Chapter 10: Respiration During Exercise

Introduction

• The Respiratory System
  – Provides a means of gas exchange between the environment and the body
  – Plays a role in the regulation of acid-base balance during exercise

Objectives

• Explain the principle physiological function of the pulmonary system
• Outline the major anatomical components of the respiratory system
• List major muscles involved in inspiration & expiration at rest & during exercise
• Discuss the importance of matching blood flow to alveolar ventilation in the lung
• Explain how gases are transported across the blood-gas interface in the lung

Objectives

• Discuss the major transportation modes of O₂ & CO₂ in the blood
• Discuss the effects of ↑ temp, ↓ pH, & ↑ levels of 2,3 DPG on the oxygen-hemoglobin dissociation curve
• Describe the ventilatory response to constant load, steady-state exercise

Objectives

• Describe the ventilatory response to incremental exercise
• Identify the location & function of chemoreceptors and mechanoreceptors that are thought to play a role in the regulation of breathing
• Discuss the neural-humoral theory of respiratory control during exercise

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Respiration

1. Pulmonary respiration
   – Ventilation (breathing) and the exchange of gases (O₂ & CO₂) in the lungs
2. Cellular respiration
   – Relates to O₂ utilization and CO₂ production by the tissues
• This chapter is concerned with pulmonary respiration.
Function of the Lungs

- Primary purpose is to provide a means of gas exchange between the external environment and the body
- Ventilation refers to the mechanical process of moving air into and out of lungs
- Diffusion is the random movement of molecules from an area of high concentration to an area of lower concentration

Major Organs of the Respiratory System

Position of the Lungs, Diaphragm, and Pleura-Visceral

Conducting and Respiratory Zones

Conducting zone
- Conducts air to respiratory zone
- Humidifies, warms, and filters air
- Components:
  - Trachea
  - Bronchial tree
  - Bronchioles

Respiratory zone
- Exchange of gases between air and blood
- Components:
  - Respiratory bronchioles
  - Alveolar sacs

Respiratory Airways

- 16 generations
  - Conducting airways
  - Bulk flow (water hose)
  - X-sections reduce forward velocity
- 7 generations
  - Transitional zone
  - Respiratory zone
  - Diffusion
**Alveolar Sites**
- Large surface area for gas exchange
- Minimal diffusion distance
- Alveolar and capillary walls-large lipid content
- O₂ diffuses, not H₂O
- X-sectional area – 500-1000 ft²

**Respiratory Zone**
- Alveoli
  - Site of gas exchange from external respiration
  - Extensive capilarization in alveoli walls
  - Blood gas barrier (2 cell layers thick)
  - Lung diffusion

**Diffusion**
- Concentration gradient
- Minimal distance
  - Smoking effects

**Pathway of Air to Alveoli**

**Mechanics of Breathing**
- Ventilatory muscles cause the size variations in the thoracic cavity
- Inspiration
  - Diaphragm pushes downward, lowering intrapulmonary pressure
- Expiration
  - Diaphragm relaxes, raising intrapulmonary pressure
- Resistance to airflow
  - Largely determined by airway diameter

**The Mechanics of Inspiration and Expiration**

![Mechanics of Inspiration and Expiration](image)
Mechanics of Breathing

• Inspiratory muscles
  – 1. Diaphragm
    • Contraction occurs when rt and lt phrenic nerve stimulated
    • Flattens and makes thoracic cavity longer

• Inspiratory muscles
  – 2. External intercostals
    • Contraction lifts ribs
    • Increases transverse diameter
    • Increase in thoracic size accompanied by decrease in intrathoracic pressure
    • Air moves from high pressure to low pressure

Mechanics of Breathing

• Expiration (rest)
  – Diaphragm and intercostals relax (passive)
  – Thoracic cavity returns to original size
  – Intrapulmonary pressure > ambient
  – Air flows outward to atmosphere

• Expiration (exercise)
  – Expiratory muscles
    – Abdominal group
    – Internal intercostals
    – Action
      • Lower ribs, moves them closer together
      • Facilitates expiration (active)

Muscles of Respiration

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[Fig 10.7]
Pulmonary Ventilation (V)

- The amount of air moved in or out of the lungs per minute
  - Product of tidal volume ($V_T$) and breathing frequency ($f$)
  \[ V = V_T \times f \]

Pulmonary Ventilation (V)

