Respiratory Physiology
Unit 4

Respiratory Physiology
Respiration

- **External respiration**
  - ventilation
  - gas exchange

- **Internal respiration**
  - cellular respiration
  - gas exchange

- **Respiratory Cycle**
  - Inspiration
    - Moving atmospheric air into the lungs
  - Expiration
    - Moving air out of the lungs
Lungs vs. Balloons

- A lung is similar to a balloon in that it resists stretch, tending to collapse almost totally unless held inflated by a pressure difference between its inside and outside.
- Lungs *and* the chest have elastic properties.
Lung Compliance

- **Compliance**
  - Elasticity
  - Tendency to recoil
  - Tendency of an elastic structure to oppose stretching or distortion
    * Resists distension

- **Surface tension**
  * Resists distension

- **Surfactant**
  - Reduces surface tension
  - Increases compliance (makes them easier to stretch)
Airway Resistance

\[ F = \frac{\Delta P}{R} \]

- Same variables that affect resistance in blood vessels
  - Tube length, tube radius, friction
  - *Tube radius* most important factor

- Airway resistance is so small that small pressure differences produce large volumes of air flow
  - Average atmosphere-to-alveoli pressure difference is 1 mmHg, but 500 mL of air is moved (*tidal volume*)

- Low pressure and low resistance
  - Pulmonary 1/10th of systemic vascular resistance
Ventilation

- Exchange of air between atmosphere and alveoli
- Atmospheric air pressure is 760 mmHg at sea level
- Air moves by bulk flow
  - \( F = \frac{\Delta P}{R} \)
  - \( F = \frac{P_{alv} - P_{atm}}{R} \)
Boyle’s Law

- Boyle’s law = \( \frac{P}{V} \)
- Pressure of a given quantity of gas is inversely proportional to volume
- An increase in the volume of the container (lungs) decreases the pressure of the gas (air)
Ventilation Mechanics

- Lung volume depends on:
  1. Transpulmonary pressure ($P_{tp}$)
     - Inside to outside of the lung
     - $P_{tp} = P_{alv} - P_{ip}$
     - The force that keeps the lungs inflated
     - Transmural pressure
       - Across the wall
  2. How compliant the lungs are
# Transmural Pressures

![Diagram of Transmural Pressures]

## Table 13–3 Two Important Transmural Pressures of the Respiratory System

<table>
<thead>
<tr>
<th>Transmural Pressure</th>
<th>( P_i - P_o )</th>
<th>Value at Rest</th>
<th>Explanatory Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpulmonary (( P_{tp} ))</td>
<td>( P_{alv} - P_{ip} )</td>
<td>( 0 - [-4] = 4 \text{ mmHg} )</td>
<td>Pressure difference holding lungs open (opposes inward elastic recoil of the lung)</td>
</tr>
<tr>
<td>Chest wall (( P_{cw} ))</td>
<td>( P_{ip} - P_{atm} )</td>
<td>( -4 - 0 = -4 \text{ mmHg} )</td>
<td>Pressure difference holding chest wall in (opposes outward elastic recoil of the chest wall)</td>
</tr>
</tbody>
</table>

\( P \) is pressure inside the structure, and \( P_o \) is pressure surrounding the structure.
What Keeps the Lungs Inflated?

• Elastic recoil of the lungs
  * At rest natural tendency is to **collapse**

• Lungs are held open by the positive $P_{tp}$
  – At rest exactly opposes elastic recoil
    • Collapsing force of the lungs is 4 mmHg
    • Intrapleural pressure is -4 mmHg

• Elastic recoil of the chest
  * At rest natural tendency is to **expand**
Pneumothorax

• A pierce in the chest wall allows atmospheric air to rush in causing $P_{ip}$ to go from -4 mmHg to 0 mmHg

• Transpulmonary pressure acting to hold the lungs open is eliminated

• Lung collapses

• Chest wall expands
Inspiration/Expiration

- In order for air to move into the lungs, the pressure in the lungs must drop below atmospheric pressure

\[ P_{\text{atm}} > P_{\text{alv}} \]

