Ch. 42
Circulatory Systems
And
Gas Exchange
In circulation...

- **What needs to be transported**
  - **nutrients & fuels**
    - from digestive system
  - **respiratory gases**
    - $O_2$ & $CO_2$ from & to gas exchange systems: lungs, gills
  - **intracellular waste**
    - waste products from cells
      - water, salts, nitrogenous wastes (urea)
  - **protective agents**
    - immune defenses
      - white blood cells & antibodies
    - blood clotting agents
  - **regulatory molecules**
    - hormones
Circulatory systems

All animals have:

- circulatory fluid = “blood”
- tubes = blood vessels
- muscular pump = heart

(a) Open circulatory system

(b) Closed circulatory system
Open circulatory system

- Taxonomy
  - invertebrates
    - insects, arthropods, mollusks

- Structure
  - no separation between blood & interstitial fluid
    - hemolymph
Closed circulatory system

- **Taxonomy**
  - **invertebrates**
    - earthworms, squid, octopuses
  - **vertebrates**

- **Structure**
  - blood confined to vessels & separate from interstitial fluid
    - 1 or more hearts
    - large vessels to smaller vessels
    - material diffuses between blood vessels & interstitial fluid
Vertebrate circulatory system

- Adaptations in closed system
  - number of heart chambers differs

What's the adaptive value of a 4 chamber heart?

4 chamber heart is double pump = separates oxygen-rich & oxygen-poor blood; maintains high pressure
Evolution of vertebrate circulatory system

- **Fish**: 2 chamber
- **Amphibian**: 3 chamber
- **Reptiles**: 3 chamber
- **Birds & Mammals**: 4 chamber

Birds AND mammals! Wassssup?!
Evolution of 4-chambered heart

- **Selective forces**
  - **increase body size**
    - protection from predation
    - bigger body = bigger stomach for herbivores
  - **endothermy**
    - can colonize more habitats
  - **flight**
    - decrease predation & increase prey capture

- **Effect of higher metabolic rate**
  - greater need for energy, fuels, O$_2$, waste removal
    - endothermic animals need 10x energy
    - need to deliver 10x fuel & O$_2$ to cells
Vertebrate cardiovascular system

- Chambered heart
  - atrium = receive blood
  - ventricle = pump blood out

- Blood vessels
  - arteries = carry blood away from heart
    - arterioles
  - veins = return blood to heart
    - venules
  - capillaries = thin wall, exchange / diffusion
    - capillary beds = networks of capillaries
Blood vessels

- arteries
- arterioles
- capillaries
- venules
- veins
Arteries: Built for high pressure pump

- **Arteries**
  - **thicker walls**
    - provide strength for high pressure pumping of blood
  - **narrower diameter**
  - **elasticity**
    - elastic recoil helps maintain blood pressure even when heart relaxes
Veins: Built for low pressure flow

**Veins**
- **thinner-walled**
- **wider diameter**
  - blood travels back to heart at low velocity & pressure
  - lower pressure
    - distant from heart
    - blood must flow by skeletal muscle contractions when we move
      - squeeze blood through veins

**valves**
- in larger veins one-way valves allow blood to flow only toward heart
Capillaries: Built for exchange

- **Capillaries**
  - very thin walls
    - lack 2 outer wall layers
    - only endothelium
      - enhances exchange across capillary
  - diffusion
    - exchange between blood & cells
Controlling blood flow to tissues

- Blood flow in capillaries controlled by pre-capillary sphincters
  - supply varies as blood is needed
  - after a meal, blood supply to digestive tract increases
  - during strenuous exercise, blood is diverted from digestive tract to skeletal muscles

- Capillaries in brain, heart, kidneys & liver usually filled to capacity

Why?
Exchange across capillary walls

Fluid & solutes flows out of capillaries to tissues due to **blood pressure**
- “bulk flow”

Interstitial fluid flows back into capillaries due to **osmosis**
- plasma proteins ↑ osmotic pressure in capillary

- BP > OP
- BP < OP

What about edema?

85% fluid returns to capillaries
15% fluid returns via lymph
Mammalian circulation

What do **blue** vs. **red** areas represent?
Mammalian heart

- Pulmonary artery
- Anterior vena cava
- Right atrium
- Pulmonary veins
- Semilunar valve
- Atrioventricular valve
- Posterior vena cava
- Right ventricle
- Left ventricle
- Aorta
- Pulmonary artery
- Left atrium
- Pulmonary veins
- Semilunar valve
- Atrioventricular valve

http://quieltube2.com/v.php/http://www.youtube.com/watch?v=JA0Wb3gc4mE
Coronary arteries

bypass surgery

http://quietube2.com/v.php/http://www.youtube.com/watch?v=YcNYxegDXa8
# Heart valves

- **4 valves in the heart**
  - flaps of connective tissue
  - prevent backflow

- **Atrioventricular (AV) valve**
  - between atrium & ventricle
  - keeps blood from flowing back into atria when ventricles contract
    - “lub”

