Section 01:
The Pulmonary System

Chapter 12 – Pulmonary Structure and Function
Chapter 13 – Gas Exchange and Transport
Chapter 14 – Dynamics of Pulmonary Ventilation

HPHE 6710 Exercise Physiology II
Dr. Cheatham

Major Functions of Pulmonary System

• Breathing, Respiration, Ventilation
  – The movement of air into and out of the pulmonary system
  – Technically, breathing and ventilation refer to the movement of air into and out of the pulmonary system, while respiration refers to the cellular use of oxygen (O₂)

• Four specific purposes of “breathing”
  – 1) The exchange of O₂
  – 2) The exchange of carbon dioxide (CO₂)
  – 3) The control of blood acidity (pH)
  – 4) Oral communication
Chapter 12

Pulmonary Structure and Function

Chapter Objectives

- Be able to identify the different anatomical components of the pulmonary system.
- Understand the mechanics of ventilation.
- Be able to define the different static and dynamic lung volumes.
- Understand the difference between minute ventilation and alveolar ventilation (and the concepts of dead space).
- Understand the pulmonary responses during acute exercise.
Anatomy of Ventilation

The Lungs
- Provide a large surface area (50–100 m²)
- Highly vascularized to allow for gas exchange

The Alveoli
- The lungs contain 600 million membranous sacs called alveoli.
- Characteristics of alveoli
  - Elastic
  - Thin walled
  - Very small blood–gas barrier
Anatomy of Ventilation

Figure 12.3: The ultrastructure of the alveolar capillary provides a minimum distance and mass of tissue between alveolar air and red blood cells in the pulmonary circulation. Modified from Guyton, 1976, p. 539. Used with permission.


Mechanics of Ventilation

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Mechanics of Ventilation

- Inspiration
  - Diaphragm contracts and flattens
  - Chest cavity elongates and enlarges and air expands in lungs
  - Intrapulmonic pressure decreases
  - Air is sucked in through nose and mouth

- Expiration
  - During rest and light exercise, expiration is predominantly passive.
    - Stretched lung tissue recoils
    - Inspiratory muscles relax
    - Air moves to atmosphere
  - During strenuous exercise
    - Internal intercostals and abdominal muscles assist
Mechanics of Ventilation

- Conducting Zone
  - Air transport
  - Humidification
  - Warming
  - Filtration
  - Vocalization
  - Immunoglobin secretion

- Respiratory Zone
  - Site of gas exchange
  - Surfactant production
  - Blood clotting function
  - Endocrine function
Mechanics of Ventilation

Fick’s Law
- Governs gas diffusion through alveolar membrane.

\[ D \propto \frac{\Delta PAS}{d \sqrt{MW}} \]

- \( \Delta P \): Pressure difference (gradient)
- \( A \): Cross-sectional area
- \( S \): Solubility coefficient
- \( d \): Diffusion distance
- \( \sqrt{MW} \): Square root of the molecular weight of the gas
Lung Volumes and Capacities

Static Lung Volumes

- Maximal FVC of lungs (stroke volume of lungs)
- Velocity of flow (breathing rate)
- Velocity of flow is influenced by lung compliance.

- FEV/FVC Ratio
  - FEV/FVC indicates pulmonary airflow capacity.
  - Healthy people average ~ 85% of FVC in 1 second.
  - Obstructive diseases result in significant lower FEV/FVC.
Lung Volumes and Capacities

Dynamic Lung Volumes

- Maximum Voluntary Ventilation (MVV)
  - MVV evaluates ventilatory capacity with rapid and deep breathing for 15 seconds.
    - MVV = 15 second volume × 4
  - MVV in healthy individuals averages 25% > ventilation than occurs during max exercise.
Lung Function, Aerobic Fitness and Exercise Performance

Table 12.1: Anthropometric Data, Pulmonary Function, and Resting Minute Ventilation in 20 Marathon Runners and Healthy Controls

