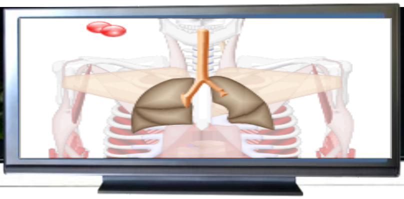

Respiration During Exercise

Objectives

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

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Objectives

6. Discuss the major transportation modes of O_2 and CO_2 in the blood.
7. Discuss the effects of increasing temperature, decreasing pH, and increasing levels of 2–3 DPG on the oxygen-hemoglobin dissociation curve.
8. Describe the ventilatory response to constant-load, steady-state exercise. What happens to ventilation if exercise is prolonged and performed in a high-temperature/humid environment?

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Objectives

9. Describe the ventilatory response to incremental exercise. What factors are thought to contribute to the alinear rise in ventilation at work rate above 50% to 70% of VO_2 max?
10. Identify the location and function of chemoreceptors and mechanoreceptors that are thought to play a role in the regulation of breathing.
11. Discuss the neural-humoral theory of respiratory control during exercise.

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Introduction

- **Pulmonary respiration**
  - Ventilation
  - Exchange of O_2 and CO_2 in the lungs
- **Cellular respiration**
  - O_2 utilization and CO_2 production by the tissues
- **Purposes of the respiratory system during exercise**
  - Gas exchange between the environment and the body
  - Regulation of acid-base balance during exercise

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pH Changes During Exercise

- Blood pH
  - Declines with increasing intensity exercise
- Muscle pH
  - Declines more dramatically than blood pH
  - Muscle has lower buffering capacity

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Regulation of Acid-Base Balance

☐ Lungs

- Increased blood PCO2
- Results in low pH
- Increases ventilation
- CO2 is “blown off”
- pH increases

☐ Kidneys

- – Regulate blood bicarbonate concentration
- – Important in long-term acid-base balance

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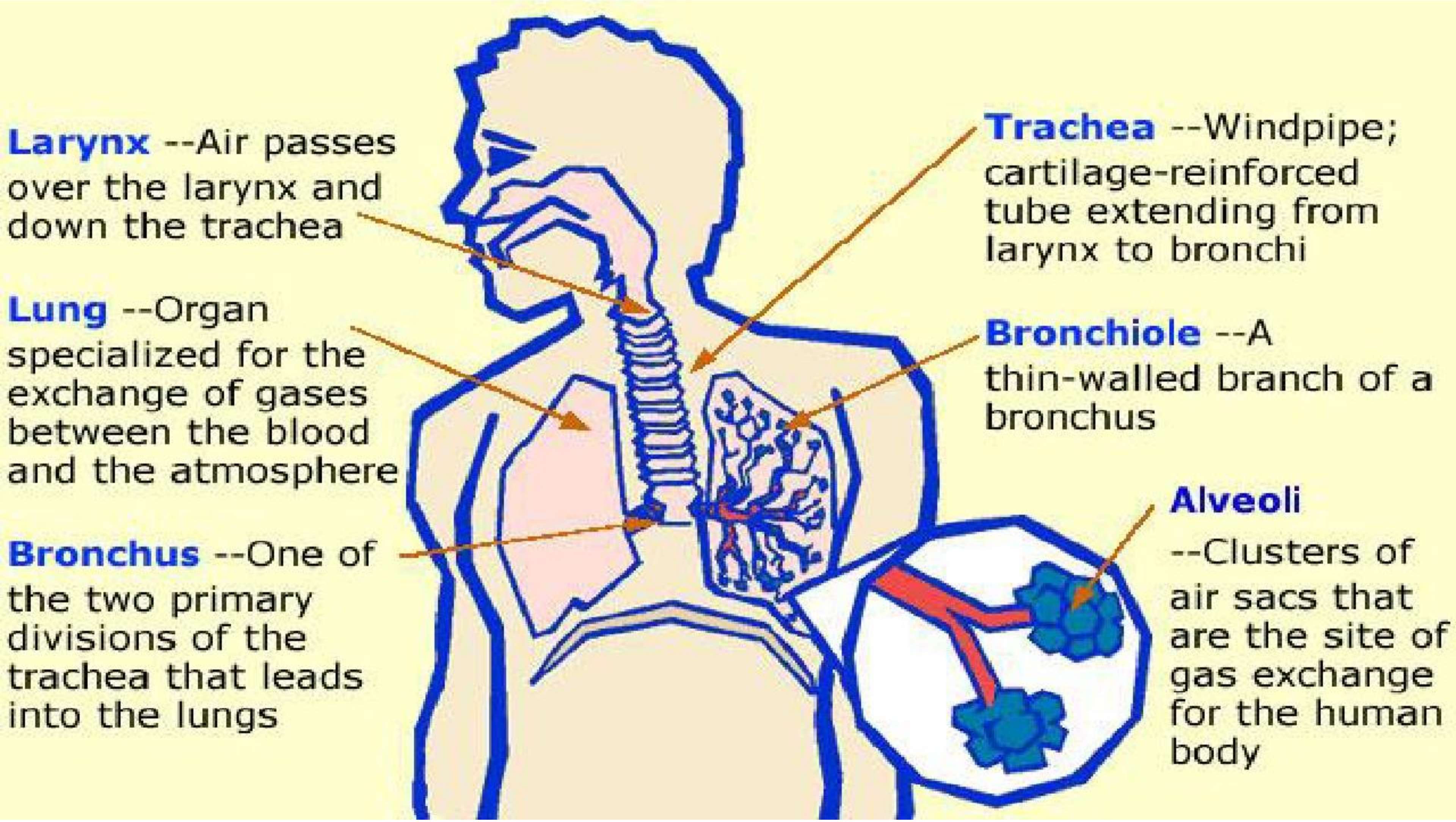

Larynx --Air passes over the larynx and down the trachea

Lung --Organ specialized for the exchange of gases between the blood and the atmosphere

Bronchus --One of the two primary divisions of the trachea that leads into the lungs

Trachea --Windpipe; cartilage-reinforced tube extending from larynx to bronchi

Bronchiole --A thin-walled branch of a bronchus

Alveoli --Clusters of air sacs that are the site of gas exchange for the human body

Function of the Lung

- **Means of gas exchange between the external environment and the body**
  - Replacing O_2
  - Removing CO_2
  - Regulation of acid-base balance
- **Ventilation**
  - Mechanical process of moving air into and out of lungs
- **Diffusion**
  - Random movement of molecules from an area of high concentration to an area of lower concentration

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In Summary

- The primary function of the pulmonary system is to provide a means of gas exchange between the environment and the body. Further, the respiratory system plays an important role in the regulation of the acid-base balance during exercise.

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Structure of the Respiratory System

- **Organs**
  - Nose and nasal cavities
  - Pharynx and larynx
  - Trachea and bronchial tree
  - Lungs
    - Alveoli
      - Site of gas exchange
- **Diaphragm**
  - Major muscle of inspiration

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Structure of the Respiratory System

- **Lungs are enclosed by membranes called pleura**
  - Visceral pleura
    - On outer surface of lung
  - Parietal pleura
    - Lines the thoracic wall
  - Intrapleural space
    - Intrapleural pressure is lower than atmospheric
      - Prevents collapse of alveoli

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Major Organs of the Respiratory System