- **Semilunar valves**
  - between ventricle & arteries
  - prevent backflow from arteries into ventricles while they are relaxing
    - “dub”
**Lub-dub, lub-dub**

- **Heart sounds**
  - closing of valves
  - “Lub”
    - recoil of blood against closed AV valves
  - “Dub”
    - recoil of blood against semilunar valves

- **Heart murmur**
  - defect in valves causes hissing sound when stream of blood squirts backward through valve
Cardiac cycle

- **1 complete sequence of pumping**
  - heart contracts & pumps
  - heart relaxes & chambers fill
  - contraction phase
    - **systole**
    - ventricles pumps blood out
  - relaxation phase
    - **diastole**
    - atria refill with blood

| systolic | diastolic | pump (peak pressure) | fill (minimum pressure) | 110 | 70 |
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.
Measurement of blood pressure

- **High Blood Pressure (hypertension)**
  - if top number *(systolic pumping)* > 140
  - if bottom number *(diastolic filling)* > 90
Maintaining the Heart’s Rhythmic Beat

- Some cardiac muscle cells are self-excitatory, 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)**.
Figure 42.9-1

SA node (pacemaker)

ECG

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Figure 42.9-2

1. SA node (pacemaker)
2. AV node

ECG
SA node (pacemaker)  AV node  Bundle branches  Heart apex

ECG
Figure 42.9-4

1. SA node (pacemaker)
2. AV node
3. Bundle branches
4. Purkinje fibers

ECG
- Impulses from the SA node travel to the atrioventricular (AV) node
- At the AV node, the impulses are delayed and then travel to the Purkinje fibers that make the ventricles contract
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 (C-Reactive Protein) is also a factor in cardiovascular disease.
Atherosclerosis, Heart Attacks, and Stroke

- One type of cardiovascular disease, **atherosclerosis**, is caused by the buildup of plaque deposits within arteries.

Figure 42.20

1. **Endothelium**
2. **Smooth muscle**
3. **LDL**
4. **Macrophage**
5. **Fibrous cap**
6. **Cholesterol**
7. **Plaque rupture**
8. **Plaque**
9. **Smooth muscle cell**
10. **Extra-cellular matrix**
11. **T lymphocyte**
A heart attack, or myocardial infarction, is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries.

Coronary arteries supply oxygen-rich blood to the heart muscle.

A stroke is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head.

Angina pectoris is caused by partial blockage of the coronary arteries and results in chest pains.
Risk Factors and Treatment of Cardiovascular Disease

- A high LDL to HDL ratio increases the risk of cardiovascular disease
- The proportion of LDL relative to HDL can be decreased by exercise, not smoking, and avoiding foods with trans fats
- Drugs called statins reduce LDL levels.
RESULTS

Individuals with two functional copies of **PCSK9** gene (control group)

- Average = 105 mg/dL

Individuals with an inactivating mutation in one copy of **PCSK9** gene

- Average = 63 mg/dL
Inflammation plays a role in atherosclerosis and thrombus formation.

Aspirin inhibits inflammation and reduces the risk of heart attacks and stroke.

Hypertension, or high blood pressure, promotes atherosclerosis and increases the risk of heart attack and stroke.

Hypertension can be reduced by dietary changes, exercise, and/or medication.
Bloody well ask some questions, already!
Gas Exchange
Respiratory Systems

alveoli

gills
elephant seals
Gas exchange

- $O_2$ & $CO_2$ exchange between environment & cells
  - need **moist membrane**
  - need **high surface area**
Optimizing gas exchange

- Why high surface area?
  - maximizing rate of gas exchange
  - CO$_2$ & O$_2$ move across cell membrane by diffusion
    - rate of diffusion proportional to surface area

- Why moist membranes?
  - moisture maintains cell membrane structure
  - gases diffuse only dissolved in water
Gas exchange in many forms...

- one-celled
- amphibians
- echinodermes

- insects
- fish
- mammals

- size
- water vs. land
- endotherm vs. ectotherm

AP Biology
Evolution of gas exchange structures

Aquatic organisms

**external** systems with lots of surface area exposed to aquatic environment

**moist internal** respiratory tissues with lots of surface area,

*Same feature with terrestrial animals!*
Gas Exchange in Water: Gills

(a) Fish

[Diagram showing the circulation of blood through gills and systemic capillaries, with labels for Artery, Heart, Ventricle (V), Atrium (A), Vein, Gill capillaries, and Systemic capillaries.]
**Counter current exchange system**

- Water carrying gas flows in one direction, blood flows in **opposite** direction

Why does it work? counter current? Adaptation!

Just keep swimming....
Uh-oh! Equilibrium with the environment... We know what that means!
Counter-Currents create disequilibriums with little energy cost!

Gas Exchange – gills and alveoli!

Fluid Exchange – the kidneys!