<table>
<thead>
<tr>
<th>Measure</th>
<th>Runners</th>
<th>Controls</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anthropometric</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age, y</td>
<td>27.8</td>
<td>27.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Height, cm</td>
<td>176.8</td>
<td>176.7</td>
<td>0.9</td>
</tr>
<tr>
<td>Surface area, m²</td>
<td>1.82</td>
<td>1.89</td>
<td>0.07</td>
</tr>
<tr>
<td><strong>Pulmonary Function</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FVC, L</td>
<td>5.13</td>
<td>5.34</td>
<td>0.21</td>
</tr>
<tr>
<td>TLC, L</td>
<td>6.91</td>
<td>7.13</td>
<td>0.22</td>
</tr>
<tr>
<td>FEV₁Ο₂ L</td>
<td>4.32</td>
<td>4.47</td>
<td>0.15</td>
</tr>
<tr>
<td>FEV₁Ο₂ / FVC, %</td>
<td>84.3</td>
<td>83.8</td>
<td>0.5</td>
</tr>
<tr>
<td>MVV, L · min⁻¹</td>
<td>170.8</td>
<td>176.0</td>
<td>3.8</td>
</tr>
<tr>
<td><strong>Resting Ventilation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VE, L · min⁻¹</td>
<td>11.9</td>
<td>11.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Breathing rate, breaths · min⁻¹</td>
<td>10.9</td>
<td>11.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Total volume, L</td>
<td>1.16</td>
<td>1.35</td>
<td>0.10</td>
</tr>
</tbody>
</table>


*An otherwise not statistically significant.

Pulmonary Ventilation

- Need to distinguish between the amount of air that moves into and out of the total respiratory tract versus the air volume that ventilates the alveoli.
  - Why?
Minute Ventilation ($V_E$)

- $V_E = F_B \times V_T$
  - Minute ventilation increases dramatically during exercise.
    - Values up to $200 \text{ L} \cdot \text{min}^{-1}$ have been reported.
    - Average person $\sim 100 \text{ L} \cdot \text{min}^{-1}$
  - Despite huge $V_E$, TVs rarely exceed 60% VC.

Alveolar Ventilation ($V_A$)

- The volume of air that ventilates the aveoli
- Essentially, $V_E$ minus the dead space

- Anatomical Dead Space
  - Air that fills the nose, mouth, trachea, and nondiffusible conducting portions of the respiratory tract.
    - Around 150 to 200 mL ($\sim 30\%$ of resting tidal volume)
**Pulmonary Ventilation**

**Figure 12-6** During each breath (tidal volume, $V_t$), inspired air enters structures in which no exchange of ventilatory gas is possible. This dead space volume ($D$) comprises part of each tidal volume. Consequently, the alveolar minute ventilation equals the pulmonary minute ventilation less the dead-space minute ventilation.

- **Alveolar Ventilation (cont'd)**
  - **Ventilation Perfusion Ratio ($V_A/Q$)**
    - Ratio of alveolar ventilation to pulmonary blood flow
    - $V/Q$ during light exercise $\sim 0.8$
    - $V/Q$ during strenuous exercise may increase up to 5.0.

  - **Physiological Dead Space**
    - Portion of the alveolar volume with a $V_A/Q$ ratio that approaches zero.
    - Occurs when there is either:
      - Inadequate ventilation
      - Inadequate blood flow
Pulmonary Ventilation

**TABLE 12.2** RELATIONSHIPS AMONG TIDAL VOLUME, BREATHING RATE, AND BOTH TOTAL AND ALVEOLAR MINUTE VENTILATION

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>TIDAL VOLUME (mL)</th>
<th>BREATHING RATE (breaths • min⁻¹)</th>
<th>TOTAL MINUTE VENTILATION (mL • min⁻¹)</th>
<th>DEAD SPACE MINUTE VENTILATION (mL • min⁻¹)</th>
<th>ALVEOLAR MINUTE VENTILATION (mL • min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow breathing</td>
<td>150</td>
<td>40</td>
<td>6000</td>
<td>(150 mL × 40)</td>
<td>0</td>
</tr>
<tr>
<td>Normal breathing</td>
<td>500</td>
<td>12</td>
<td>6000</td>
<td>(150 mL × 12)</td>
<td>4200</td>
</tr>
<tr>
<td>Deep breathing</td>
<td>1000</td>
<td>6</td>
<td>6000</td>
<td>(150 mL × 6)</td>
<td>5800</td>
</tr>
</tbody>
</table>

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Pulmonary Responses During Exercise

**TYPICAL VALUES FOR PULMONARY VENTILATION DURING REST AND MODERATE AND INTENSE EXERCISE**

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>Breathing Rate (breaths • min⁻¹)</th>
<th>Total Volume (L)</th>
<th>Pulmonary Ventilation (L • min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>15</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>Moderate</td>
<td>20</td>
<td>2.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Intense</td>
<td>30</td>
<td>5.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

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Pulmonary Responses During Exercise

