Lecture 19, 25 Oct 2005
Chapter 20-24
Circulation, Oxygen and Carbon Dioxide Transport

Vertebrate Physiology
ECOL 437 (aka MCB 437, VetSci 437)
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instr: Kevin Bonine
t.a.: Kristen Potter

1. Circulatory System
2. Respiration

Text:
Chapters 23 & 24
(skip the invert material if you like)
Then chapters 21 & 22
(skim Chapter 20)
Gravity and BP

![Diagram showing arterial and venous pressures in a man in different postures, indicating pressures at various points in relation to the pressure in the right atrium of the heart.](modified_from_Burton_1972)

Knut Schmidt-Nielsen 1997
(a) Electrocardiogram
(Eckert, 12-8)

P = Atrial depolarization
Q,R,S = Ventricular depolarization
T = Ventricular repolarization

(Q,R,S masks atrial repolarization)

(b) Cardiac action potentials
(Pacemaker potential
Sinoatrial node
Atrium
Atrioventricular node
Bundle of His
Purkinje fiber in false tendon
Terminal Purkinje fiber
Ventricular muscle fiber)

(Eckert, 12-8)
Wiggers Diagram

Valves open/close where pressure curves cross

760 mmHg = 1 atm = 9.8 m blood

Figure 9-22 Ventricular Filling Profiles during Normal and Rapid Heart Rates Because much of ventricular filling occurs early in diastole during the rapid-filling phase, filling is not seriously impaired when diastolic time is reduced as a result of an increase in heart rate.

Sherwood 1997

Atrial Kick

Heart filled ~same with increased HR
Systole = Ventricular Emptying
Diastole = Ventricular Filling
(rest)

Cardiac Output:

\[ \text{CO} = \text{cardiac output (ml/min from 1 ventricle)} \]
\[ \text{SV} = \text{stroke volume (ml/beat from 1 ventricle)} \]
\[ = \text{EDV} - \text{ESV} \text{ (end-diastolic - end-systolic volume)} \]
\[ \text{HR} = \text{heart rate (beats/min)} \]

\[ \text{CO} = \text{HR} \times \text{SV} \]
\[ \text{MABP} = \text{CO} \times \text{TPR} \]
\[ \text{MABP} = \text{DP} + \frac{1}{3}(\text{SP-DP}) \]

- Heart can utilize different types of energy sources (unlike brain)
Cardiac Output Control

**Sympathetic** speeds heart rate and increases contractility

1. Norepinephrine binds to beta\(_1\) adrenergic receptors
2. Increases cAMP levels and phosphorylation
3. Activates cation channels (Na\(^+\)) and increases HR

4. Epi and Norepi activate alpha and beta\(_2\) adrenoreceptors which increase **contractility** and rate of signal conduction across heart
How increase contractility?

More Ca\(^{2+}\)

**HR control**

Parasympathetic vs. Sympathetic

(Eckert, 12-5)
HR control

**Parasympathetic** slows heart rate
- Innervate *Atria* (Vagus nerve = Xth cranial nerve)
- Cholinergic (ACh)
  - Alter SA node pacemaker potential by ↑ K⁺ permeability
     ↓ Ca²⁺ permeability

Parasympathetic innervation of *AV node slows passage* of signal between atria and ventricles

Peripheral Circulation
- Endothelium lining vessels
- Middle layer with smooth muscle (esp. arteries)
- Outer fibrous layer

Capillaries with ~ only Endothelium
Peripheral Circulation

**Compliance vs. Elasticity**

~ Veins vs. Arteries

**Volume Reservoir vs. Pressure Reservoir**
**Volume Reservoir vs. Pressure Reservoir**

- Constant P and Q at Capillaries!

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**Venous System**

- **low pressure** (11 mm Hg or less)
- **thin walled** veins with **less muscle**
- **more compliant** and **less elastic**
- **valves**
- blood moved by **skeletal muscle** (and smooth)
- **breathing** creates **vacuum** (low pressure) in chest to aid blood flow to heart
Microcirculation

- endothelium in capillaries is permeable

1. continuous
2. Fenestrated (kidney, gut)
3. Sinusoidal (liver, bone)

- Movement across walls, between walls, in vesicles

- Bulk Flow...

Bulk Flow...

