Respiratory System

Objectives

- Pulmonary Structure & function
- Gas exchange and transport
- Exercise & pulmonary ventilation

Pulmonary Anatomy

Respiration Generals

- Respiration:
  - Process of gas exchange, which for the human body involves oxygen and carbon dioxide
    - Internal respiration (cellular)
    - External respiration (lung)

- Lungs
  - Provide a large surface area (50 – 100 m²)
  - Highly vascularized

Respiration Generals (cont.)

- Alveoli (~300 million)
  - Elastic & thin walled (~ 0.3mm in diameter
    - During submaximal exercise, the integrity of wall does not change
    - Maximal exercise may induce stress on the wall
      - Large ventilation & pulmonary blood flow

Lung Specifics

- Surfactant (within the alveoli):
  - Phospholipoprotein molecule secreted by specialized cells of the lung that lines the surface of alveoli & respiratory bronchioles
  - Lowers surface tension of the alveolar membranes
    - Prevents the collapse of alveoli during exhalation
    - Increases compliance during inspiration
  - Distribution aided by Pores of Kohn
**Mechanics of Ventilation**

**Inspiration & Expiration**
- **Inspiration (muscles involved):**
  a) Diaphragm: primary ventilatory muscle during exercise
  - Scalene and external intercostals assist diaphragm
- **Expiration (during rest and light exercise):**
  a) Predominantly passive
  b) During strenuous exercise:
    - Internal intercostals
    - Abdominal muscles assist

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**Mechanics of Ventilation (cont.)**

**Airflow in the Lungs**
- Forward airflow increases as cross-sectional area increases

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**Fick’s Law of Diffusion**
- Explains gas exchange through the alveolar membranes
- Gas diffuses through a tissue at a rate:
  a) Proportional to surface area (or tissue area)
  b) Inversely proportional to its thickness

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**Lung Volumes & Capacities**
- Measured using a spirometer
Lung Volumes & Capacities (cont.)

- Lung volumes vary with:
  a) Age
  b) Size (mainly stature)
  c) Gender

1. TV: Tidal Volume (0.4–1.0L)
2. IRV: Inspiratory Reserve Volume (2.5–3.5L)
3. ERV: Expiratory Reserve Volume (1.0–1.5L)
4. FVC or VC: Vital Capacity (3.5L)
5. RLV: Residual Lung Volume (0.8–1.4L)

Estimating Residual Volume

- Normal-weight men & women:
  \[
  RLV = 0.0275(\text{AGE}) + 0.0189(\text{HT}) - 2.6139
  \]

- Overweight men and women:
  \[
  RLV = 0.0277(\text{AGE}) + 0.0048(\text{WT}) + 0.0138(\text{HT}) - 2.3967
  \]

Dynamic Lung Volume

- Dynamic ventilation dependent upon:
  a) FVC (Forced Vital Capacity)
  b) Rate (or speed) of breathing
    - Dictated by lung compliance

- Measurement techniques:
  a) FEV to FVC Ratio
    - Forced Expiratory Volume over 1 second (FEV\textsubscript{1.0}) / Forced Vital Capacity
    - Pulmonary airflow capacity
    - Average person – 85% of FVC in 1 second
    - Pulmonary disease – as low as 40%

Examples of FEV\textsubscript{1.0}/FVC

- Maximum Voluntary Ventilation (MVV)
  - Evaluates rapid and deep breathing for 15 seconds & extrapolates to 1 minute
  - ~ 25% higher than ventilation during max exercise
  - College aged men – 140 to 180L·min\textsuperscript{-1}
  - College aged females – 80 to 120L·min\textsuperscript{-1}

- Gender differences
  a) Compromised in trained females
  - Mechanical constraints & pulmonary ventilation may affect arterial saturation

- Variations in MVV measurements will not predict exercise tolerance
**Pulmonary Ventilation**

- Minute ventilation:
  a) Volume of air breathed each minute, $V_E$

  $$V_E = \text{Breathing rate} \times \text{Tidal Volume}$$

- Minute ventilation increases dramatically during exercise
  a) Average person ~ $100\, \text{L}\cdot\text{min}^{-1}$
  b) Values up to $200\, \text{L}\cdot\text{min}^{-1}$ have been reported

- Despite huge increases in $V_E$ during maximal exercise, tidal volumes rarely exceed 60% VC

**Alveolar Ventilation**

- Anatomic Dead Space:
  a) Averages 150 – 200 mL

- Only ~ 350 mL of the 500 mL TV enters alveoli

**Ventilation Comparisons**

- Dead Space vs. Tidal Volume
  a) Anatomic Dead Space increases as TV increases

  ✓ Despite the increase, increases in TV result in more effective alveolar ventilation

- Ventilation-Perfusion Ratio
  a) Ratio of alveolar ventilation to pulmonary blood flow

  ✓ $V/Q$ during light exercise ~ 0.8
  ✓ $V/Q$ during strenuous exercise may increase up to 5.0