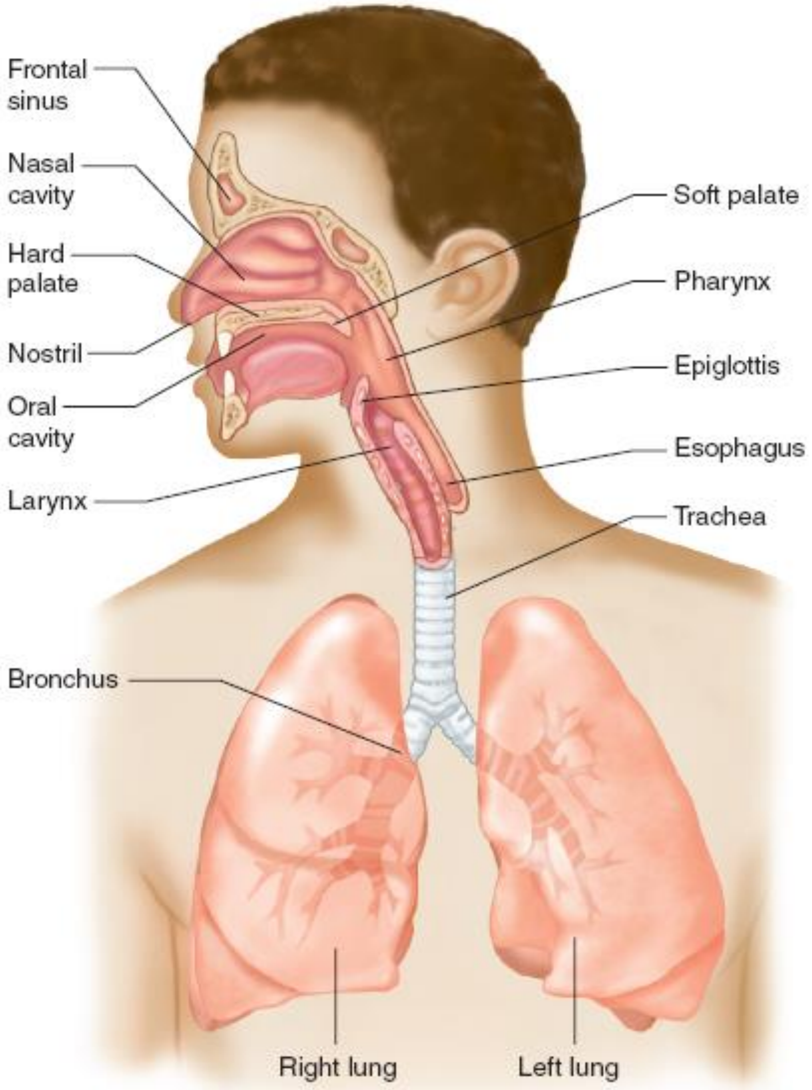

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Figure 10.1

Position of the Lungs, Diaphragm, and Pleura

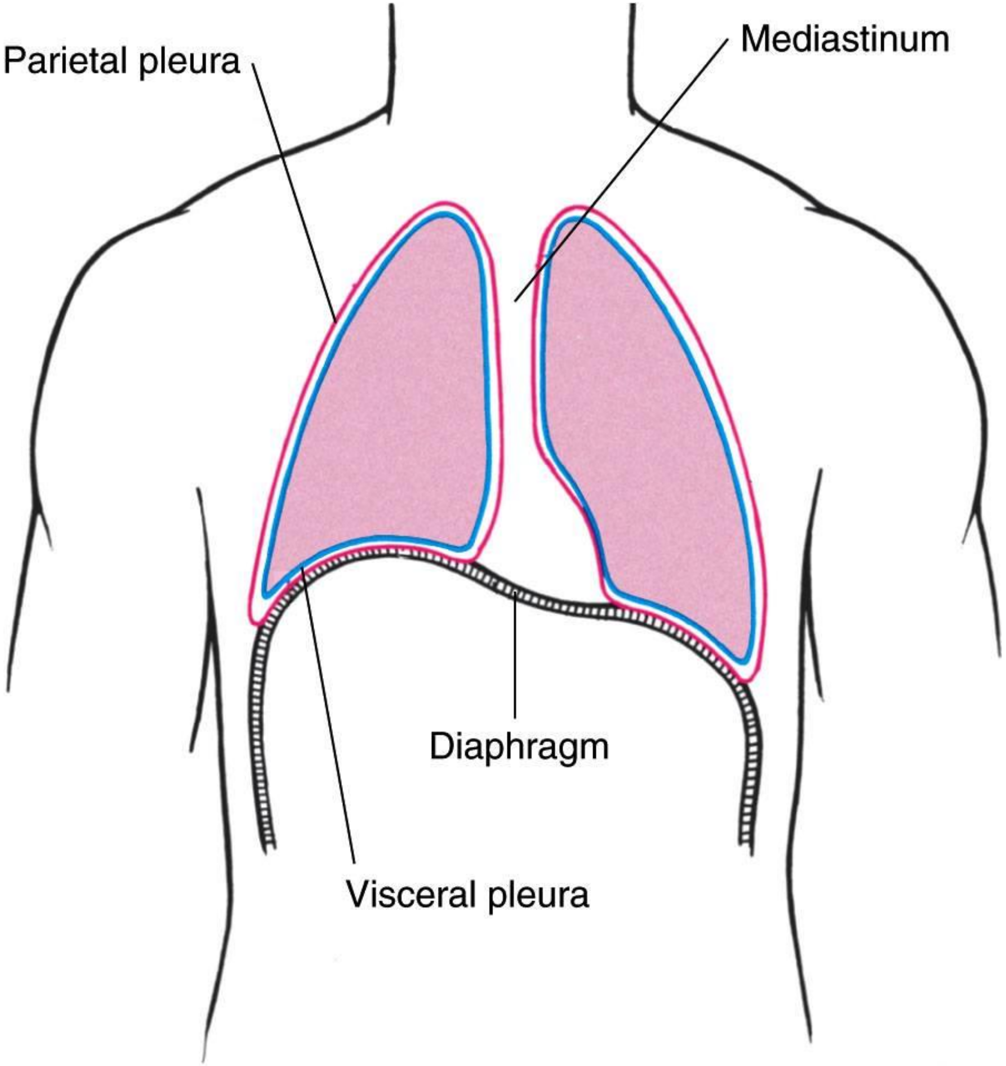

Figure 10.2

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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
    - Surfactant prevents alveolar collapse

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Conducting and Respiratory Zones

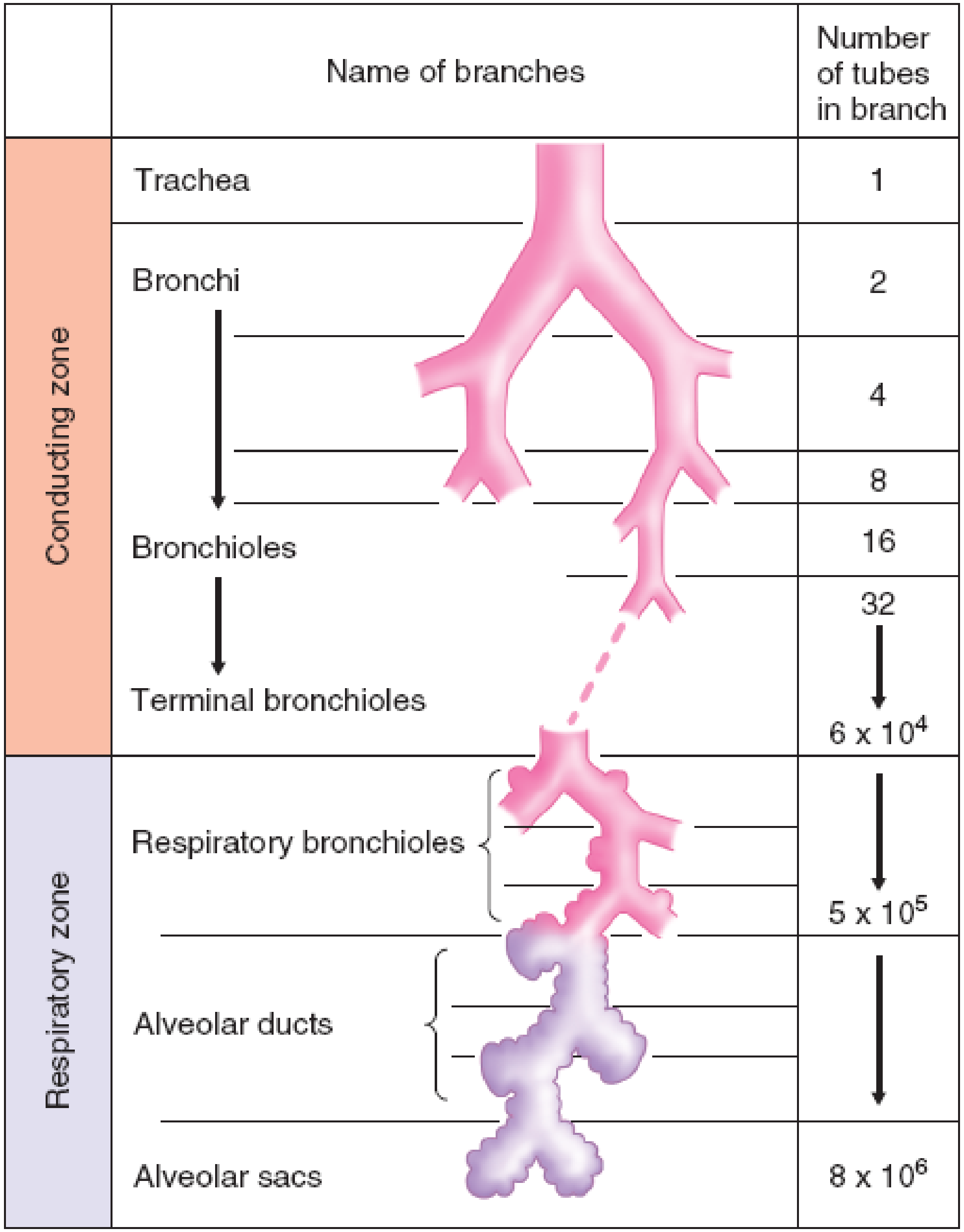

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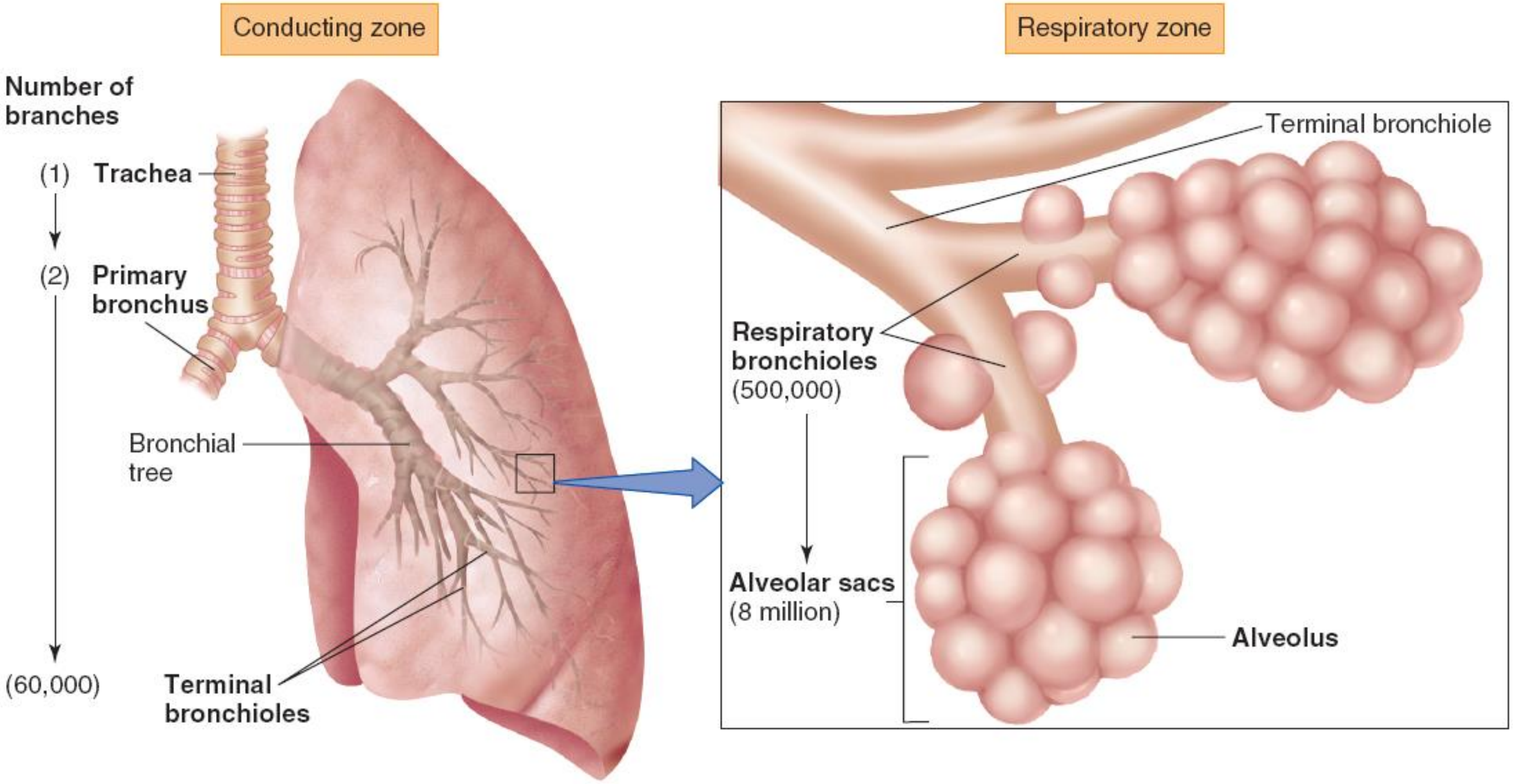
Figure 10.3

