Topic 16: Circulation and Gas Exchange - Circulatory and Respiratory Systems (Ch. 42)

I. circulation required for all animals that are more than a few cells thick so that cells can get oxygen and nutrients and get rid of wastes

A. two main types of circulatory systems, open and closed
   1. open systems
      - no distinction between circulating fluid and extracellular fluid of body (lymph)
      - hemolymph is the circulating fluid
      - less efficient for transport (little pressure, slower)
      - may still have heart(s) for pumping and some vessels
      - examples: arthropods, mollusks
   2. closed systems
      - circulating fluid (blood) distinct from lymph
      - at least one heart always present
      - blood vessels – tubular network for blood flow from heart of body and back
        - arteries carry blood away from heart
        - veins return blood to heart
        - capillaries between arteries and veins are the thinnest vessel and allow exchanges with body tissues
      - lymph system - when blood reaches capillaries, liquid seeps out of blood, most is mopped up, but much remains behind and needs to be mopped up or an edema (swelling) will form, lymph vessels return liquid to blood

B. vertebrate circulatory systems functions
   1. transportation of gasses, nutrients, wastes
   2. regulation of temperature
   3. transportation of hormones
   4. protection (immune defense; blood clotting)

C. blood plasma
   1. metabolites, wastes and hormones including carbon dioxide
   2. ions - mostly sodium, chloride, and bicarbonate, lower total ion concentration than sea water
   3. proteins - albumin, globulins (carry lipids and steroid hormones and fibrinogen) serum = fluid after fibrinogen clots out
   4. formed elements – blood cells

D. blood cells
   1. erythrocytes - red blood cells
      - cell that carries hemoglobin
      - mammals - anucleate, donut shaped
      - humans - 5 million/cm^3; 45% of blood (hematocrit)
      - live 120 days before replacement in humans
      - formed in bone marrow
   2. leukocytes - white blood cells
      - larger, nucleated, can migrate out of capillaries
      - humans - 1% of cells in blood
      - granular leukocyte - neutrophils (most common), eosinophils, and basophils
      - nongranular leukocytes - monocytes and lymphocytes (T and B cells involved in immune response)
      - neutrophils accumulate at injury and then joined by monocytes that change into macrophages
      - phagocytosis by neutrophils and macrophages eliminate disease-causing organisms
   3. platelets
      - megakaryocytes in marrow break off bits of their cytoplasm to form platelets (actually cell fragments)
      - accumulate at wound and form a plug by sticking to each other and tissues
      - plug reinforced by fibrin (formed by fibrinogen in complex chain of events)

E. blood vessels
   1. structure - endothelium then elastic fibers then smooth muscle layer then connective tissue (except capillaries)
   2. arteries
      - large ones - very elastic to absorb force of heart
      - small ones (arterioles) - more muscular - to control blood flow (vasoconstriction and vasodilation)
   3. capillaries
      - only endothelial lining (one-cell thick)
      - about one red blood cell wide
      - all exchange occurs here
      - little blood pressure after exit
   4. veins and venules (smaller veins, just after capillaries)

- less muscular than arteries
- blood pressure greatly reduced in venous system - possibility for retrograde (back) flow
- valves - present in ascending veins to halt retrograde flow
- descending veins - no valves, gravity helps
- skeletal muscles help move blood - contract leg muscles to avoid fainting, which is typically caused by blood pooling in the legs

F. the mammal heart
1. 4 chambers
2. right side - atrium receives blood from body, pumps to ventricle, which pumps to lungs
3. left side - atrium receives blood from lungs, pumps to ventricle, which pumps to body
4. atria both pump at the same time, then after about 100 ms delay both ventricles pump; both sides must pump the same volume, but the left pumps at greater pressure because it is going through greater resistance
5. valves prevent backflow
6. sinoatrial node (SA node) - pacemaker - starts impulse at atria and sends impulse to atrioventricular (AV) node
7. AV node shunts impulse to the apex (bottom) of the heart through Purkinje fibers - modified cardiac muscle cells that look like neurons (unique to mammals)
8. shunted impulse squeezes the heart from the bottom up - more efficient just like squeezing the toothpaste from the bottom of the tube is more efficient
9. heart rate increases under exercise to get enough oxygen to muscles

II. respiration – general term for use of oxygen and production of carbon dioxide;

cellular respiration – direct biochemical use to break down simple sugars for energy
body respiration (respiratory system) – exchange with environment

A. components of respiratory systems in vertebrates
1. air exchange surface – gills and lungs, sometimes skin
2. transporting system – hemoglobin, red blood cells, and blood plasma