Fluid Pressure
vs.
Osmotic Pressure

Faster than diffusion

Filtration > Uptake

Lymph System to return excess fluid
Bulk Flow...  
- Edema
- Starvation
- Lungs
- Kidneys

Lymph System
- No RBCs; therefore not red
- Drains interstitial spaces
- has valves and smooth musculature
- empties into thoracic duct at vena cavae
- transport system for large hormones and fats into blood stream
- filariasis, elephantiasis
- Reptiles and Amphibians with lymph hearts

Circulatory System Regulation
1. Feed Brain and Heart First
2. Next Feed Tissues in Need
3. Maintain volume, prevent edema, etc.
   - Baroreceptors
   - Chemoreceptors
   - Mechanoreceptors
   - Thermoreceptors

Info. integrated at Medullary Cardiovascular Center
   medulla oblongata and pons

Depressor Center \(\rightarrow\) Parasympathetic Effectors
Pressor Center \(\rightarrow\) Sympathetic Effectors
Circulatory System Regulation

Baroreceptors increase AP firing rate when BP increases

Sensed at carotid sinus, aortic arch, subclavian, common carotid, pulmonary

Usually leads to Sympathetic suppression to decrease BP

(Eckert, 12-43)

Circulatory System Regulation

Arterial Chemoreceptors in carotid and aortic bodies
(More details when discuss ventilation)

e.g., low O₂, high CO₂, low pH
leads to bradycardia and peripheral vasoconstriction
(diving and not inflating lungs)

What about when not diving?
Circulatory System Regulation

Cardiac Mechanoreceptors and Chemoreceptors

Alter heart rate AND blood volume

e.g.,
ANP (Atrial Natruiretic Peptide) released in response to stretch

- leads to increased Na+ excretion
and therefore greater urine output

Circulatory System Regulation

Extrinsic vs. Local Control

\[ \downarrow \]
Neuronal or Hormonal

Most arterioles with sympathetic innervation
Also respond to circulating catecholamines:
- At high levels, alpha adrenoreceptors are stimulated \( \rightarrow \) vasoconstriction (to increase BP)
- At low levels, beta\(_2\) adrenoreceptors are stimulated \( \rightarrow \) vasodilation (to increase flow to tissue)
- Response depends on tissue type, receptor type(s), level of catecholamines (epi, norepi), etc.
Circulatory System Regulation

Extrinsic vs. Local Control

- Vasodilation
- Relaxation

Decreased O₂ levels with opposite effect in lungs

- NO (nitric oxide)
- Released from vascular endothelium:
- Viagra acts by blocking breakdown of cGMP

(Eckert, 12-45)
Circulatory System Regulation
Extrinsic vs. Local Control

Histamine

Released in response to injury of connective tissue and leukocytes:

-Vasodilation

(Hill et al., 2004 Fig 23.11)
Hemodynamics in Vessels

Flow depends primarily on pressure gradient and resistance

Flow rate depends on:
- Pressure Gradient
- Resistance

**Flow**


\[ Q = \frac{(P_1 - P_2) \pi r^4}{8L\eta} \]

**Poiseuille’s Law**

- **Pressure Gradient**
- **radius**
- **length**
- **viscosity**

Small change in radius → large change in flow rate
Hemodynamics

- From Poiseuille’s Law:

\[
R = \frac{(P_1 - P_2)}{Q} = \frac{8L\eta}{\pi r^4}
\]

Small change in radius \(\rightarrow\) large change resistance
Modifiable if vessel distensible under pressure

Summed resistance reduces pressure...

(Eckert, 12-25)
Total Flow Rate **same** all along Circulatory System

Shapes of curves slightly different because of RBCs (viscosity)

**(a) Continuous laminar flow**
Why does blood in the lower extremities of aquatic organisms not pool as it may do in legs of humans, giraffes, etc.?