- Dead-space ventilation ($V_D$)
  - "unused" ventilation
  - Does not participate in gas exchange
  - Anatomical dead space: conducting zone
  - Physiological dead space: disease
- Alveolar ventilation ($V_A$)
  - Volume of inspired gas that reaches the respiratory zone
  \[ V = V_A + V_D \]

Pulmonary Volumes and Capacities

- Measured by spirometry
- Vital capacity (VC)
  - Maximum amount of air that can be expired following a maximum inspiration
- Residual volume (RV)
  - Air remaining in the lungs after a maximum expiration
- Total lung capacity (TLC)
  - Sum of VC and RV

Pulmonary Volumes and Capacities

- Tidal Volume
  - Volume of air inspired or expired per breath
- Inspiratory Reserve Volume (IRV)
  - Volume of air that can be inspired after a normal inspiration

Pulmonary Volumes and Capacities

- Inspiratory Capacity (IC)
  - Volume of air inspired from rest to maximal inspiration
    - $TV + IRV$
- Functional Residual Capacity (FRC)
  - Volume of air in lungs at rest
- Expiratory Reserve Volume (ERV)
  - Volume of air that can be expired after a normal expiration

Pulmonary Volumes and Capacities

- Inspiratory Reserve Volume
- Expiratory Reserve Volume
- Residual Volume
- Total Lung Capacity

Fig 10.9
**Lung Disease**

- Obstructive lung disease
  - COPD and asthma
- Narrowing of airways
- Restrictive lung disease
  - Fibrosis

**Partial Pressure of Gases**

**Dalton’s Law**

- The total pressure of a gas mixture is equal to the sum of the pressure that each gas would exert independently
- The partial pressure of oxygen (PO\textsubscript{2})
  - Air is 20.93% oxygen
    - Expressed as a fraction: 0.2093
    - Total pressure of air = 760 mmHg
    \[ \text{PO}_2 = 0.2093 \times 760 = 159 \text{ mmHg} \]

**Partial Pressure and Gas Exchange**

**Blood Flow to the Lung**

- Pulmonary circuit
  - Same rate of flow as systemic circuit
  - Lower pressure

**Ventilation-Perfusion Relationships**

- Ventilation/perfusion ratio
  - Indicates matching of blood flow to ventilation
  - Ideal: ~1.0
- Base
  - Overperfused (ratio <1.0)
  - Greater blood flow than ventilation
- Apex
  - Underperfused (ratio >1.0)
  - Less blood flow than ventilation
**O₂ Transport in the Blood**
- Approximately 99% of O₂ is transported in the blood bound to hemoglobin (Hb)
  - Oxyhemoglobin: O₂ bound to Hb
  - Deoxyhemoglobin: O₂ not bound to Hb
- Amount of O₂ that can be transported per unit volume of blood is dependent on the concentration of hemoglobin.

**O₂-Hb Dissociation Curve: Effect of pH**
- Blood pH declines during heavy exercise.
- Results in a "rightward" shift of the curve.
  - Bohr effect
  - Favors "offloading" of O₂ to the tissues.

**O₂-Hb Dissociation Curve: Effect of Temperature**
- Increased blood temperature results in a weaker Hb-O₂ bond.
- Rightward shift of curve.
  - Easier "offloading" of O₂ at tissues.

**O₂-Hb Dissociation Curve: 2-3 DPG**
- RBC must rely on anaerobic glycolysis to meet the cell's energy demands.
  - RBC have no nucleus or mitochondria.
- 2-3 DPG is a by-product of RBC glycolysis.
  - It can combine with hemoglobin reducing hemoglobin's affinity of O₂.
- 2-3 DPG increases during exposure to altitude.
- 2-3 DPB increases during anemia.
**O₂-Hb Dissociation Curve:** 2-3 DPG

- **Exercise**
  - Little change in blood 2-3 DPG
- **Therefore, at sea level**
  - Right shift of curve not to changes in 2-3 DPG, but to
    - Degree of acidosis
    - Blood temperature

**O₂ Transport in Muscle**

- Myoglobin (Mb) shuttles O₂ from the cell membrane to the mitochondria
- Higher affinity for O₂ than hemoglobin
  - Allows MbO₂ to release oxygen at lower PO₂ values
  - Mb stores O₂ and then transports as needed