- In order for air to move out of the lungs, the pressure in the lungs must exceed atmospheric pressure

\[ P_{\text{alv}} > P_{\text{atm}} \]
The Respiratory Cycle

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Partial Pressure of Gases

• *Dalton’s Law*
  – Pressure of each gas is independent of the pressure of other gases
  – Pressure of the gas is directly proportional to its concentration
  – Individual gas pressures in air is termed the partial pressure of a gas
  – Atmospheric air 760 mmHg at sea level
    • Air is 78% nitrogen
      – $0.78 \times 760 \text{ mmHg} = 593 \text{ mmHg}$
      – $P_{N_2} = 593 \text{ mmHg}$
    • Air is 21% oxygen
      – $0.21 \times 760 \text{ mmHg} = 159 \text{ mmHg}$
      – $P_{O_2} = 159 \text{ mmHg}$
  – Altitude and Temperature also affect pressure
Partial Pressure of $O_2$ and $CO_2$ in Blood

Table 13–7 Normal Gas Pressure

<table>
<thead>
<tr>
<th></th>
<th>Venous Blood</th>
<th>Arterial Blood</th>
<th>Alveoli</th>
<th>Atmosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{O_2}$</td>
<td>40 mmHg</td>
<td>100 mmHg*</td>
<td>105 mmHg*</td>
<td>160 mmHg</td>
</tr>
<tr>
<td>$P_{CO_2}$</td>
<td>46 mmHg</td>
<td>40 mmHg</td>
<td>40 mmHg</td>
<td>0.3 mmHg</td>
</tr>
</tbody>
</table>

*The reason that the arterial $P_{O_2}$ and alveolar $P_{O_2}$ are not exactly the same is described later in this chapter.
Transport of $O_2$ in the Blood

• 1 Liter of blood contains 200 mL of oxygen
  – Dissolved in plasma
  – Bound to hemoglobin (Hb)

• Solubility of $O_2$ is relatively low
  – Only 3 mL of $O_2$ can dissolve in 1 L of blood at arterial $P_{O_2}$ of 100 mmHg (2%)
  – Remaining 197 mL of oxygen bound Hb (98%)
Transport of O$_2$ in the Blood

- Hemoglobin
  - Heme, globin
  - 280 million Hb per RBC x 4 = >1 billion molecules of oxygen per RBC
- States of Hb
  - Hb
    - deoxyhemoglobin
  - O$_2$ + Hb $\rightleftharpoons$ HbO$_2$
    - Oxyhemoglobin
- Oxygen carrying-capacity of blood – a %
  - Amount of HbO$_2$ is 80 % of total Hb, the sample is 80% saturated
Oxygen-Hemoglobin Dissociation Curve

- **Sigmoid curve**
  - Each Hb molecule has 4 sub-units
  - Binding cooperativity
    - Binding of first $O_2$ increases the affinity for $O_2$ at remaining three heme units

- **Significance of the shape of the curve**
  - Steep slope between 20-60 mmHg
    - Increased unloading
  - Plateau
    - At 60 mmHg, 90% saturation
    - Oxygen reserve
Shifts in the Oxygen-Hemoglobin Dissociation Curve

- Other factors influence the degree of Hb saturation
  - 2,3-diphosphoglycerate (DPG)
  - Temperature
  - pH
  - PCO2

- A shift to the **right** decreases the affinity of Hb for O₂
  - increased unloading in the tissues

- A shift to the **left** increases the affinity of Hb for O₂
  - increased loading in the lungs
Hb Saturation

Effects of DPG Concentration

• 2,3-diphosphoglycerate (DPG)
  – Always produced by RBCs
  – Increase in DPG causes a shift to the right

• RBCs increase production of DPG when there is a decrease in $P_{O_2}$
  – Higher altitude
  – Anemia
  – Transfer from maternal blood to fetal Hb

• Increased unloading in the tissues to maintain $O_2$ delivery
Hb Saturation
Effects of Temperature

- Higher temperature in tissue capillary blood than in arterial blood
- The more metabolically active the tissue is, the higher the temperature will be
- Increased unloading in the tissue
  - Provides more metabolically active cells with more $O_2$
Hb Saturation

Effects of pH

- Higher \([H^+]\) in tissue capillary blood than in arterial blood
  - Elevated \(P_{CO_2}\)
  - Metabolically produced acids such as lactic acid
- The more metabolically active the tissue is, the greater the \([H^+]\)
  - Lower pH
  - Higher acidity
- Increased unloading in the tissue
  - Provides more metabolically active cells with more \(O_2\)
Transport of CO₂ in Blood