Chapter 13

Gas Exchange and Transport
Chapter Objectives

- Identify the partial pressures of oxygen and carbon dioxide in the lungs, blood, tissues
- Understand determinants of the diffusion of gases in a fluid or air space
- Understand how oxygen is transported in the blood
- Understand how oxygen is released to the tissues
- Understand the transport of carbon dioxide

Concentrations and Partial Pressures of Respired Gases

<table>
<thead>
<tr>
<th>Table 13.1</th>
<th>PARTIAL PRESSURE AND VOLUME OF GASES IN DRY AMBIENT AIR AT SEA LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>PERCENTAGE</td>
</tr>
<tr>
<td>Oxygen</td>
<td>20.93</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>79.04*</td>
</tr>
</tbody>
</table>

* At 760 mm Hg ambient air pressure.
* Includes 0.93% argon and other trace rare gases.

<table>
<thead>
<tr>
<th>Table 13.2</th>
<th>PARTIAL PRESSURE AND VOLUME OF DRY ALVEOLAR GASES AT SEA LEVEL (37°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GAS</td>
<td>PERCENTAGE</td>
</tr>
<tr>
<td>Oxygen</td>
<td>14.5</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>5.5</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>80.0</td>
</tr>
<tr>
<td>Water vapor</td>
<td></td>
</tr>
</tbody>
</table>

* At 370 mm Hg alveolar gas pressure.
* Nitrogen occupies a slightly greater percentage of alveolar air than ambient air because energy metabolism generally produces less carbon dioxide than oxygen consumed (i.e., the respiratory quotient [R] = VCO₂ / VO₂).
* R equals less than 1.00. Because of this exchange imbalance, the nitrogen percentage increases.
Concentrations and Partial Pressures of Respired Gases

Movement of Gas in Air and Fluids

- Henry’s Law
  - Gases diffuse from high to low pressure
  - Movement of gas is also effected by the solubility of the gas
    - Carbon Dioxide: 57.03 mL per dL of fluid
    - Oxygen: 2.26 mL per dL of fluid
      - What is the significance of this difference?

<table>
<thead>
<tr>
<th>Gas</th>
<th>Water</th>
<th>Plasma</th>
<th>Blood</th>
<th>Quantity Dissolved (per dL Blood)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>2.39</td>
<td>2.14</td>
<td>2.26</td>
<td>0.3 mL</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>56.7</td>
<td>51.5</td>
<td>57.03</td>
<td>3.0 mL</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>1.23</td>
<td>1.18</td>
<td>1.30</td>
<td>0.8 mL</td>
</tr>
</tbody>
</table>
Gas Exchange in the Lungs and Tissues

*Diagram showing the process of gas exchange in the lungs and tissues.*

- **Inspired air**: Po2 = 159 mm Hg, Pco2 = 0.3 mm Hg
- **Trachea**: Po2 = 159 mm Hg, Pco2 = 0.3 mm Hg
- **Atelectasis**:
  - Po2: 40 mm Hg
  - Pco2: 46 mm Hg
- **Arterial blood**: Po2: 100 mm Hg
- **Tissue capillary**: Po2: 40 mm Hg
- **Vein**:
  - Po2: 40 mm Hg
  - Pco2: 40 mm Hg
- **Po2**:
  - Venous: 40 mm Hg
  - Pulmonary capillary: 46 mm Hg
  - Arterial: 100 mm Hg
  - Tissue capillary: 40 mm Hg
  - Venous: 100 mm Hg

**Gas Exchange in the Lungs and Tissues**

*Graph showing the changes in Po2 and Pco2 over time.*

- **Venous**:
  - Po2: decrease
  - Pco2: increase

- **Pulmonary capillary**:
  - Po2: increase
  - Pco2: decrease

- **Arterial**:
  - Po2: decrease
  - Pco2: increase

- **Tissue capillary**:
  - Po2: decrease
  - Pco2: increase

- **Venous**:
  - Po2: decrease
  - Pco2: increase

*Abnormal response indicated.*
Gas Exchange in the Lungs and Tissues

- In the Lungs:
  - \( P_{O_2} \) in alveoli \( \sim 100 \) mm Hg
  - \( P_{O_2} \) in pulmonary capillaries \( \sim 40 \) mm Hg
  - Result: \( O_2 \) moves into pulmonary capillaries
  - \( P_{CO_2} \) in pulmonary capillaries \( \sim 46 \) mm Hg
  - Average arterial blood gases equal
    - \( P_{O_2} \) 100 mm Hg
    - \( P_{CO_2} \) 40 mm Hg