B. air exchange surfaces
1. mechanical issues (diffusion)
- net movement of molecules is diffusion; parameters involved covered by **Fick's Law of Diffusion**, which includes that the rate of diffusion:
  - is proportional to surface area
  - is proportional to the partial pressure difference
  - is inversely proportional to travel distance
- consequences
  - air exchange organs have very large surface areas
  - efficient air exchange mechanics tend to maximize partial pressure difference
  - air exchange organs and capillaries are thin (1-2 cells thick)

2. gills
- mainly epithelial tissues coated with capillaries for gas exchange
- **gill arches** help spread the tissue
- **countercurrent flow** of blood to water maximizes oxygenation
- gills do not work in terrestrial environments
  - collapse without water to keep them open, greatly reducing surface area for exchange
  - allow too much water loss – need some sort of enclosure for exchange, or limited to water or moist areas

3. lungs
- primitive versions apparent in early jawed vertebrate fossils; original use for buoyancy in water (swim bladder in modern bony fishes)
- air has more oxygen than water, and is easier to get and easier to move than water; however, all exchange surfaces must remain moist
- internal placement limits water loss (stays humid inside)
- typically has two-way flow, modified in birds to a one-way flow
  - two-way flow: air enters and exits through same tube system
  - residual volume of air retained in lung after each breath
  - diffusion surfaces exposed to mix of fresh and residual air
  - partial pressure difference far from maximal
  - less efficient than one-way flow of gills
- amphibians
  - surface area for diffusion not large – large terminal air sacs (**alveoli**)

- alveoli
  - sacs one epithelial layer thick
  - surrounded by capillaries, essentially bathed in blood
  - surface coated with a **surfactant** that affects surface tension and stabilizes surface; surfactant in lungs is a complex substance composed of lipid and protein
- force air into lungs by **positive pressure breathing** ("mouth breathing" – like bony fish with their gills)
- much of exchange actually across skin

- amniotes
  - more advanced than amphibians, greater metabolic need
  - all possess lungs with a larger relative surface area than amphibian lungs, due to many small alveoli (or specialized **parabronchi** in birds)
  - all gas exchange in lungs occurs at alveoli or parabronchi
  - thoracic breathing
    - negative pressure in chest due to increasing volume of lungs to draw air into lungs
    - more efficient than positive pressure breathing
    - requires connection of lungs to chest wall
- mammals
  - air taken unto mouth and nose, through **larynx** (voice box) into **trachea** (derived from gill arches) that splits into two **bronchi**, each subdivide into **bronchioles** that deliver air to alveoli
  - inhalation (aspiration) – contract external rib **intercostals** (lifts ribs) and **diaphragm** (pushes on abdomen and expands chest cavity)
  - exhalation – elastic recoil; relaxing muscles snaps ribs and chest cavity back into place, forces air out
  - humans – about 300 million alveoli combine for up to 80 m^2 of surface area for gas exchange, 42x body surface area
- birds
  - flying demands very high metabolism, thus a more advanced respiratory system
  - air flow is unidirectional from posterior to anterior
    - birds have no residual volume as do mammals
    - only fresh, fully oxygenated air at diffusing surfaces
    - thus, bird lungs are more efficient because they increase the partial pressure difference
  - birds can survive at much higher altitudes than mammals
  - avian lung works like a two-cycle pump
    - air passes through trachea into nondiffusing posterior air sacs with inhalation
    - air flows into lung with exhalation
    - air passes from lung to anterior air sacs with next inhalation
    - air flows out through trachea at next exhalation
  - air flow is different from the flow of blood through the lung
    - air in lungs flows across parabronchi (tubes instead of sacs, but otherwise like alveoli – only one cell thick for effective diffusion)
    - parabronchi coated with capillaries
    - **cross-current flow** – flow of air and blood at 90° angles to each other
    - less efficient than countercurrent flow of fish, but more efficient than other amniotes

C. gas transport and exchange in tissue

1. simple vs. facilitated diffusion
   - simple diffusion of gases too slow over more than 0.5 mm
   - diffusion is facilitated by using carrier proteins in a moving fluid
   - example: human blood plasma holds only 3mL O_2/L, but blood holds 200 m L O_2/L because of L O_2 bound to the carrier protein **hemoglobin**
2. carrier proteins: hemoglobin and hemocyanin
   - **hemoglobin**
     - oxygen carrier protein in blood of all vertebrates, many invertebrates such as echinoderms, annelids, some mollusks, and even some protists
     - synthesized by and contained within erythrocytes
     - 4 polypeptides and 4 organic heme groups, iron molecule at center of each heme group
     - oxygen bound reversible with iron portion of each heme group; thus, each molecule of hemoglobin can bind 4 molecules of O_2