The Bronchial Tree



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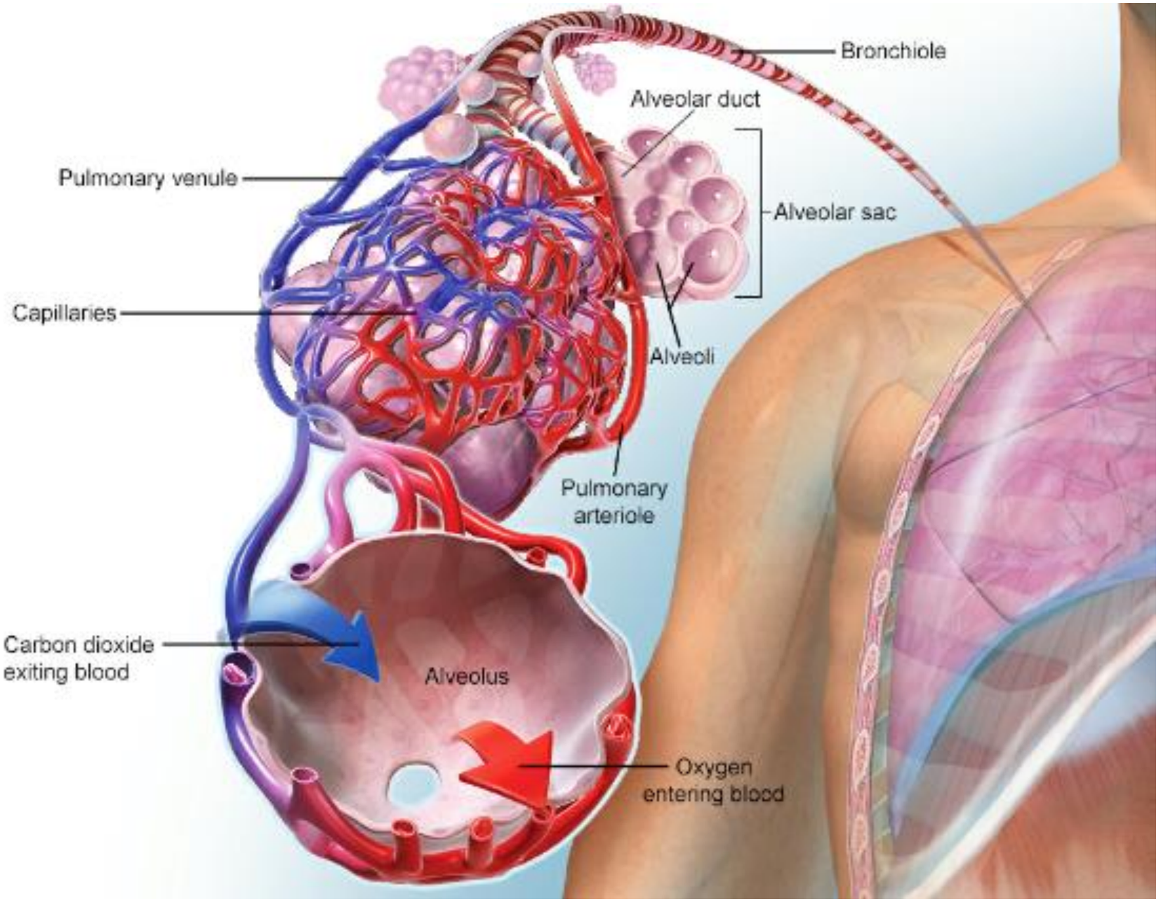
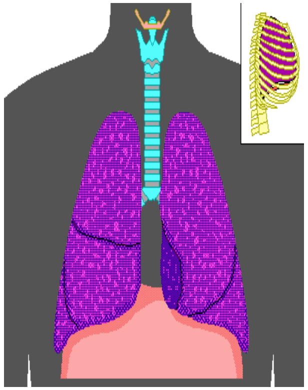
REVIVE


Bronchiole
Alveolar duct
Pulmonary venule
Alveolar sac
Capillaries
Alveoli
Pulmonary arteriole
Carbon dioxide exiting blood
Alveolus
Oxygen entering blood

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Normal Inhalation

In Summary

- Anatomically, the pulmonary system consists of a group of passages that filter air and transport it into the lungs where gas exchange occurs within tiny air sacs called *alveoli*.

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Mechanics of Breathing

- **Movement of air occurs via bulk flow**
  - Movement of molecules due to pressure difference
- **Inspiration**
  - Diaphragm pushes downward, ribs lift outward
  - Volume of lungs increases
  - Intrapulmonary pressure lowered
- **Expiration**
  - Diaphragm relaxes, ribs pulled downward
  - Volume of lungs decreases
  - Intrapulmonary pressure raised

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The Mechanics of Inspiration and Expiration