- In the Tissues:
  - Pressure gradients cause diffusion of \( O_2 \) into and \( CO_2 \) out of tissues.
**Transport of O₂ in the Blood**

- Oxygen is carried by the blood two ways:
  - 1) Physically dissolved
    - 0.3 mL per dL of blood
    - Dissolved O₂ determines PO₂ of blood
  - 2) Combined with hemoglobin
    - 1.34 mL per gram of hemoglobin

\[
C_{a}O_{2} = 0.3 \text{ mL O}_2 \cdot \text{dL}^{-1} \text{ blood} + (1.34 \text{ mL O}_2 \cdot \text{g}^{-1} \text{Hb}) (15 \text{ g Hb} \cdot \text{dL}^{-1} \text{ blood})
\]

\[
C_{a}O_{2} = 20.4 \text{ mL O}_2 \cdot \text{dL}^{-1} \text{ blood or 20.4 vol %}
\]

---

**Fun Fact!**

If we had no hemoglobin, we would need a cardiac output of almost **1000 liters/minute** (versus a normal maximum of approximately **30 liters/minute**) to deliver enough physically dissolved oxygen to support high rates of exercise!
Transport of O₂ in the Blood

[Image ofhemoglobin structure and chemical formula]

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Transport of O₂ in the Blood

[Image of oxyhemoglobin dissociation curve]

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Transport of $O_2$ in the Blood

![Graph showing the transport of oxygen in the blood](image)

Transport of $O_2$ in the Blood

![Diagram of oxygen transport cascade](image)
**Transport of O₂ in the Blood**

• PO₂ in the lungs:
  – Hb ~ 98% saturated under normal conditions
  – Increased PO₂ doesn’t increase saturation.

• PO₂ in the tissues:
  – At rest
    • PO₂ = 40 mm Hg
    • Venous blood carries ~ 70% of the O₂ content of arterial blood.
    • Venous blood carries 15 mL O₂ per dL blood.
    • Tissues have extracted 5 mL O₂ per dL blood.

**Transport of O₂ in the Blood**

• Arteriovenous Oxygen 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.
**Transport of \(O_2\) in the Blood**

- **The Bohr Effect**
  - A shift in the dissociation curve downward and to the right.
  - Explain this in the context of exercise?

- **Transport of \(O_2\) in the Blood**
  - **Myoglobin, the Muscle’s Oxygen Store**
    - Myoglobin is an iron-containing globular protein in skeletal and cardiac muscle.
    - Stores \(O_2\) intramuscularly
    - Myoglobin contains only 1 iron atom.
    - \(O_2\) is released at low \(PO_2\).
Transport of O₂ in the Blood

- Thinking Question:
  - Does aerobic/endurance-type exercise training increase the ability to transport oxygen?
    - If no, why?
    - If yes, why?

Transport of O₂ in the Blood

<table>
<thead>
<tr>
<th>TABLE 11-1</th>
<th>Representative Values for Blood Hemoglobin Concentration, Hematocrit, and Arterial Oxygen Content in Young Men Before and After Endurance Training</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>Before Training</td>
</tr>
<tr>
<td>Hemoglobin (g/dl)</td>
<td>15.3</td>
</tr>
<tr>
<td>Blood volume (l)</td>
<td>5.25</td>
</tr>
<tr>
<td>Total hemoglobin (g)</td>
<td>803</td>
</tr>
<tr>
<td>Arterial O₂ content (ml/dl)</td>
<td>20.8</td>
</tr>
<tr>
<td>Hematocrit (%)</td>
<td>42</td>
</tr>
</tbody>
</table>

Source: Kjellberg et al., 1949; Waaler et al., 1991, 1998; and other sources.
**Carbon Dioxide Transport**

- Carbon dioxide is transported three ways:
  - 1) Physically dissolved in solution
  - 2) Combined with hemoglobin (carbamino compounds)
  - 3) As plasma bicarbonate
• Physically dissolved in solution
  – ~ 5% CO₂ is transported as dissolved CO₂.
  – The dissolved CO₂ establishes the PCO₂ of the blood.
• Carbamino compounds
  – ~ 20% is transported as carbamino compounds
  – CO₂ reacts directly with amino acids arginine and lysine in Hb to form carbamino compounds.
  – Haldane Effect: Hb interaction with O₂ reduces its ability to combine with CO₂.
  – This aids in releasing CO₂ in the lungs.