Heat Exchange – Deer feet in the snow! Duck feet in freezing water!
How counter current exchange works

- Blood & water flow in opposite directions
  - maintains **diffusion gradient** over whole length of gill capillary
  - maximizing $O_2$ transfer from water to blood
Gas Exchange on Land

- **Advantages of terrestrial life**
  - air has many advantages over water
    - higher concentration of $O_2$
    - $O_2$ & $CO_2$ diffuse much faster through air
      - respiratory surfaces exposed to air do not have to be ventilated as thoroughly as gills
    - air is much lighter than water & therefore much easier to pump
      - expend less energy moving air in & out

- **Disadvantages**
  - keeping large respiratory surface moist causes high water loss
    - reduce water loss by keeping lungs internal

Why don't land animals use gills?
Terrestrial adaptations

**Tracheae**
- air tubes branching throughout body
- gas exchanged by diffusion across moist cells lining terminal ends, *not* through open circulatory system
Lungs

Why is this exchange with the environment RISKY?

Exchange tissue: spongy texture, honeycombed with moist epithelium
Alveoli

- Gas exchange across thin epithelium of millions of alveoli
  - total surface area in humans ~100 m²
Negative pressure breathing

- Breathing due to changing pressures in lungs
  - air flows from higher pressure to lower pressure
  - pulling air instead of pushing it
Mechanics of breathing

- Air enters nostrils
  - filtered by hairs, warmed & humidified
  - sampled for odors
- Pharynx → glottis → larynx (vocal cords) → trachea (windpipe) → bronchi → bronchioles → air sacs (alveoli)
- Epithelial lining covered by cilia & thin film of mucus
  - mucus traps dust, pollen, particulates
  - beating cilia move mucus upward to pharynx, where it is swallowed
Autonomic breathing control

- **Medulla** sets rhythm & **pons** moderates it
  - coordinate respiratory, cardiovascular systems & metabolic demands

- Nerve sensors in walls of aorta & carotid arteries in neck detect O₂ & CO₂ in blood
Medulla monitors blood

- Monitors CO₂ level of blood
  - measures pH of blood & cerebrospinal fluid bathing brain
    - CO₂ + H₂O → H₂CO₃ (carbonic acid)
    - if pH decreases then increase depth & rate of breathing & excess CO₂ is eliminated in exhaled air
Breathing and Homeostasis

- Homeostasis
  - keeping the internal environment of the body balanced
  - need to balance $O_2$ in and $CO_2$ out
  - need to balance energy (ATP) production

- Exercise
  - breathe faster
    - need more ATP
    - bring in more $O_2$ & remove more $CO_2$

- Disease
  - poor lung or heart function = breathe faster
    - need to work harder to bring in $O_2$ & remove $CO_2$
Diffusion of gases

- Concentration gradient & pressure drives movement of gases into & out of blood at both lungs & body tissue.
Hemoglobin

- Why use a carrier molecule?
  - O₂ not soluble enough in H₂O for animal needs
    - blood alone could not provide enough O₂ to animal cells
    - hemocyanin in insects = copper (bluish/greenish)
    - hemoglobin in vertebrates = iron (reddish)

- Reversibly binds O₂
  - loading O₂ at lungs or gills & unloading at cells
Cooperativity in Hemoglobin

- **Binding O₂**
  - binding of O₂ to 1ˢᵗ subunit causes shape change to other subunits
    - conformational change
  - increasing attraction to O₂

- **Releasing O₂**
  - when 1ˢᵗ subunit releases O₂, causes shape change to other subunits
    - conformational change
  - lowers attraction to O₂
O₂ dissociation curve for hemoglobin

Bohr Shift

- A drop in pH lowers the affinity of Hb for O₂.
- Active tissue (producing CO₂) lowers blood pH and induces Hb to release more O₂.

Effect of pH (CO₂ concentration)
O₂ dissociation curve for hemoglobin

Bohr Shift

- increase in **temperature** lowers affinity of Hb for O₂
- active muscle produces heat

Effect of Temperature

More O₂ delivered to tissues
Transporting CO$_2$ in blood

- Dissolved in blood plasma as bicarbonate ion

- CO$_2$ + H$_2$O $\rightarrow$ H$_2$CO$_3$

- Bicarbonate: H$_2$CO$_3$ $\rightarrow$ H$^+$ + HCO$_3^-$

- Carbonic anhydrase

- CO$_2$ dissolves in plasma

- CO$_2$ combines with Hb

- H$_2$CO$_3$ $\rightarrow$ H$^+$ + HCO$_3^-$

- Carbonic anhydrase
Releasing CO$_2$ from blood at lungs

- Lower CO$_2$ pressure at lungs allows CO$_2$ to diffuse out of blood into lungs

![Diagram showing the process of CO$_2$ release from blood to plasma in the lungs.]
Adaptations for pregnancy

- Mother & fetus exchange $O_2$ & $CO_2$ across placental tissue

Why would mother’s Hb give up its $O_2$ to baby’s Hb?
Fetal hemoglobin (HbF)

- HbF has greater attraction to O\textsubscript{2} than Hb
  - low % O\textsubscript{2} by time blood reaches placenta
  - fetal Hb must be able to bind O\textsubscript{2} with greater attraction than maternal Hb

What is the adaptive advantage?

2 alpha & 2 gamma units
Don’t be such a baby…
Ask Questions!!