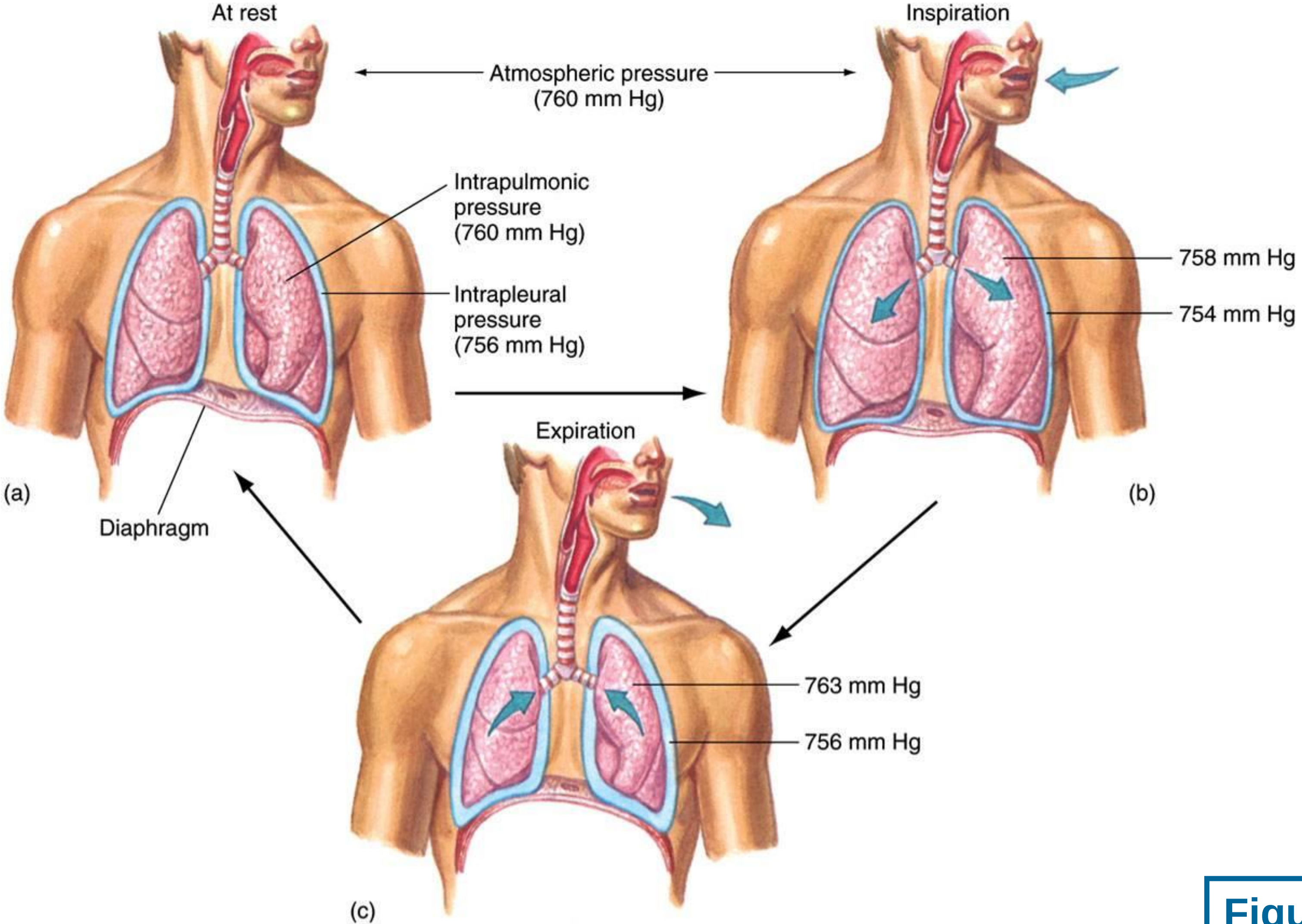

Figure 10.6

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The Muscles of Respiration

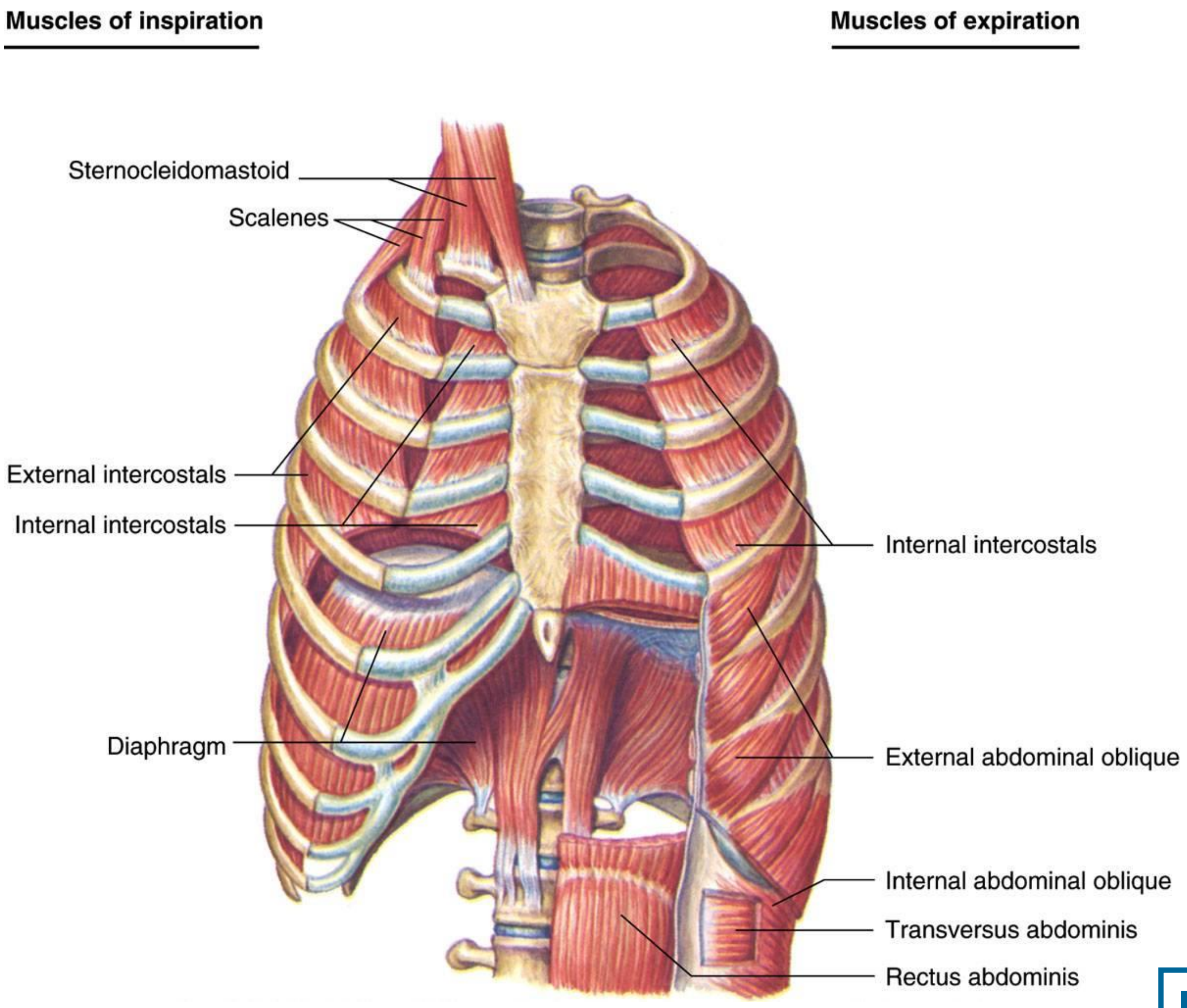

Figure 10.7

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A Closer Look 10.1
Respiratory Muscles and Exercise

- **Do respiratory muscles fatigue during exercise?**
  - – Historically believed that respiratory muscles do not fatigue during exercise
  - – Current evidence suggests that respiratory muscles do fatigue during exercise
    - ▪ Prolonged (>120 minutes)
    - ▪ High-intensity (90–100% VO_2 max)
- **Do respiratory muscle adapt to training?**
  - – Yes!
    - ▪ Increased oxidative capacity improves respiratory muscle endurance
    - ▪ Reduced work of breathing

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Airway Resistance

- **Airflow depends on:**
  - Pressure difference between two ends of airway
  - Resistance of airways

$$\text{Airflow} = \frac{P_1 - P_2}{\text{Resistance}}$$

- **Airway resistance depends on diameter**
  - Chronic obstructive lung disease
  - Asthma and exercise-induced asthma

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Clinical Applications 10.1
Exercise-Induced Asthma

- **Asthma results in bronchospasm**
  - – Narrowing of airways
    - Increased work of breathing
    - Shortness of breath (dyspnea)
  - – Many potential causes
- **Exercise-induced asthma**
  - – During or immediately following exercise
  - – May impair exercise performance

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Clinical Applications 10.2

Exercise and Chronic Obstructive Lung Disease

- **Chronic obstructive lung disease (COPD)**
  - Increased airway resistance
    - Due to constant airway narrowing
  - Decreased expiratory airflow
- **Includes two lung diseases:**
  - Chronic bronchitis
    - Excessive mucus blocks airways
  - Emphysema
    - Airway collapse and increased resistance
- **Increased work of breathing**
  - Leads to shortness of breath
  - May interfere with exercise and activities of daily living

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In Summary

- The major muscle of inspiration is the diaphragm. Air enters the pulmonary system due to intrapulmonary pressure being reduced below atmospheric pressure (bulk flow). At rest, expiration is passive. However, during exercise, expiration becomes active, using muscles located in the abdominal wall (e.g., rectus abdominis and internal oblique).
- The primary factor that contributes to airflow resistance in the pulmonary system is the diameter of the airway.

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33%

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Pulmonary Ventilation

- **The amount of air moved in or out of the lungs per minute (V)**
  - Tidal volume (V_T)
    - Amount of air moved per breath
  - Breathing frequency (f)
    - Number of breaths per minute

$$V = V_T \times f$$

  - Alveolar ventilation (V_A)
    - Volume of air that reaches the respiratory zone
  - Dead-space ventilation (V_D)
    - Volume of air remaining in conducting airways

$$V = V_A + V_D$$

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In Summary

- Pulmonary ventilation refers to the amount of gas moved into and out of the lungs.
- The amount of gas moved per minute is the product of tidal volume times breathing frequency.

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Pulmonary Volumes and Capacities

- **Vital capacity (VC)**
  - Maximum amount of gas that can be expired after a maximum inspiration
- **Residual volume (RV)**
  - Volume of gas remaining in lungs after maximum expiration
- **Total lung capacity (TLC)**
  - Amount of gas in the lungs after a maximum inspiration.

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Definitions of Pulmonary Volumes and Capacities

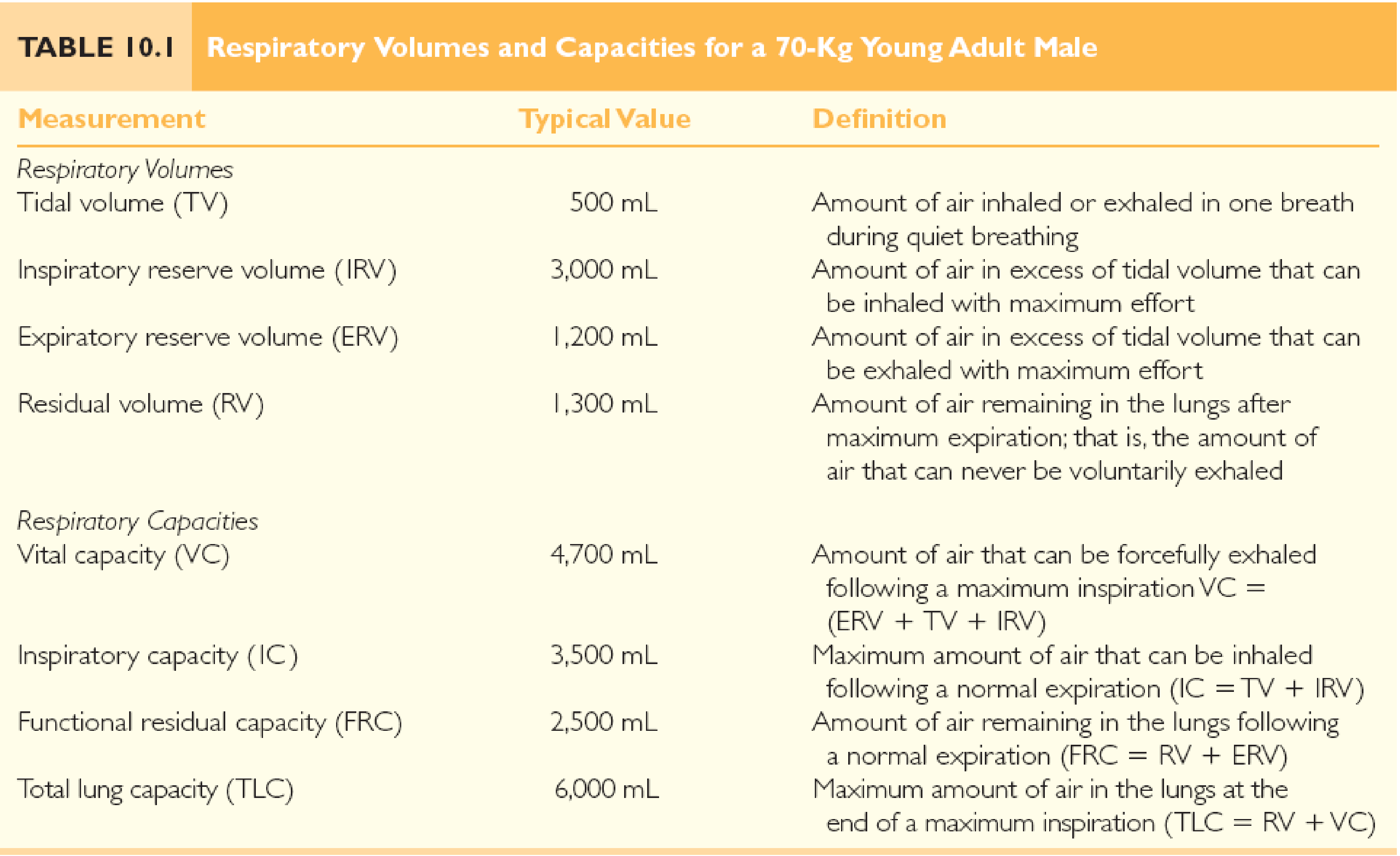

TABLE 10.1 **Respiratory Volumes and Capacities for a 70-Kg Young Adult Male**

Measurement	Typical Value	Definition
Respiratory Volumes		
Tidal volume (TV)	500 mL	Amount of air inhaled or exhaled in one breath during quiet breathing
Inspiratory reserve volume (IRV)	3,000 mL	Amount of air in excess of tidal volume that can be inhaled with maximum effort
Expiratory reserve volume (ERV)	1,200 mL	Amount of air in excess of tidal volume that can be exhaled with maximum effort
Residual volume (RV)	1,300 mL	Amount of air remaining in the lungs after maximum expiration; that is, the amount of air that can never be voluntarily exhaled
Respiratory Capacities		
Vital capacity (VC)	4,700 mL	Amount of air that can be forcefully exhaled following a maximum inspiration VC = (ERV + TV + IRV)
Inspiratory capacity (IC)	3,500 mL	Maximum amount of air that can be inhaled following a normal expiration (IC = TV + IRV)
Functional residual capacity (FRC)	2,500 mL	Amount of air remaining in the lungs following a normal expiration (FRC = RV + ERV)
Total lung capacity (TLC)	6,000 mL	Maximum amount of air in the lungs at the end of a maximum inspiration (TLC = RV + VC)