- Physiologic dead space
  a) Negligible in healthy lung

**Variations in Breathing**

- Hyperventilation
  a) An increase in pulmonary ventilation that exceeds $O_2$ needs of metabolism

  ✓ Decreases $PCO_2$

- Dyspnea

- Valsalva Maneuver
  a) Closing the glottis following a full inspiration while maximally activating the expiratory muscles

  ✓ Increase intra-thoracic pressure
  ✓ Stabilizes chest during lifting
Physiologic Consequences of Valsalva
• An acute drop in BP may result from a prolonged Valsalva maneuver
  a) Decreased venous return & blood flow to brain

Concentration & Partial Pressure of Respired Gases
• Partial Pressure: percentage of concentration x total pressure of a gas
  a) \( \text{PO}_2, \text{PCO}_2 \)

• Dalton’s Law: total pressure = sum of partial pressure of all gases in a mixture
  a) Ambient Air
    \[ \text{O}_2 = 20.93\% \text{ or } 159 \text{mmHg PO}_2 \]
    \[ \text{CO}_2 = 0.03\% \text{ or } 0.23 \text{mmHg PCO}_2 \]
    \[ \text{N}_2 = 79.04\% \text{ or } 600 \text{mmHg PN}_2 \]

Movement of Gas in Air & Fluids
• Henry’s Law: gases diffuse from high pressure to low pressure

  a) Pressure differential (of specific gas)
    ✓ Capillary to alveolar sacs
  b) Solubility of the gas in the fluid
    ✓ \( \text{CO}_2 \) is about 25 times more soluble than \( \text{O}_2 \)
    ✓ \( \text{CO}_2 \) and \( \text{O}_2 \) are both more soluble than \( \text{N}_2 \)

Gas Exchange & Transport

Gas Exchange in Lungs:
• \( \text{PO}_2 \) in alveoli ~ 100mmHg
  a) Drop due to venous myocardial shunt & venous draining in lungs

• \( \text{PO}_2 \) in pulmonary capillaries ~ 40mmHg

• Tracheal air:
  a) Water vapor reduces the \( \text{PO}_2 \) in the trachea about 10mmHg to 149mmHg
  \[ 0.2093 \times (760 - 47 \text{mmHg}) \]

• Alveolar air:
  a) Alveolar air contains ~ 14.5% \( \text{O}_2 \),
    5.5% \( \text{CO}_2 \), and 80.0% \( \text{N}_2 \)
  ✓ Average alveolar \( \text{PO}_2 \) = 103mmHg,
    \( \text{PCO}_2 \) = 39mmHg
  \[ \text{PO}_2 = 0.145 \times (760 - 47 \text{mmHg}) \]
  \[ \text{PCO}_2 = 0.145 \times (760 - 47 \text{mmHg}) \]
**O₂ Transport in Blood**

1. **Dissolved in plasma (~ 1%)**
2. **Combined with hemoglobin (~ 99%)**

   - **Hemoglobin (Hb)**
     a) Iron-bearing protein contained in RBC
     b) Hb has potential to carry 4 O₂ molecules
     c) Each gram of Hb combines with 1.34 mL O₂

   \[
   \text{Blood's O₂ carrying capacity (mL/dL blood)} = \text{Hb (g/dL)} \times \text{O₂ capacity of Hb}
   \]

   \[
   20 \text{ mL O}_2 = 15 \times 1.34
   \]

   - PO₂ is primary determinant of %Hb saturation
**Arteriovenous O₂ Difference**

- The a-vO₂ difference shows the amount of O₂ extracted by tissues.
- During exercise a-vO₂ difference increases up to 3 times the resting value.

**Bohr Effect**

1. An increased PCO₂ content
   - Decreases affinity of Hb for O₂
     - Hb unloads more O₂ than normal at the tissue level.

2. Increased acidity
   - Increased acidity results in greater concentration of CO₂ (from carbonic acid).

3. Increased temperature
   - Results in more unloading (exercise).

4. 2,3 DPG
   - Produced by RBC when Hb is low.

**RBC 2,3 DPG**

- RBC contain no mitochondria
  a) Rely on glycolysis

- 2,3 DPG increases with intense exercise and may increase due to training.
- Helps deliver O₂ to tissues by reducing affinity of O₂.

**Myoglobin, Muscle’s O₂ Store**

- Myoglobin is an iron-containing globular protein in skeletal and cardiac muscle.

- Stores O₂ intramuscularly.
- Myoglobin only contains one iron atom.
- O₂ is released at low PO₂.

**CO₂ Transport**

- Three mechanisms:
  a) Bound to Hb
  b) Dissolved in plasma
  c) Plasma bicarbonate

- Haldane effect: Hb interaction with O₂ reduces its ability to combine with CO₂.
- This aids in releasing CO₂ in the lungs.

![Figure 13.6](image_url)