thin walls allow exchange of materials between blood and cells.

(4) Capillaries have a huge total surface area.

(5) Blood velocity decreases in capillary beds to allow time for exchange of materials with extracellular fluid.

(6) Blood releases oxygen and nutrients, picks up carbon dioxide and wastes.

(7) Exchange

(a) At the arterial end of capillaries blood pressure forces fluid out and into the surrounding tissues. As blood moves through the capillary, the blood pressure decreases so that near the venous end, less is leaking into the surrounding tissues.

(b) As blood flows through the capillary and fluid moves out, the blood that remains behind becomes more concentrated. Osmosis then causes fluid to move back into the capillary near the venous end.

(8) Lymphatic system

(a) During the exchange, some fluid is also removed from the blood. Most fluid reenters the blood by osmosis but some does not.

(b) The remaining fluid is returned to blood by the lymphatic system.

(c) Lymphatic vessels contain vein-like one-way valves .

(d) The lymphatic system connects to the circulatory into veins on the side of the neck.

(e) Blockage of the lymphatic systems leads to the retention of water in the tissues. The resulting swelling is called edema.

iv. Venules - Capillaries merge to form venules and venules merge into veins.

v. Veins
  (1) Large vessels that carry blood back to the heart.
  (2) Blood pressure is quite low in the veins.
  (3) The pressure is too low to allow the return of blood to the heart from the lower body.
  (4) The return is aided by the contraction of skeletal muscles and one-way valves that prevent blood from flowing backward in the veins.

d. The diameter of arteries and arterioles can be changed as needed
  i. Vasoconstriction - contraction of the muscular layer causes the diameter to narrow, decreasing blood flow.
  ii. Vasodilation - relaxation of the muscular layer causes the diameter to increase, increasing blood flow.
  iii. Sphincter muscles (called precapillary sphincters) in arterioles can open and close specific capillary beds as needed.

e. The heart
  i. In birds and mammals, the heart is a double pump with four chambers, the ventricles being completely separated.
  ii. The left side of the heart pumps oxygenated blood to the body tissues. This is systemic circulation.
  iii. The right side of the heart pumps unoxygenated blood to the lungs. This is pulmonary circulation.
  iv. The left ventricle is much more muscular than the right as it must move blood through the whole body.
  v. Human heart
    (1) Oxygenated blood from the lungs is carried through pulmonary veins to the left atrium.
    (2) Blood flows from the atrium into the left ventricle as it relaxes.
    (3) The ventricle then contracts, to force blood out to the aorta.
    (4) Valves between the atrium and ventricle (AV valve) and between the ventricle and the aorta (semilunar valve) prevent blood from flowing backward.
    (5) Oxygenated blood is carried to all parts of the body.
    (6) The heart itself receives blood from the coronary arteries. They have a very small diameter and may become blocked, producing a heart attack.
    (7) Blood from the upper body enters the heart through the superior vena cava while blood from the lower body enters through the inferior vena cava.
    (8) Blood moves from the right atrium through an AV valve to the right ventricle.
    (9) When the right ventricle contracts, blood moves through a semilunar valve into the pulmonary arteries to the lungs.
    (10) Blood returns from the lungs through the pulmonary veins to the left side of the heart to complete the cycle.
  vi. Control of the heartbeat
    (1) The heartbeat does not require nerves but generates its own beat.
    (2) If all the nerves to the heart are cut it will continue to beat.

(3) Nerve signals from the brain can influence the heart rate though, slowing it or speeding it up.
(4) Muscle cells in the heart can all contract to produce a regular heartbeat but they must be coordinated.
(5) This coordination is accomplished by the pacemaker which causes all the cells to contract together. The pacemaker (or SA node) is a group of cells in the wall of the right atrium near the superior vena cava called the sinoatrial node (SA node) that sets the origin of the heartbeat in mammals.
(6) To be filled with blood from the atria, the ventricles must contract slightly later than the atria. This is the job of the atrioventricular (AV) node. It recieves the signal from the SA node but delays it for about 0.1 s before passing it along to the ventricles. This ensures that the atria completely empty before the ventricles contract.

vii. Heart sounds
(1) The sounds of the heartbeat are caused by the closing of the heart valves.
(2) The first sound (lub) is caused by blood hitting the AV valves as they close.
(3) The second sound (dub) is caused by blood hitting the semilunar valves as they close.
(4) If the valves do not close properly, some blood can pass through the valves and cause a heart murmur. The heart must work harder to get the same volume of blood circulating. This can be corrected by replacing the valve.