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Lung Volumes and Capacities

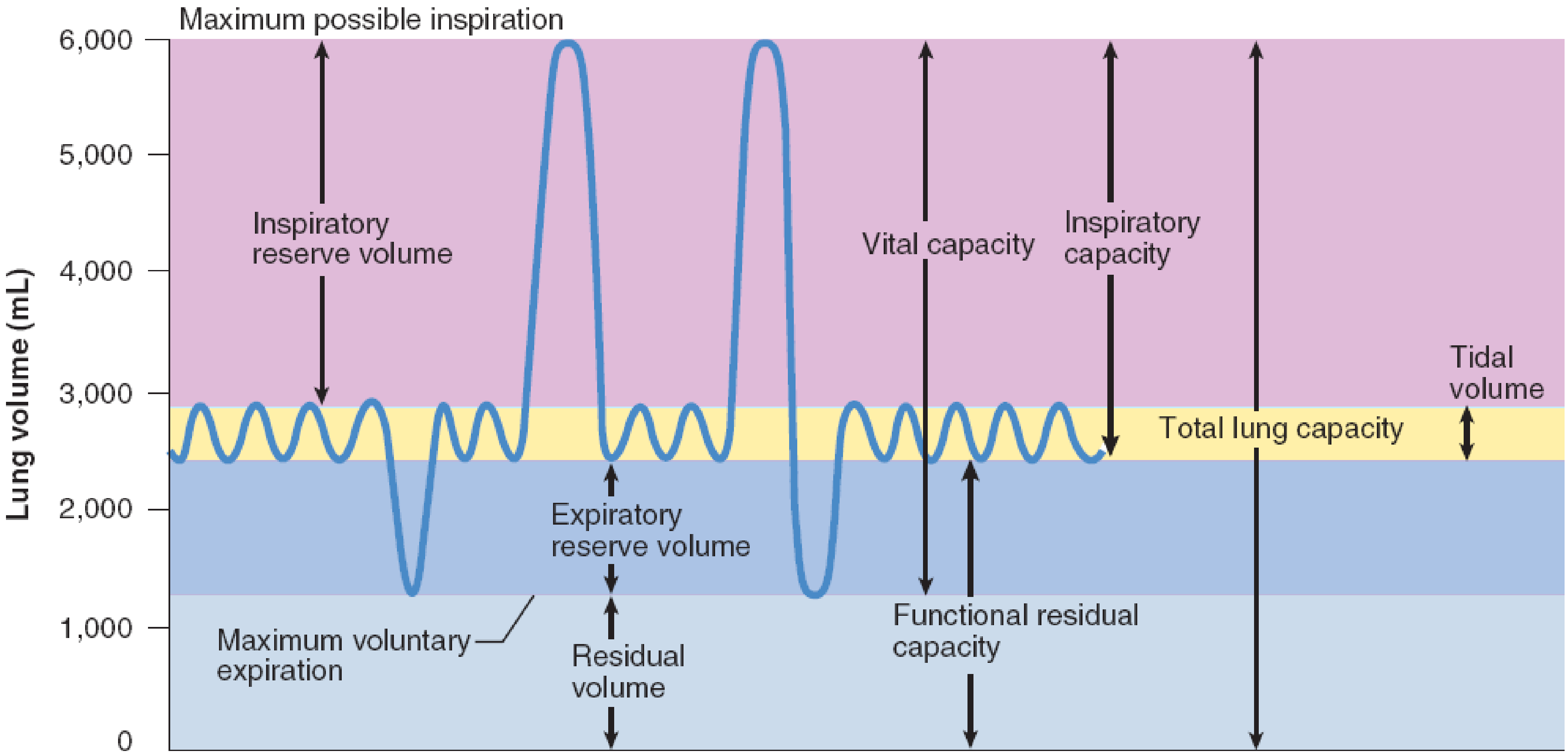

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Figure 10.9

Spirometry

- **Measurement of pulmonary volumes and rate of expired airflow**
- **Useful for diagnosing lung diseases**
  - Chronic obstructive lung disease (COPD)
- **Spirometric tests**
  - Vital capacity (VC)
    - Maximal volume of air that can be expired after maximal inspiration
  - Forced expiratory volume (FEV_1)
    - Volume of air expired in 1 second during maximal expiration
  - FEV_1/VC ratio
    - ≥80% is normal

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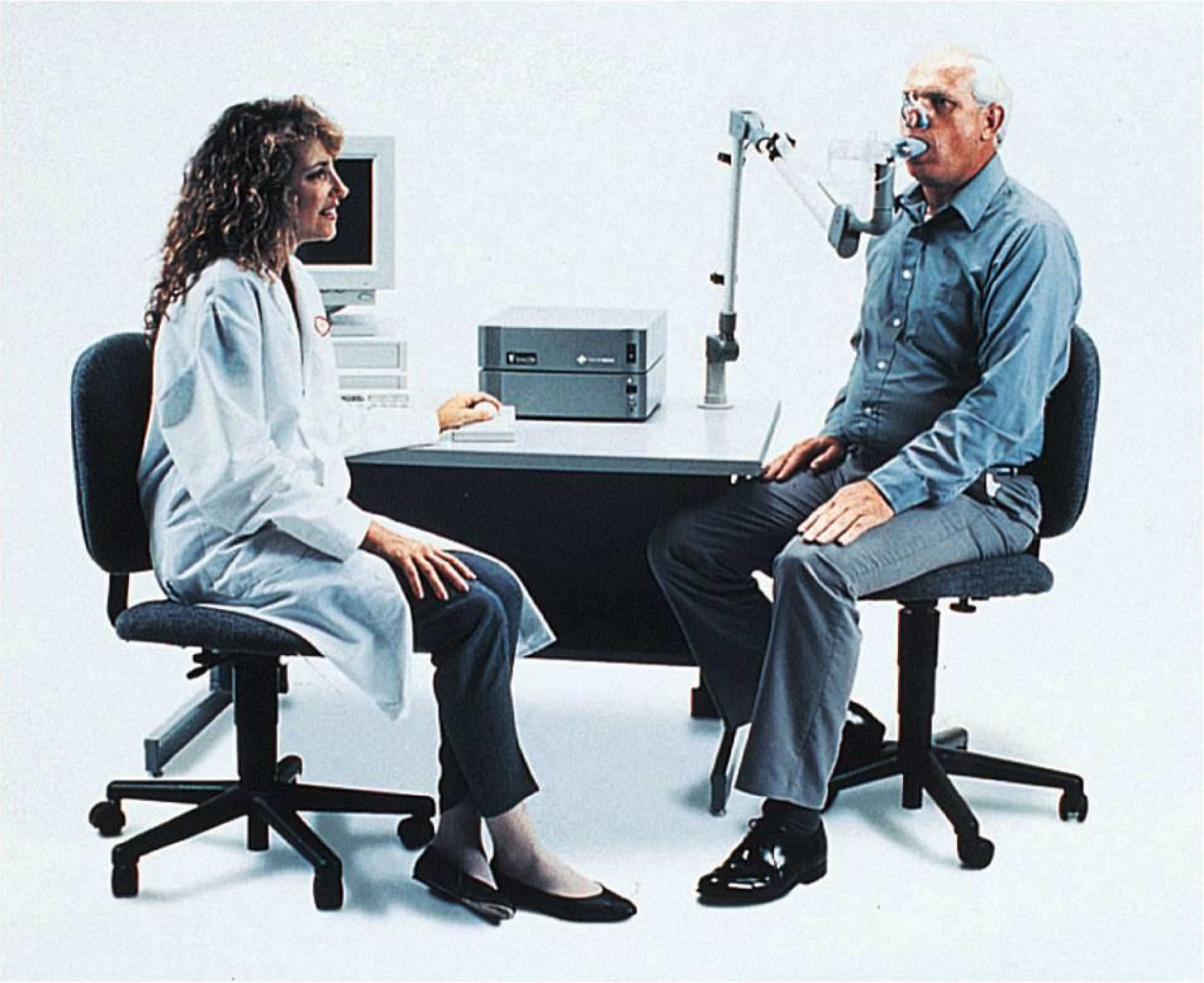
A Computerized Spirometer



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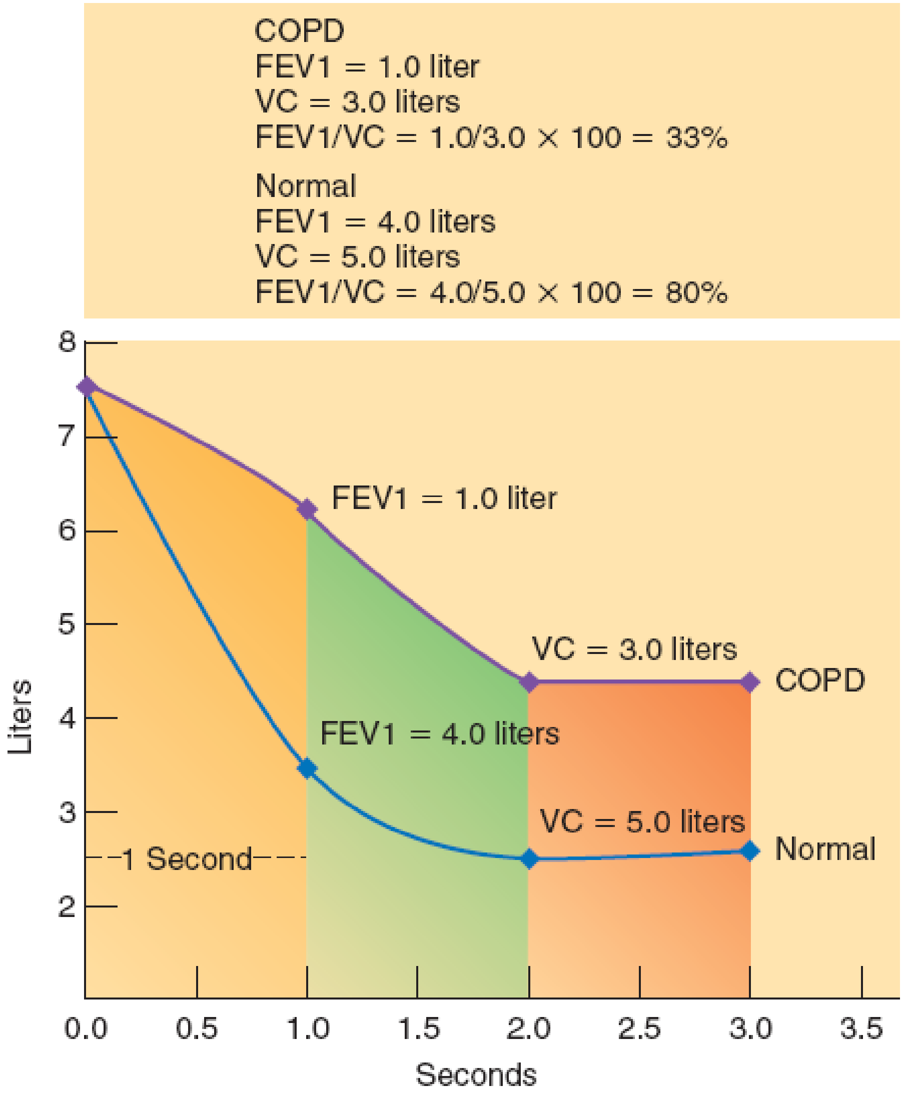
Forced Expiratory Airflow Used to Diagnose Airway Obstruction



COPD
FEV1 = 1.0 liter
VC = 3.0 liters
FEV1/VC = 1.0/3.0 × 100 = 33%

Normal
FEV1 = 4.0 liters
VC = 5.0 liters
FEV1/VC = 4.0/5.0 × 100 = 80%

Figure 10.10

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In Summary

- Pulmonary volumes can be measured using spirometry.
- Vital capacity is the maximum amount of gas that can be expired after a maximal inspiration.
- Residual volume is the amount of gas left in the lungs after a maximal expiration.

