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 O$_2$ & CO$_2$ in the blood
- Discuss the effects of ↑ temp, & ↓ pH 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
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

Fig 10.1
Position of the Lungs, Diaphragm, and Pleura-

Visceral-adheres to outer lung surface

Parietal-lines thoracic walls, diaphragm

Fig 10.2
Lungs

- Lung/chest wall
  - Pleural cavity
  - Serous fluid
    - Thin membranes
      - Pleura
- Suction
  - Outward pull chest wall
  - Inward pull lungs
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
Conducting & Respiratory Zones
Respiratory Airways

- 16 generations
  - Conducting airways
  - Bulk flow (water hose)
  - X-sections reduces 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
- $O_2$ diffuses, not $H_2O$
- X-sectional area
  - 500-1000 ft$^2$
Respiratory Zone

- Alveoli
  - Site of gas exchange from external respiration
  - Extensive capillarization in alveoli walls
  - Blood gas barrier (2 cell layers thick)
    - Lung diffusion
Diffusion

- Concentration gradient
- Minimal distance
  - Smoking effects
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

Fig 10.6
Mechanics of Breathing

• Inspiratory muscles
  – 1. Diaphragm
    • Contraction occurs when right and left phrenic nerves stimulated
    • Flattens and makes thoracic cavity longer
Mechanics of Breathing

• 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
Mechanics of Breathing

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

\[ V_E = V_T \times f \]
Pulmonary Ventilation

\[ V_E = V_T \times f \]

- Rest
  \[ V_T = 500 \text{ ml/breath} \]
  \[ f = 12 \text{ breaths/min} \]
  \[ 500 \text{ ml/breath} \times 12 \text{ breaths/min} \]
  \[ = 6,000 \text{ ml/min} \]
  \[ V_E = 6.0 \text{ L/min} \]
Pulmonary Ventilation

- $VE = V_T \times f$
  - Exercise
    - $V_T = 3 \text{ L/breath}$
    - $f = 40 \text{ br/min}$
    - $V_E = 120 \text{ L/min}$
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

$$V_I = V_A + V_D$$
Pulmonary Ventilation (V)

- \( V_E = V_A + V_D \)
  - \( V_E = 6 \text{ L/min} \)
  - \( V_T = 500 \text{ ml/breath} \)
  - \( f = 12 \text{ br/min} \)
- \( V_A = V_T - V_D \)
  - \( 500 \text{ ml} - 150 \text{ ml} = 350 \text{ ml} \)
  - \( 350 \text{ ml/breath} \times 12 \text{ breaths/min} \)
  - \( 4200 \text{ ml/min} \)
  - \( 4.2 \text{ L/min} \)
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

Fig 10.9
Lung Volumes: Exercise
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 ($PO_2$)
  – Air is 20.93% oxygen
    • Expressed as a fraction: 0.2093
  – Total pressure of air = 760 mmHg

\[
PO_2 = 0.2093 \times 760 = 159 \text{ mmHg}
\]
Partial Pressure of Gases

<table>
<thead>
<tr>
<th>Gas</th>
<th>Percentage</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>20.93</td>
<td>.2093</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>79.04</td>
<td>.7904</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>.03</td>
<td>.0003</td>
</tr>
</tbody>
</table>

» 100.00

- \( \text{PO}_2 = 0.2093 \times 760 = 159 \text{ mmHg} \)
Partial Pressure and Gas Exchange

Fig 10.10
Blood Flow to the Lung

- Pulmonary circuit
  - Same rate of flow as systemic circuit
  - Lower pressure
Blood Flow to the Lung

• When standing, most of the blood flow is to the base of the lung
  – Due to gravitational force
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
Ventilation/Perfusion Ratios

Fig 10.13
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 in dependent on the concentration of hemoglobin
Oxyhemoglobin Dissociation Curve

Fig 10.14
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

Fig 10.15
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

Fig 10.16
O$_2$ Transport in Muscle

- Myoglobin (Mb) shuttles O$_2$ from the cell membrane to the mitochondria
- Higher affinity for O$_2$ than hemoglobin
  - Allows MbO$_2$ to release oxygen at lower PO$_2$ values
  - Mb stores O$_2$ and then transports as needed
Dissociation Curves for Myoglobin and Hemoglobin

![Graph showing dissociation curves for Myoglobin and Hemoglobin](Fig 10.17)
CO$_2$ Transport in Blood