viii. Blood pressure
(1) When the heart relaxes between beats (diastole) the arterial pressure drops to about 80 mm Hg. This is called diastolic pressure. The pressure does not drop to 0 because the arterial walls are elastic and squeeze the blood. The 80 mm Hg diastolic pressure keeps blood flowing between beats.
(2) When the ventricles contract (systole) the pressure in the arteries leaving the heart rises to about 120 millimeters of mercury (mm Hg). This is called systolic pressure.
(3) Normal values: systolic/diastolic = 120/80 mm Hg.
(4) Blood pressure is monitored by the medulla oblongata through sensors in the aorta and carotid arteries. Vasoconstriction can be used to increase blood pressure and vasodilation can be used to lower it as needed.

ix. Cardiac output
(1) Cardiac output (CO) is the volume of blood pumped by each ventricle per minute. Stroke volume (SV) is the volume of blood pumped per cycle.
(2) Cardiac output = rate of heart beat (HR) x stroke volume
(3) It is normally about 5 L/min in humans. Doubling the HR or the SV will double the CO.
(4) It can be increased with exercise. Exercise increases stroke volume over time so that the heart can pump more blood with fewer strokes. A lower heart rate decreases the risk of heart disease. In humans, HR can rise to ~200 beats/min during exercise. Faster rates are inefficient because the heart does not have time to fill completely. SV can increase about 50% with exercise, to 100 to 120 mL.
(5) This allows the exercise CO to increase to 20-24 L/min. A healthy heart beats more slowly but as a higher stroke volume.

x. Heart disorders - heart disease is the leading cause of death in North America.

(1) Atherosclerosis
(a) A diet high in cholesterol can result in the deposit of fatty material in the wall of the artery.
(b) The diameter narrows which increases pressure and decreases flow.
(c) If the artery is blocked completely it can cause a heart attack or stroke.
(d) The condition can be improved by decreasing fat and cholesterol in the diet and with exercise.
(2) High blood pressure (hypertension)
(a) High blood pressure is associated with cardiovascular disease and can be caused by a high salt diet or stress.
(b) In males under 45 years, pressures greater than 130/90 are considered to be high. In males over 45 years, pressures greater than 140 /95 are high. Females are becoming more and more at risk of high blood pressure.
(c) The stress of the heart having to work harder can cause a heart attack.
(3) Aneurysm
(a) A localized, blood-filled balloon-like bulge in the wall of a blood vessel.
(b) As the aneurysm increases in size, the risk of rupture increases. A rupture results in severe hemorrhage which can lead to death.
(c) Aneurysms can be hereditary or caused by disease, both of which cause the wall of the blood vessel to weaken.
(4) Heart murmur
(a) Can be the result of narrowing or leaking heart valves, or the presence of abnormal passages through which blood flows in or near the heart.
(5) Angina and heart attack
(a) Angina is chest pain due to lack of oxygen to the heart muscle. The main cause coronary artery disease, due to atherosclerosis of the coronary arteries. The symptoms are usually described as a pressure, heaviness, tightness, squeezing, burning, or choking sensation.
(b) If the oxygen deprivation to the heart is severe enough to interrupt blood supply to the heart, myocardial infarction (heart attack) results.

5. Blood - the average adult human has ~5L
a. Plasma (55% of blood volume)
i. Fluid portion of the blood containing a variety of dissolved materials including gases, glucose, amino acids, ions and vitamins. The plasma also contains wastes and hormones.
ii. Proteins
(1) Albumin.
(2) Proteins that carry lipids (HDL and LDL).
(3) Fibrinogen needed for blood clotting.
(4) The concentration of plasma proteins is important for osmosis and controlling the water balance in the blood.

b. Cells (45% of blood volume)

i. Red blood cells (RBCs) or erythrocytes (~5 million/microliter)

(1) Red blood cells are continuously produced in the red marrow of the skull, ribs, vertebrae, and ends of the long bones.

(2) Cells are shaped like biconcave disks to increase surface area. This surface area increases the rate of exchange between RBCs and tissue. They lack a nucleus to have more space for hemoglobin so they can carry more oxygen.

(3) RBCs have membrane glycoproteins of specific types which allow us to divide them into the 4 blood types.

(4) They live for between 3 and 4 months. Dead RBCs are removed by the liver and spleen.

ii. White blood cells (WBCs) or leukocytes (4,000 - 11,000/microliter)

(1) Leukocytes are less than 1% of total blood cells but are an important part of the immune system.

(2) They circulate in blood and can exit into the fluid surrounding the tissues.

iii. Platelets (200,000 - 500,000/microliter)

(1) Platelets are tiny cells that play important role in blood clotting.

(2) When a vessel is damaged, platelets stick to the exposed inner wall of the vessel. They release a protein which makes other platelets stick to them, forming a plug to stop any bleeding.

(3) The clumping platelets also release a protein which causes a blood protein called fibrinogen to convert to fibrin.

(4) Fibrin is a thread-like protein that forms a net (or mesh) to cover the injury and trap RBCs and other platelets.

iv. Other proteins (called clotting factors) are also involved. A defect in any one of the clotting factors causes hemophilia, a disorder in which blood clotting does not occur properly and excessive bleeding can result from even minor injuries.