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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

$$P_{air} = PO_2 + PCO_2 + PN_2$$

- **Calculation of partial pressure**

Gas	***% in air***	***Fraction***		***Barometric P***		***Partial P***
O_2	**20.93**	**0.2093**	**x**	**760 mmHg**	**=**	**159 mmHg**
CO_2	**0.03**	**0.0003**	**x**	**760 mmHg**	**=**	**0.3 mmHg**
N_2	**79.04**	**0.7904**	**x**	**760 mmHg**	**=**	**600.7 mmHg**
Total	**100**					**760 mmHg**

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Diffusion of Gases

- **Fick's law of diffusion**
  - The rate of gas transfer (V gas) is proportional to the tissue area, the diffusion coefficient of the gas, and the difference in the partial pressure of the gas on the two sides of the tissue, and inversely proportional to the thickness.

$$V\ gas = \frac{A}{T} \times D \times (P_1 - P_2)$$

V gas = rate of diffusion
A = tissue area
T = tissue thickness
D = diffusion coefficient of gas
$P_1 - P_2$ = difference in partial pressure

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Partial Pressures of O_2 and CO_2 and Gas Exchange

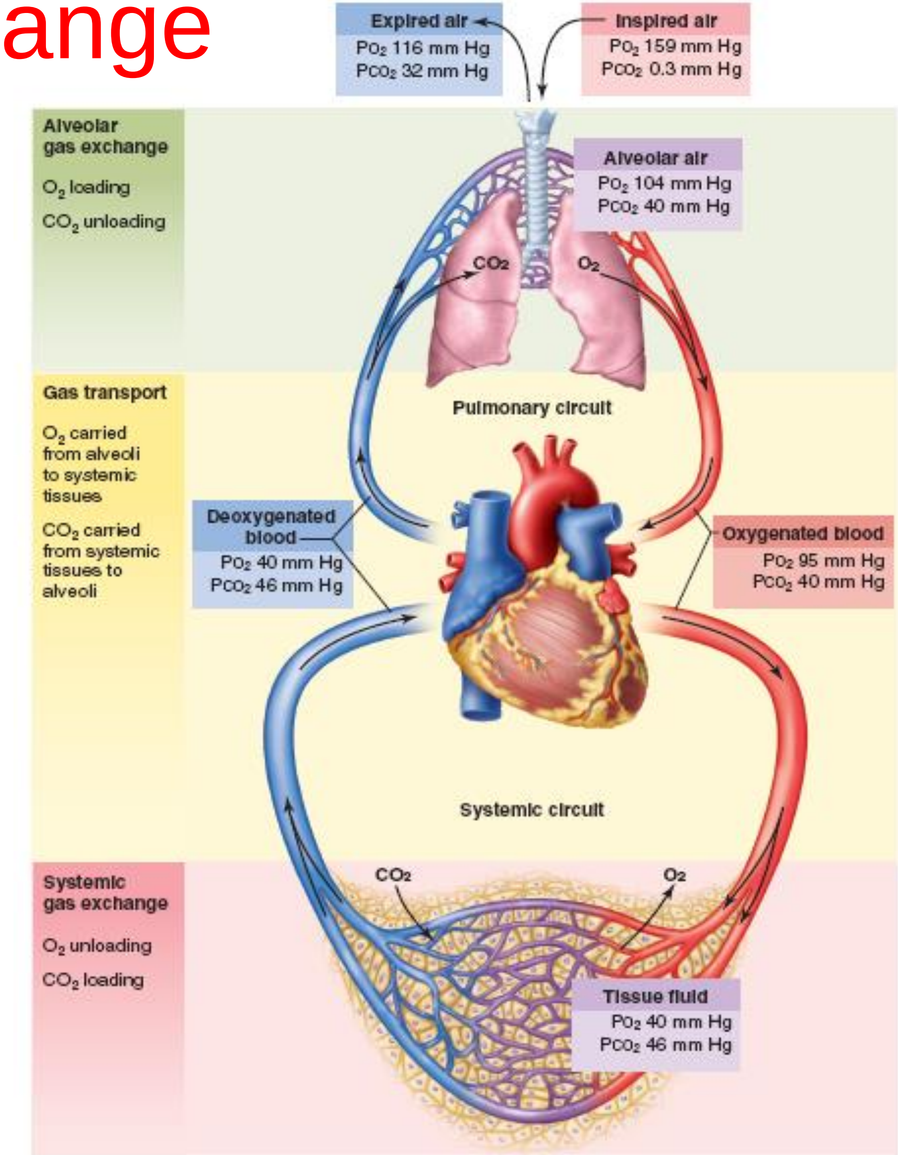

Figure 10.11

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In Summary

- Gas moves across the blood-gas interface in the lung due to simple diffusion.
- The rate of diffusion is described by Fick’s law, which states: the volume of gas that moves across a tissue is proportional to the area for diffusion and the difference in partial pressure across the membrane, and is inversely proportional to membrane thickness.

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Blood Flow to the Lung

- **Pulmonary circuit**
  - Same rate of flow as systemic circuit
  - Lower pressure
- **When standing, most of the blood flow is to the base of the lung**
  - Due to gravitational force
- **During exercise, more blood flow to apex**

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The Pulmonary and Systemic Circulation