**Dissociation Curves for Myoglobin and Hemoglobin**

**CO₂ Transport in Blood**

- Dissolved in plasma (10%)
- Bound to Hb (20%)
- Bicarbonate (70%)
  - CO₂ + H₂O ↔ H₂CO₃ ↔ H⁺ + HCO₃⁻
  - Also important for buffering H⁺

**CO₂ Transport in Blood**

- **Bicarbonate**
  - Tissue cell
    - PCO₂ = 45 mmHg
  - Diffuses into blood-RBC (carbonic anhydrase)
    - Conversion to bicarbonate by
      - CO₂ + H₂O ↔ H₂CO₃ ↔ H⁺ + HCO₃⁻

- In lungs
  - H⁺ (from HHb or dissolved in plasma) + HCO₃⁻ ↔
    - H₂CO₃ ↔ CO₂ + H₂O
CO₂ Transport in Blood

Fig 10.18

Release of CO₂ From Blood

Fig 10.19

Rest-to-Work Transitions

• Initially, ventilation increases rapidly
  – Then, a slower rise toward steady-state
• PO₂ and PCO₂ are maintained

Fig 10.20

Exercise in a Hot Environment

• During prolonged submaximal exercise:
  – Ventilation tends to drift upward
  – Little change in PCO₂
  – Higher ventilation not due to increased PCO₂

Fig 10.21

Incremental Exercise

• Linear increase in ventilation
  – Up to ~50-75% VO₂max
• Exponential increase beyond this point
• Ventilatory threshold (T₀vent)
  – Inflection point where VE increases exponentially

Ventilatory Response to Exercise: Trained vs. Untrained

• In the trained runner
  – Decrease in arterial PO₂ near exhaustion
  – pH maintained at a higher work rate
  – T₀vent occurs at a higher work rate

Fig 10.22
Ventilatory Response to Exercise:
Trained vs. Untrained

Exercise-Induced Hypoxemia

- 1980’s: 40-50% of elite male endurance athletes were capable of developing
- 1990’s: 25-51% of elite female endurance athletes were also capable of developing

Exercise-Induced Hypoxemia

- Causes:
  - Ventilation-perfusion mismatch
  - Diffusion limitations
    - Due to reduced time of RBC in pulmonary capillaries
    - Because of high cardiac outputs

Control of Ventilation

- Respiratory control center-medulla
  - Rhythm area
  - Neurons for
    - Inspiration
    - Expiration

Control of Ventilation

- Receptors regulate respiratory rate
  - Neural input
    - Motor cortex – central command
      - Overrides control in medulla
  - Skeletal muscle
    - Muscle spindles
    - GTO
    - Joint receptors

Input to the Respiratory Control Centers

- Humoral chemoreceptors
  - Central chemoreceptors
    - Located in the medulla
    - PCO₂ and H⁺ concentration in cerebrospinal fluid
  - Peripheral chemoreceptors
    - Aortic and carotid bodies
    - PO₂, PCO₂, H⁺, and K⁺ in blood
Effect of Arterial PCO₂ on Ventilation

Ventilatory Control During Exercise
- Submaximal exercise
  - Linear increase due to:
    - Central command
    - Humoral chemoreceptors
    - Neural feedback
- Heavy exercise
  - Exponential rise above \( T_{\text{vent}} \)
  - Increasing blood H⁺

Ventilatory Control During Submaximal Exercise

Effect of Training on Ventilation
- Ventilation is lower at same work rate following training
  - May be due to lower blood lactic acid levels
  - Results in less feedback to stimulate breathing

Effects of Endurance Training on Ventilation During Exercise

Do the Lungs Limit Exercise Performance?
- Low-to-moderate intensity exercise
  - Pulmonary system not seen as a limitation
- Maximal exercise
  - Not thought to be a limitation in healthy individuals at sea level
  - May be limiting in elite endurance athletes
  - New evidence that respiratory muscle fatigue does occur during high intensity exercise
Oxygen Cost of Ventilation

- Respiratory muscles require portion of oxygen consumption
  - Rest – 1-2% VO₂ (minimal)
    - Resting VO₂ = 300 ml/min
    - 3 to 6 ml/min used for respiratory muscles
  - Heavy exercise – 8-10% VO₂
    - Exercise VO₂ = 3-5 L/min
    - 240 to 500 ml/min used for respiratory muscles