- 1. Dissolved in plasma (10%)
- 2. Bound to Hb (20%)
  - H$^+$ + Hb = HHb
- 3. Bicarbonate (70%)
  - Also important for buffering H$^+$
CO$_2$ Transport in Blood

• Bicarbonate
  – Tissue cell
    • PCO$_2$ = 45 mmHg (40 mmHg capillary)
    • CO$_2$ diffuses into blood-RBC
      – carbonic anhydrase catalyzes formation of carbonic acid
      – CO$_2$ + H$_2$O $\leftrightarrow$ H$_2$CO$_3$
      – H$_2$CO$_3$ $\leftrightarrow$ H$^+$ + HCO$_3^-$
CO$_2$ Transport in Blood

- Bicarbonate ion (HCO$_3^-$)
  - Diffuses out of RBC into plasma
  - Exchange with Cl$^-$ (chloride shift)
    - Maintains electrochemical balance
- In lungs –
  - H$^+$ (from HHb or dissolved in plasma) + HCO$_3^-$ $\leftrightarrow$
  - H$_2$CO$_3$ $\leftrightarrow$ CO$_2$ + H$_2$O
CO$_2$ Transport in Blood

Fig 10.18
Rest-to-Work Transitions

- Initially, ventilation increases rapidly
  - Then, a slower rise toward steady-state
- \( \text{PO}_2 \) and \( \text{PCO}_2 \) 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
  – Due to temperature increase in blood - respiratory control center

Fig 10.21
Incremental Exercise

- Linear increase in ventilation
  - Up to ~50-75% VO_{2max}
- Exponential increase beyond this point
- Ventilatory threshold (T_{vent})
  - Inflection point where V_{E} increases exponentially
Ventilation during Exercise

• What causes the ventilatory break?
  – Anaerobic threshold-point at which the intensity of the workload shifts metabolism towards-
  – Anaerobic sources now meet ATP demands
    • Ventilatory threshold-$T_{vent}$
    • Lactate accumulation-$T_{lact}$
    • Onset of blood lactic acidosis-OBLA
Ventilation during Exercise

- $V_E$ breakpoint
- Easiest way to determine AT

- Bla breakpoint
- Most accurate way to determine AT
Anaerobic Threshold

- Lactic acid accumulation in blood
- Increase in \([H^+]\) decreases pH
- Fatigue results because glycolysis is inhibited by low pH
- Is the intensity (HR) level at which this occurs important to performance?
Anaerobic Threshold

- 1-untrained
- 2-trained, average
- 3-international competitor
- LT around 4 mmol/L
- Difference?
  - Running velocity at which LT occurs

Figure 7.9
The detection of the lactate threshold involves measurement of blood lactic acid levels at different exercise intensities, such as while running on a treadmill at various speeds, as shown here. The running speed at which the lactate threshold (LT) is found ( ~ 4 mmol · L⁻¹) varies from one athlete to another. Runner 1 is an example of a beginner who is totally untrained; runner 2, an experienced but only average competitor; and runner 3, a highly experienced international competitor.
Ventilatory Response to Exercise: Trained vs. Untrained

- In the trained runner
  - Decrease in arterial PO$_2$ near exhaustion
  - pH maintained at a higher work rate
  - $T_{vent}$ occurs at a higher work rate

Fig 10.22
Ventilatory Response to Exercise: Trained vs. Untrained

Fig 10.22
Exercise-Induced Hypoxemia

• 1980’s: 40-50% of elite male endurance athletes were capable of developing hypoxemia
• 1990’s: 25-51% of elite female endurance athletes were also capable of developing hypoxemia
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
  - Rhythmicity area
  - Neurons for
    - Inspiration
    - Expiration
Control of Ventilation

• Receptors regulate respiratory rate
  – Neural input-efferent
• Motor cortex – central command
  – Overrides control in medulla
  – Skeletal muscle-afferent
    – Muscle spindles
    – GTO
    – Joint receptors
Input to the Respiratory Control Centers

- **Humoral chemoreceptors-afferent**
  - Central chemoreceptors
    - Located in the medulla
    - $\text{PCO}_2$ and $\text{H}^+$ concentration in cerebrospinal fluid
  - Peripheral chemoreceptors-afferent
    - Aortic and carotid bodies
    - $\text{PO}_2$, $\text{PCO}_2$, $\text{H}^+$, and $\text{K}^+$ in blood
Effect of Arterial PCO$_2$ on Ventilation

\[ \bar{V}_E (\ell/min) \]