- 200 mL CO₂/min produced by metabolism
- 10% dissolved in plasma
- 30% as carbaminohemoglobin (HbCO₂)
  - CO₂ + Hb <--→ HbCO₂
- 60% as bicarbonate (HCO₃⁻)
  - CO₂ + H₂O <--→ H₂CO₃ <--→ HCO₃⁻ + H⁺
  - Carbonic anhydrase
  - Present in RBCs
Chloride Shift
Tissue Level

- **Bicarbonate reaction** shifts to the right... **WHY??**
  - \( \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \)

- **Steps:**
  - \( \text{CO}_2 \) diffuses out of the tissue cells into the blood
  - \( \text{CO}_2 \) moved into the red blood cells
  - \( \text{CO}_2 \) combines with \( \text{H}_2\text{O} \) to produce \( \text{H}_2\text{CO}_3 \)
    - Carbonic anhydrase makes this reaction fast
  - \( \text{H}_2\text{CO}_3 \) dissociates producing \( \text{H}^+ + \text{HCO}_3^- \)
  - \( \text{H}^+ \) buffered by hemoglobin, facilitating the offloading of \( \text{O}_2 \)
    - Forms HHb
  - \( \text{Cl}^- \) moves into the RBC in exchange for \( \text{HCO}_3^- \) moving into plasma
  - **Bohr effect**
    - Increased oxygen unloading in tissues
    - Enhanced transport of \( \text{CO}_2 \)
Chloride Shift
Tissue Level

(a) Oxygen release and carbon dioxide pickup at the tissues

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Reverse Chloride Shift
Pulmonary Capillaries

• Equation shifts to the left.....WHY??
  – \( \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{HCO}_3^- + \text{H}^+ \)

• Steps:
  – Hb oxygenated
  – Hb decrease in affinity for \( \text{H}^+ \)
  – Reverse chloride shift as Cl\(^-\) moves into plasma and HCO\(_3^-\) moves into the RBC
  – \( \text{H}_2\text{CO}_3 \) dissociates to \( \text{CO}_2 + \text{H}_2\text{O} \)
  – \( \text{CO}_2 \) expired out

• Remember:
  – \( \text{H}^+ \) is buffered by Hb in RBC
  – HCO\(_3^-\) goes into the plasma and buffers incoming \( \text{H}^+ \)
Reverse Chloride Shift
Pulmonary Capillaries

(b) Oxygen pickup and carbon dioxide release in the lungs

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Respiratory Control Centers
Rhythmical Breathing

• Medulla oblongata
  – *Respiratory Rhythmicity Center*
    • Controls the diaphragm and intercostals

• Pons
  – *Apneustic Center*
    • Terminates inspiration
  – *Pneumotaxic Center*
    – Modulates activity of apneustic center
    – Smoothes the transition from inspiration to expiration
      • Cyclic inhibition

• Pulmonary stretch receptors
  – Cut off signal for inspiration to allow expiration to occur
Control of Ventilation

Monitoring $P_{O_2}$, $P_{CO_2}$, $H^+$

- Respiratory rate and tidal volume can be altered
- Peripheral chemoreceptors
  - *Aortic and Carotid bodies*
  - Provides afferent input to the medulla via the Vagus Nerve
  - Sensitive to $P_{O_2}$
- Central chemoreceptors
  - In the Medulla
  - Highly sensitive to $P_{CO_2}$
Control of Ventilation
Monitoring $P_{O_2}$, $P_{CO_2}$, $H^+$

• Peripheral chemoreceptors
  – Aortic and Carotid Bodies
  – Sensitive to:
    • Decreased $P_{O_2}$ (hypoxia)
    • Increased $H^+$ due to the build up of other acids (metabolic acidosis)
    • Increased $H^+$ due to $CO_2$ retention (respiratory acidosis)

• Central chemoreceptors
  – Medulla
  – Sensitive to
    • Increased $H^+$ in brain extracellular fluid (CSF)
      – $CO_2$ crosses blood brain barrier to stimulate receptors
Protective Reflexes

• Pulmonary irritant reflexes
  – Reflex constriction to prevent particulates from entering lungs
  – Receptors located between airway epithelial cells
  – Cough reflex
  – Sneeze reflex
  – Cessation of breathing reflex
    – Triggered when noxious agents are inhaled
    – Chronic smoking causes loss of this reflex