• As plasma bicarbonate
  – ~ 75 to 80% of carbon dioxide is transported as bicarbonate

\[
\text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^-
\]
Carbon Dioxide Transport

Chapter 14

Dynamics of Pulmonary Ventilation
Chapter Objectives

• Understand the control of ventilation both at rest and during exercise
• Understand the link between ventilation and the intensity or consequences of exercise
• Understand the link between lactic acid production and ventilation during exercise
• Be able to discuss the concept of ventilation as a limit (or not a limit) to aerobic exercise performance
• Understand the link between ventilation and acid-base balance

Ventilatory Control

• Complex mechanisms adjust rate and depth of breathing in response to metabolic needs.
• Neural circuits relay information.
• Receptors in various tissues monitor pH, Pco₂, Po₂, and temperature.
  – Higher brain centers (medulla)
  – Lungs
  – Chemoreceptors (aortic, carotid, peripheral)
Ventilatory Control

- Neural Control
  - The Central Controller (Brain)
    - Ventral, lateral medulla (brain)
    - Generates an oscillatory, respiratory-like rhythm
      - Six types of neurons (three inspiration, three expiration)
    - Signal is passed via the spinal cord to motor nerves controlling the respiratory musculature
    - Signal is augmented by sensory feedback
  - Inspiration
    - Neurons activate diaphragm and external intercostals
  - Expiration
    - Passive: Recoil of diaphragm and external intercostals
    - Active: Activation of internal intercostals
  - Integration of Signals
    - Afferent signals relaying mechanical and chemical information
Ventilatory Control

• Humoral Factors
  – At rest, chemical state of blood exerts the greatest control of pulmonary ventilation
    • \(\text{PaO}_2\), \(\text{PaCO}_2\), pH, temperature

  – Plasma \(\text{PO}_2\) and Peripheral Chemoreceptors
    • Changes in \(\text{PO}_2\) are primarily sensed by peripheral chemoreceptors (NOT respiratory center in brain)
      – Carotid and aortic bodies
        » Why are the location of these important?
Ventilatory Control

• Humoral Factors (cont’d)
  – Plasma PCO₂ and H⁺ Concentration (pH)
    • At rest, CO₂ pressure in arterial plasma provides the most important respiratory stimulus
      – If you increase inspired CO₂ from 0.03% to 0.22%, respiration nearly doubles
    • Molecular CO₂, in itself, does not really stimulate ventilation, but rather the changes that CO₂ causes in blood acidity (pH).
      – Why?

\[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \]

Ventilatory Control

• Hyperventilation and Breath Holding
  – Experiment #1
    • At the end of a normal expiration, hold your breath and record the time when the urge to breathe causes inspiration
  – Experiment #2
    • Hyperventilate for 15 seconds, and then hold your breath at the end of an expiration. Record the time when the urge to breathe causes inspiration
Ventilatory Control

Regulation of Ventilation During Exercise

- Chemical Control
  - Dilemma: Changes in PO$_2$ or PCO$_2$ cannot entirely account for changes in ventilation observed during exercise.
    - Pulmonary ventilation during light and moderate intensity exercise is closely coupled to metabolism (i.e. an increase in oxygen consumption ($VO_2$) and carbon dioxide production ($VCO_2$)).
    - During strenuous exercise, increase in PCO$_2$ and decrease in pH provide a stimulus to ventilation
      - But, the hyperventilation will decrease PCO$_2$ and thus reduce the ventilatory stimulus (but this obviously doesn’t happen)
Regulation of Ventilation During Exercise

- Nonchemical Control
  - The rapid increase in ventilation that is observed at the start of exercise and the rapid decrease that is observed at the cessation of exercise occurs before any substantial chemical changes could take place.

- Neurogenic Factors
  - Corticol influence
    - Anticipatory response (Central Command)
  - Peripheral influence
    - Local mechanoreceptor and chemoreceptor afferent feedback
Regulation of Ventilation During Exercise

- Integrated Regulation
  - During exercise
    - Phase I (beginning of exercise): Neurogenic stimuli from cortex increase respiration.
    - Phase II: After about 20 seconds, $V_e$ rises exponentially to reach steady state.
      - Central command
      - Peripheral chemoreceptors
    - Phase III: Fine tuning of steady-state ventilation through peripheral sensory feedback mechanisms
  - During recovery
    - An abrupt decline in ventilation reflects removal of central command and input from receptors in active muscle
    - Slower recovery phase from gradual metabolic, chemical, and thermal adjustments
Regulation of Ventilation During Exercise