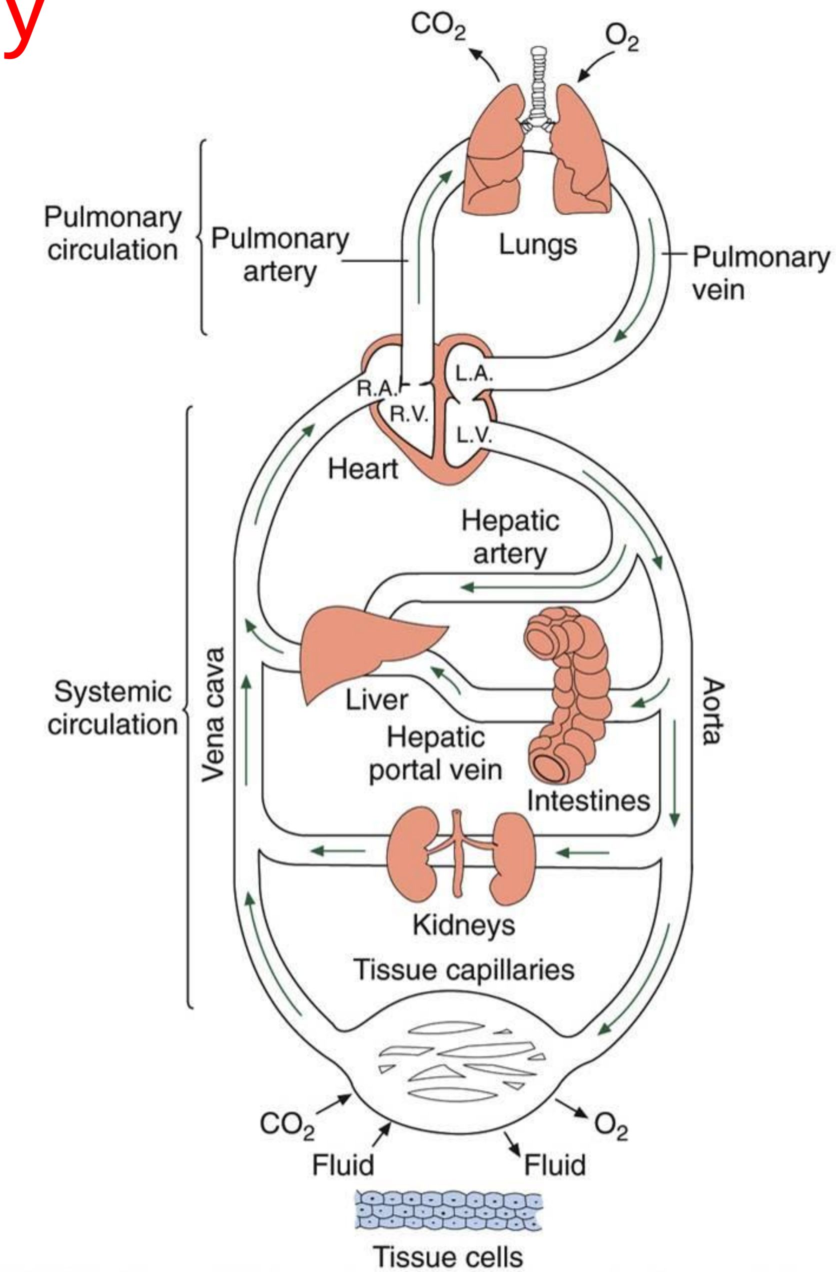

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Figure 10.12

Regional Blood Flow within the Lung

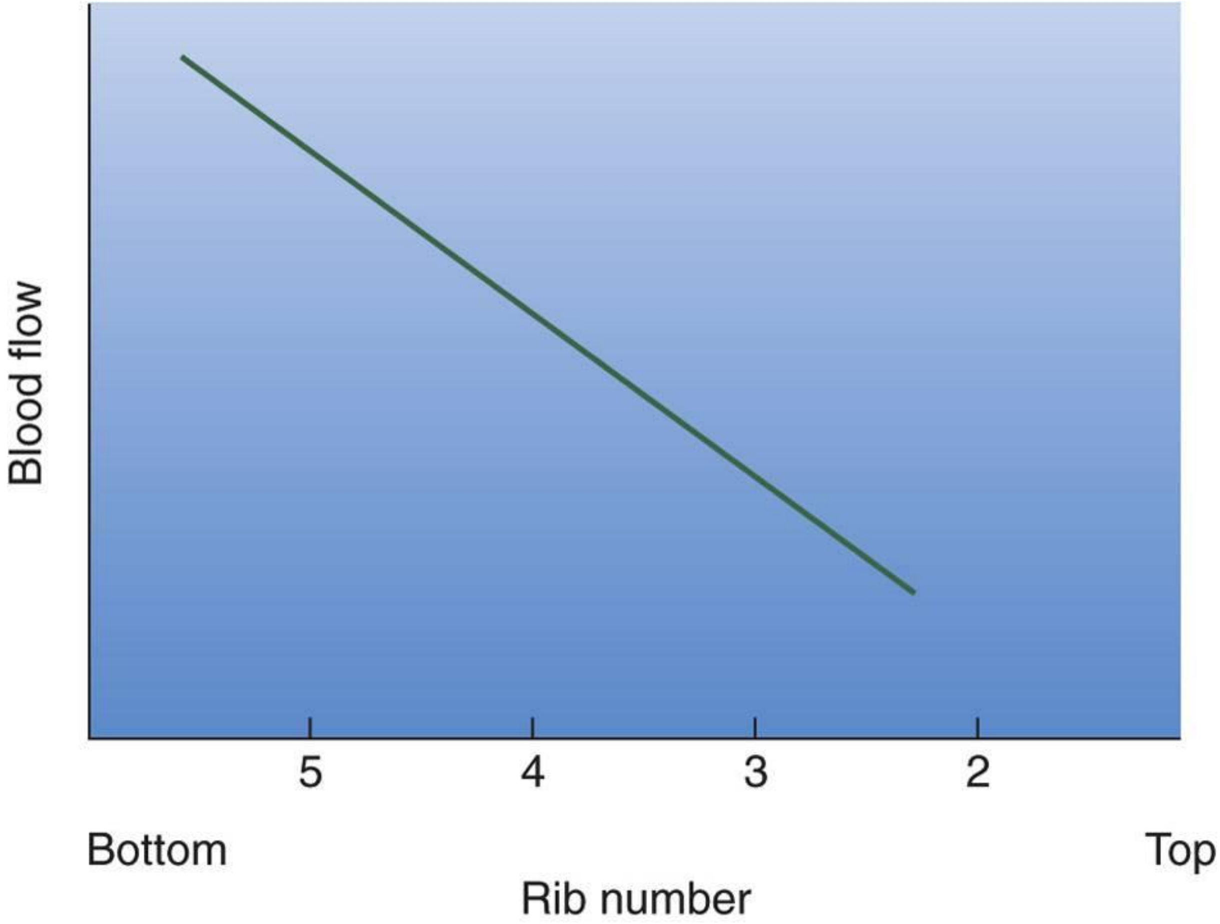

Figure 10.13

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In Summary

- The pulmonary circulation is a low-pressure system with a rate of blood flow equal to that in the systemic circuit.
- In a standing position, most of the blood flow to the lung is distributed to the base of the lung due to gravitational force.

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Ventilation-Perfusion Relationships

- **Ventilation/perfusion ratio (V/Q)**
  - – Indicates matching of blood flow to ventilation
  - – Ideal: ~1.0
- **Apex of lung**
  - – Underperfused (ratio <1.0)
- **Base of lung**
  - – Overperfused (ratio >1.0)
- **During exercise**
  - – Light exercise improves V/Q ratio
  - – Heavy exercise results in V/Q inequality

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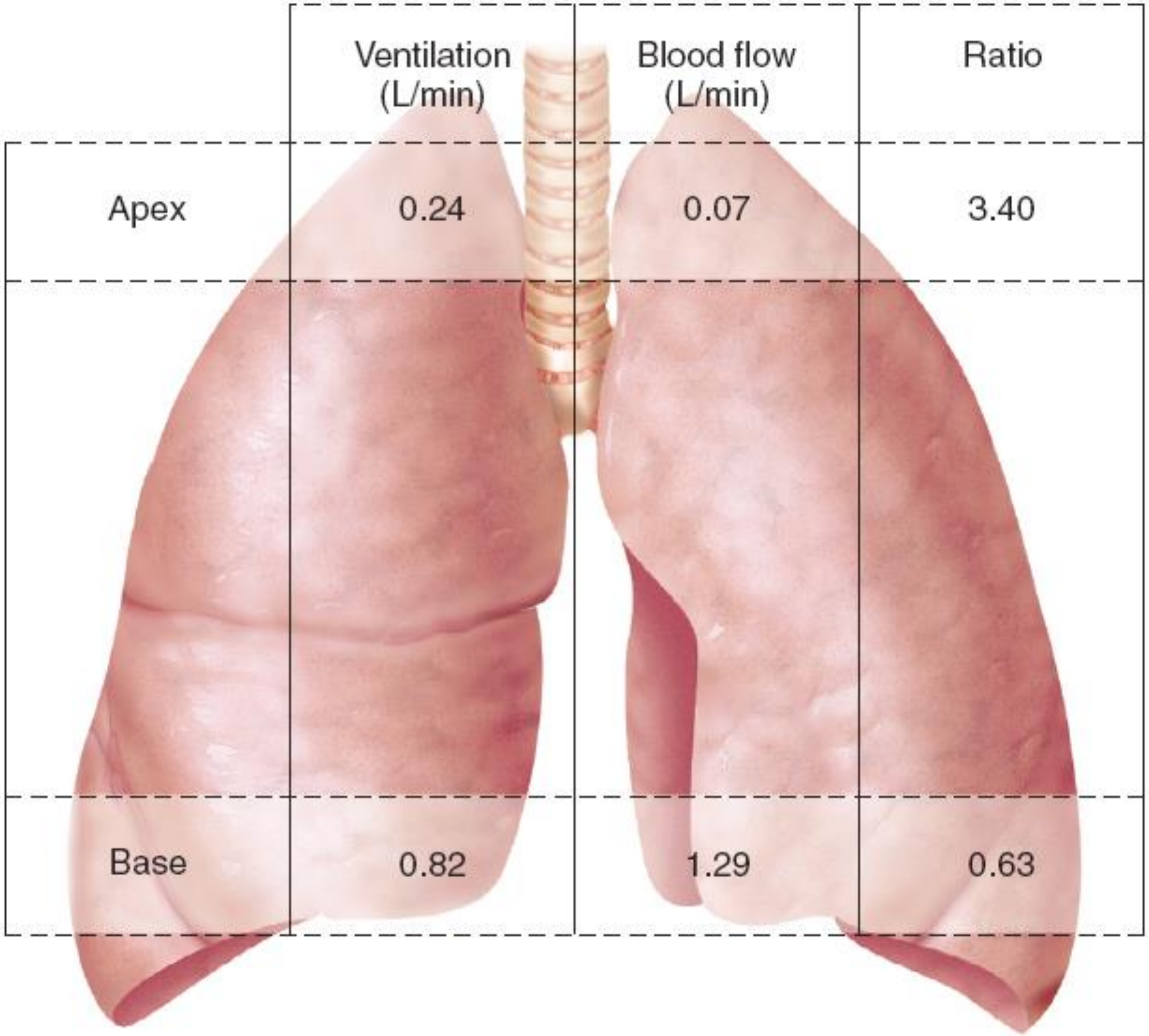
Ventilation/Perfusion Ratios



	Ventilation (L/min)	Blood flow (L/min)	Ratio
Apex	0.24	0.07	3.40
Base	0.82	1.29	0.63

Figure 10.14

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In Summary

- Efficient gas exchange between the blood and the lung requires proper matching of blood flow to ventilation (called *ventilation-perfusion relationships*).
- The ideal ratio of ventilation to perfusion is 1.0 or slightly greater, since this ratio implies a perfect matching on blood flow to ventilation.

54%

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O_2 Transport in the Blood

- **99% of O_2 is transported bound to hemoglobin (Hb)**
  - – Oxyhemoglobin: Hb bound to O_2
  - – Deoxyhemoglobin: Hb not bound to O_2
- **Amount of O_2 that can be transported per unit volume of blood is dependent on the Hb concentration**
  - – Each gram of Hb can transport 1.34 ml O_2
- **Oxygen content of blood (100% Hb saturation)**
  - – Males:

    150 g Hb/L blood x 1.34 ml O_2/g Hb = 200 ml O_2/L blood
  - – Females:

    130 g Hb/L blood x 1.34 ml O_2/g Hb = 174 ml O_2/L blood

55%

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Oxyhemoglobin Dissociation Curve

- **Deoxyhemoglobin + O_2 ↔ Oxyhemoglobin**
- **Direction of reaction depends on:**
  - PO_2 of the blood
  - Affinity between Hb and O_2
- **At the lung**
  - High PO_2 = formation of oxyhemoglobin
- **At the tissues**
  - Low PO_2 = release of O_2 to tissues

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Oxygen-Hemoglobin Dissociation Curve