Arterial PCO$_2$ (mm Hg)

**Fig 10.24**
Ventilatory Control During Exercise

• Submaximal exercise
  – Linear increase due to:
    • Central command
    • Humoral chemoreceptors
    • Neural feedback
• Heavy, incremental exercise
  – Exponential rise above $T_{vent}$
    • Increasing blood $H^+$
Ventilatory Control During Submaximal Exercise

- Higher brain centers
- Primary drive to increase ventilation during exercise
- *Peripheral chemoreceptors*
- Respiratory control center (Medulla oblongata)
- *Chemoreceptors*
- Skeletal muscle
- *Mechanoreceptors*
- Respiratory muscles

*Act to fine tune ventilation during exercise*
Ventilatory changes with exercise

- Pre exercise
  - Anticipatory rise
  - Central command in higher brain centers (cerebral cortex)

- Early exercise
  - Rapid rise
  - Central command
Ventilatory changes with exercise

- Rapid rise replaced by slower rise
  - With maximal exercise
  - Plateaus in submax
- Slow rise due to
  - Central command
  - Chemo receptors that respond to chemical stimuli (CO₂, H⁺)
Ventilatory changes with exercise

- Initial Recovery
  - Sudden decrease in $V_E$
  - Decrease in central command
- Slower decrease to resting values
  - Proportional to chemoreceptor stimuli
  - $\text{CO}_2$, $\text{H}^+$
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

Fig 10.27

Training Reduces Exercise Ventilation

Ventilation (liters • min⁻¹)

Work rate (watts)

Before training

After training
Ventilatory Equivalent

- Amount of air ventilated for oxygen consumed
  - $VE = \text{liters of air breathed for every liter of oxygen consumed}$
  - Greater efficiency with training means less air breathed per unit of oxygen consumed

- $VE = \underline{V_E} \text{L/min}$
- $VO_2 \text{L/min}$
Ventilatory Efficiency

- $V_E = 6 \text{ l/min}$
- $VO_2 = 250 \text{ ml/min}$
- $VE = 6$
- $.25$
- $VE = 24 \text{ L air/L O}_2$
Ventilatory Efficiency

- Submax workload the same
- \( V_E \) 100 L/min 90 L/min
- \( VO_2 \) 2.5 L/min 2.5 L/min
- \( VE \) 100/2.5 90/2.5
- \( VE \) 40 L air/L \( O_2 \) 36 L air/LO\( O_2 \)
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
    - With disease
  - 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% VO$_2$ (minimal)
    - Resting VO$_2$ = 300 ml/min
    - 3 to 6 ml/min used for respiratory muscles
  - Heavy exercise – 8-10% VO$_2$
    - Exercise VO$_2$ = 3-5 L/min
    - 240 to 500 ml/min used for respiratory muscles
Oxygen cost of smoking

• Smoking increases airway resistance
• Respiratory muscles must work harder
  – 2 x at rest
  – 4 x at work
• Respiratory muscles consume more O$_2$
• Less O$_2$ for skeletal muscles
Oxygen cost of smoking

• Rest
  – 3-6 ml O₂ x 2 = 6 – 12 ml O₂

• Maximal Exercise
  – Respiratory muscles use 8-10% of 3-5 L O₂
  – Normal oxygen consumption 240 ml – 500 ml
  – Smoker: 8-10% x 4 = 960-2000 ml O₂
Second Wind

- Phenomenon
  - Sudden transition from feelings of distress or fatigue
  - To a more comfortable, less stressful feeling
Second Wind

• Theories to explain
  – Early breathlessness due to slow ventilatory adjustments early in exercise are relieved
Second Wind

• Theories (cont)
  – Removal of lactic acid produced early in exercise because of slow blood flow changes in working muscles
  – Adequate warm up
Second Wind

• Theories (cont)
  – Relief from local muscle fatigue
  • Especially respiratory muscles (stitch in side)
  – Psychological factors
  – Study – second wind occurred 2 to 18 min
Terminology

• Hyperventilation
  – Increased ventilation
  – Disproportionate increase in $V_E$ that occurs at the ventilatory breakpoint
Terminology

• Dyspnea
  – Difficult or labored breathing
  – One is unable to respond to the demand for ventilation
• Heart failure, emphysema, chronic bronchitis