- Summary:
  - The Primary Stimulus for Exercise Hyperpnea
    - Carbon dioxide flow to the lungs
      - Strong correlation between $V_A$ and $VCO_2$ during exercise
    - Feedback from working locomotor muscles
    - Central command
      - Anticipatory mechanisms that occurs before there could be any substantial afferent, sensory feedback
Regulation of Ventilation - Summary

Ventilation and Energy Demands

- Exercise places the most profound physiologic stress on the respiratory system.
  - Goal: Increase alveolar ventilation in order to maintain the proper gas concentrations to facilitate rapid gas exchange

- Ventilation in Steady-Rate Exercise
  - During light to moderate exercise
    - Ventilation increases linearly with O₂ consumption and CO₂ production
      - Most tightly linked to VCO₂
Ventilation and Energy Demands

• Ventilation in Non-Steady-Rate Exercise
  – $V_e$ rises sharply and the ventilatory equivalent rises as high as 35 – 40 L of air per liter of oxygen.
  – Ventilatory Threshold (VT)
    • The point at which pulmonary ventilation increases disproportionately with oxygen consumption during a graded exercise test

![Chemical Reaction]

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

Ventilation and Energy Demands

![Graph]

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**Ventilation and Energy Demands**

- Onset of Blood Lactate Accumulation (OBLA)
  - Lactate threshold
    - Describes highest O₂ consumption of exercise intensity with less than a 1-mM per liter increase in blood lactate above resting level
  - OBLA signifies when blood lactate shows a systemic increase equal to 4.0 mM.
Ventilation and Energy Demands

Energy Costs of Breathing

• At rest and during light exercise, the O₂ cost of breathing is small.

• During maximal exercise, the respiratory muscles require a significant portion of total blood flow (up to 15%).
Does Ventilation Limit Aerobic Power and Endurance?

- Healthy individuals over breathe at higher levels of O₂ consumption.
- At max exercise, there usually is a breathing reserve.
- Ventilation in healthy individuals is not the limiting factor in exercise.

Does Ventilation Limit Aerobic Power and Endurance?

- Exercise-induced arterial hypoxemia may occur in elite endurance athletes.
- Potential mechanisms include
  - V/Q inequalities
  - Shunting of blood flow bypassing alveolar capillaries
  - Failure to achieve end-capillary PO₂ equilibrium

Acid-Base Regulation

- Buffering
  - Reactions to minimize changes in pH (H⁺ concentration)
    - Acids dissociate in solution and release H⁺.
    - Bases accept H⁺ to form OH⁻ ions.
    - Buffers minimize changes in pH.
  - Alkalosis increases pH.
  - Acidosis decreases pH.
  - Three mechanisms help regulate internal pH.
    - Chemical buffers
    - Pulmonary ventilation
    - Renal function
Acid-Base Regulation

• Chemical Buffers
  – Chemical buffers consist of a weak acid and the salt of that acid.
  – Bicarbonate buffers = weak acid, carbonic acid, salt of the acid, and sodium bicarbonate

  – Bicarbonate Buffers
    • Result of acidosis
      \[ \text{H}_2\text{O} + \text{CO}_2 \rightleftharpoons \text{H}_2\text{CO}_3 \rightleftharpoons \text{H}^+ + \text{HCO}_3^- \]
    • Result of alkalosis
      \[ \text{H}_2\text{O} + \text{CO}_2 \leftrightharpoons \text{H}_2\text{CO}_3 \leftrightharpoons \text{H}^+ + \text{HCO}_3^- \]

• Bicarbonate Buffers (cont’d)
  – Acidosis will stimulate ventilation in order to eliminate “excess” carbon dioxide
  – Alkalosis will inhibit ventilation in order to retain carbon dioxide and increase (or normalize pH)

• Phosphate Buffers
  – Phosphoric acid and sodium phosphate
  – Act similarly to bicarbonate buffers but in the kidney tubules

• Protein Buffer
  – Hemoglobin: \( \text{H}^+ + \text{Hb}^- \rightarrow \text{HHb} \)

• Ventilatory Buffer
  – \( \text{H}^+ \) directly stimulates ventilation
  – How will this increase pH?

• Renal Buffer
  – More long-term defense. Kidney secretion of \( \text{H}^+ \)
**Acid-Base Regulation**

- Respiratory Acidosis/Alkalosis

\[
\text{H}_2\text{O} + \text{CO}_2 \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- 
\]

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**Acid-Base Regulation**

- Metabolic Acidosis/Alkalosis

\[
\text{H}_2\text{O} + \text{CO}_2 \leftrightarrow \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- 
\]