FISH:
Blood tends to pool in tail b/c inertia and compression waves when swimming

- Veins in middle of body
- Accessory caudal (tail) heart in some species

Hill et al., 2004, Fig. 21.1
Lung Anatomy

Nonrespiratory
- Trachea ->
- Bronchi ->
- Bronchioles ->

Respiratory
- Terminal bronchioles ->
- Respiratory bronchioles ->
- Alveoli

- Cilia and Mucus

-Gas Diffusion Barriers:

(Eckert, 13-21)
Lung Ventilation

-Small mammals with greater per gram O₂ needs and therefore greater per gram respiratory surface area

-Dead Space (anatomic and physiological)

(Eckert, 13-24)
Mammalian Ventilation

- lungs are **elastic bags**
- suspended in **pleural cavity** within **thoracic cage** (ribs and diaphragm define, fluid lines)
- low volume **pleural “space”** between lung and thoracic wall
- **negative pressure** to inflate lungs (increase volume)
- **pneumothorax**
Mammalian Ventilation

expiration usually passive

Mammalian Lung

Alveoli and Capillaries

RBC (not to scale)

Knut Schmidt-Nielsen 1997
Bird Lung Ventilation

Unidirectional!!

Bird Ventilation

-lung volume changes very little, air sacs instead

(Eckert, 13-32)

Unidirectional
Frog Ventilation

-Positive pressure ventilation

1. Into mouth (buccal cavity)

2. Close nares, open glottis and force air into lungs by raising buccal floor

(Eckert, 13-33)
Pulmonary **Surfactants**

- Reduce liquid surface tension in alveoli
- Allows for compliance and low-cost expansion of lung
- Lipoproteins
- keep alveoli from getting stuck closed
  
**Atelectasis** = collapsed lung

- premature babies may need artificial surfactant

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**Panting Dogs?**

![Image of panting dog]

**Figure 17.** As the total respiratory ventilation (abscessa) increases in the panting ox, the dead space ventilation increases steadily. The alveolar ventilation, however, does not increase until the total ventilation exceeds about 900 liters per minute. In extreme panting the respiratory frequency (f) is decreased as tidal volume (Vt) is increased (figures at top of graph). (From Hales, 1966.)

Knut Schmidt_Nielsen 1972
Fish Gill

(a) Two types of convective transport

Unidirectional flow

Tidal flow

(b) Calculation of the rate of convective gas transport

\[ \text{Rate of convective gas transport} = C \times F \]

\[ C = \text{Total concentration of gas in flowing fluid (mol/L)} \]
\[ F = \text{Flow rate of fluid (L/second)} \]

Hill et al., 2004, Fig. 20.3
Hill et al., 2004, Fig. 21.10

Relative Gill Surface Area in Fishes
Fish Gill

- breathing in water
- need much higher ventilation rate
- unidirectional
- pump water across gills (or ram ventilation)

Figure 1.9 Water is pumped over the gills of a fish by a dual pumping system. With the aid of suitable valves, the pumps provide a unidirectional flow of water over the gill surface. [Hughes 1960]

GILLS - breathing in water
- need much higher ventilation rate
- unidirectional
- pump water across gills (or ram ventilation)

Floor of Mouth (buccal cavity)
Lake Titicaca Frog
(Bolivian Navy; Peru-Bolivia border)

A frog that breathes through its skin: The Titicaca frog (Ranitomeya aurantiaca) lives in the depths of Lake Titicaca at 3812 m altitude. This animal does not surface to breathe and obtains oxygen entirely by diffusion through the skin surface, which is highly vascularized and enlarged by lobes. [Courtesy of Walter M. Huxley, University of Oklahoma]

Knut Schmidt-Nielsen

Gas Exchange Across Skin

Hill et al., 2004, Fig. 21.8
Hill et al., 2004, Fig. 21.7
Rate and Depth Regulation

- Primarily via CO₂ changes (central)

- Peripheral Chemoreceptors
  PO₂, PCO₂, pH

- Innervate Medullary Respiratory Center
  (phrenic nerve to diaphragm and intercostals)

- Emotions, sleep, light, temperature, speech, volition, etc.

- O₂ controls respiration in aquatic vertebrates

Rate and Depth Regulation

- Central Chemoreceptors

(CSF formation Cerebrospinal fluid)

Long term

CO₂ + H₂O ⇌ H⁺ + HCO₃⁻

↑ P₈O₂ = ↓ pH
**Hering-Breuer reflex**

- Stimulation of *stretch receptors* inhibits medullary inspiratory center
- Prevent *overinflation*

- Ectotherms often breathe intermittently
Oxygen Partial Pressure

(b) The oxygen cascade in people

Hill et al., 2004, Fig. 20.5