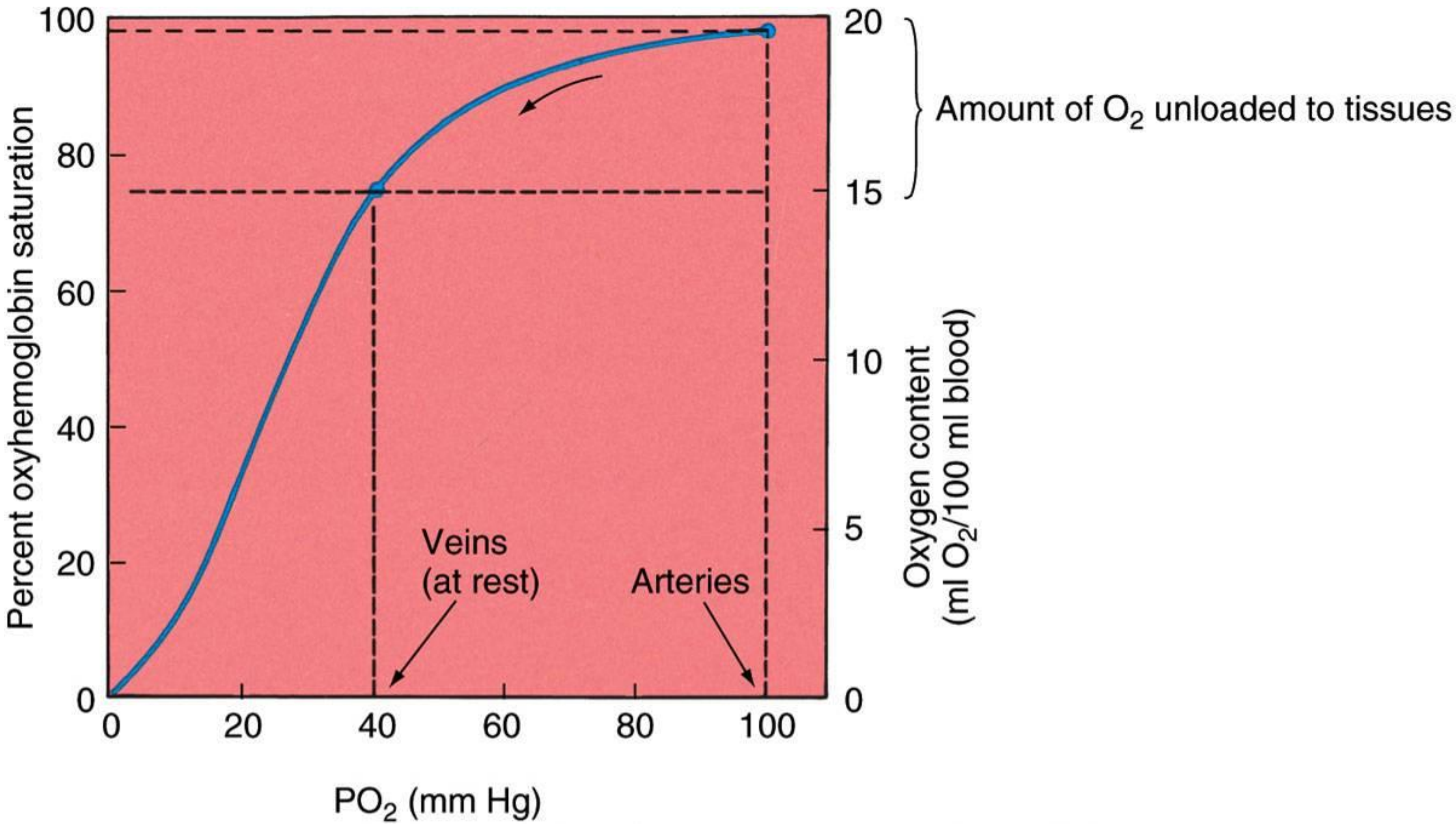

Figure 10.15

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Effect of pH, Temperature, and 2–3 DPG on the O_2-Hb Dissociation Curve

- **pH**
  - Decreased pH lowers Hb-O_2 affinity
  - Results in a “rightward” shift of the curve
    - Favors “offloading” of O_2 to the tissues
- **Temperature**
  - Increased blood temperature lowers Hb-O_2 affinity
  - Results in a “rightward” shift of the curve
- **2–3 DPG**
  - Byproduct of RBC glycolysis
  - May result in a “rightward” shift of the curve
    - During altitude exposure
    - Not a major cause of rightward shift during exercise

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Effect of pH on the Oxygen-Hemoglobin Dissociation Curve

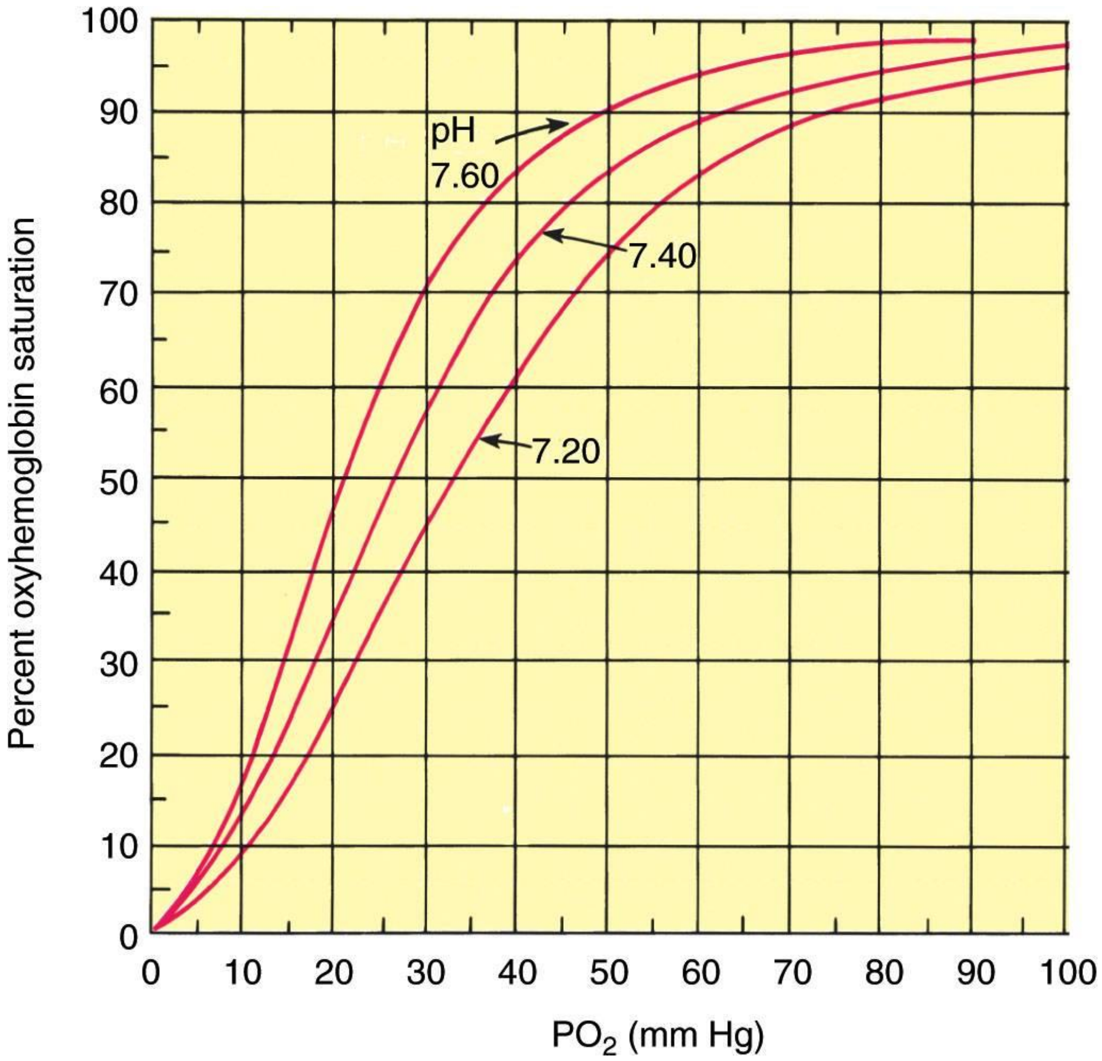

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Figure 10.15

Effect of Temperature on the Oxygen-Hemoglobin Dissociation Curve

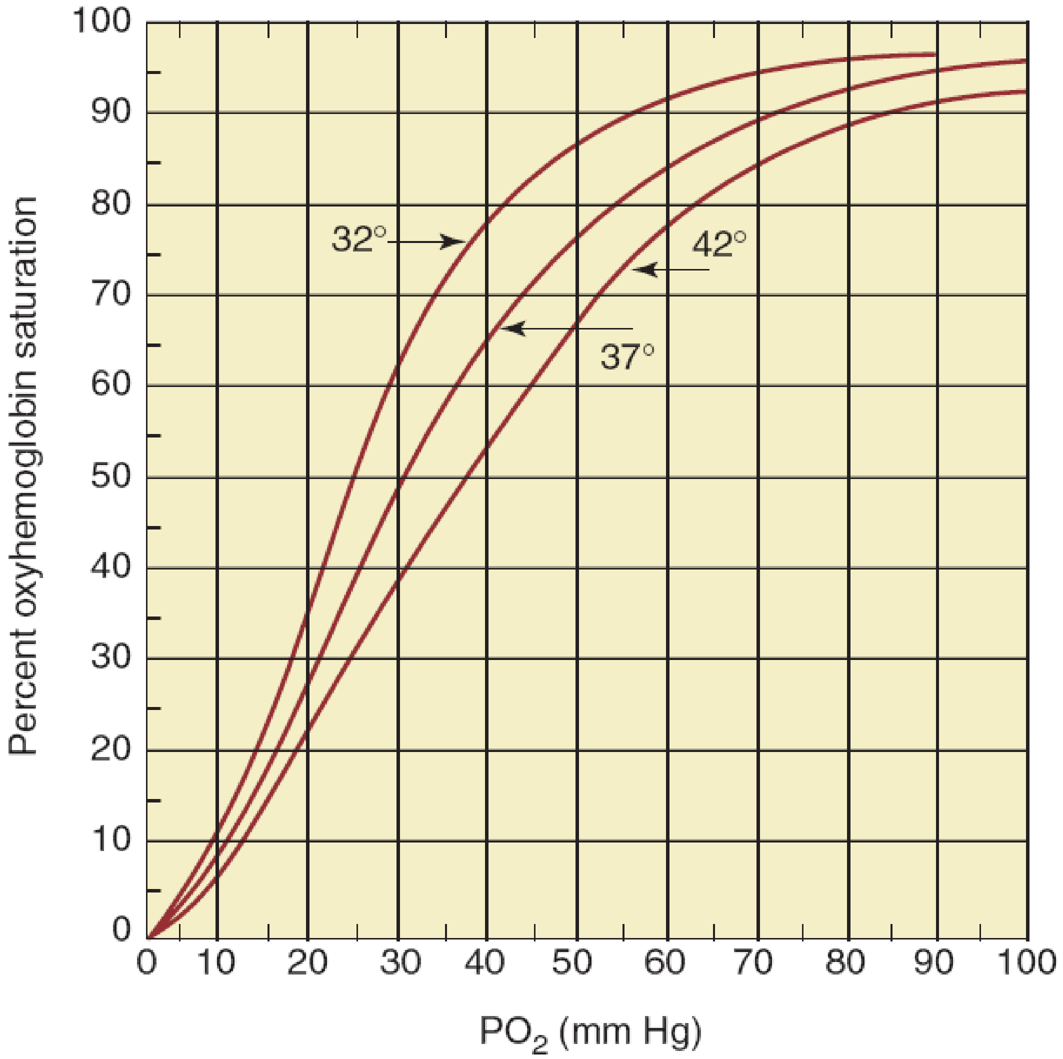

Figure 10.17

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O_2 Transport in Muscle

- **Myoglobin (Mb)**
  - Shuttles O_2 from the cell membrane to the mitochondria
- **Mb has a higher affinity for O_2 than hemoglobin**
  - Even at low PO_2
  - Allows Mb to store O_2
    - O_2 reserve for muscle

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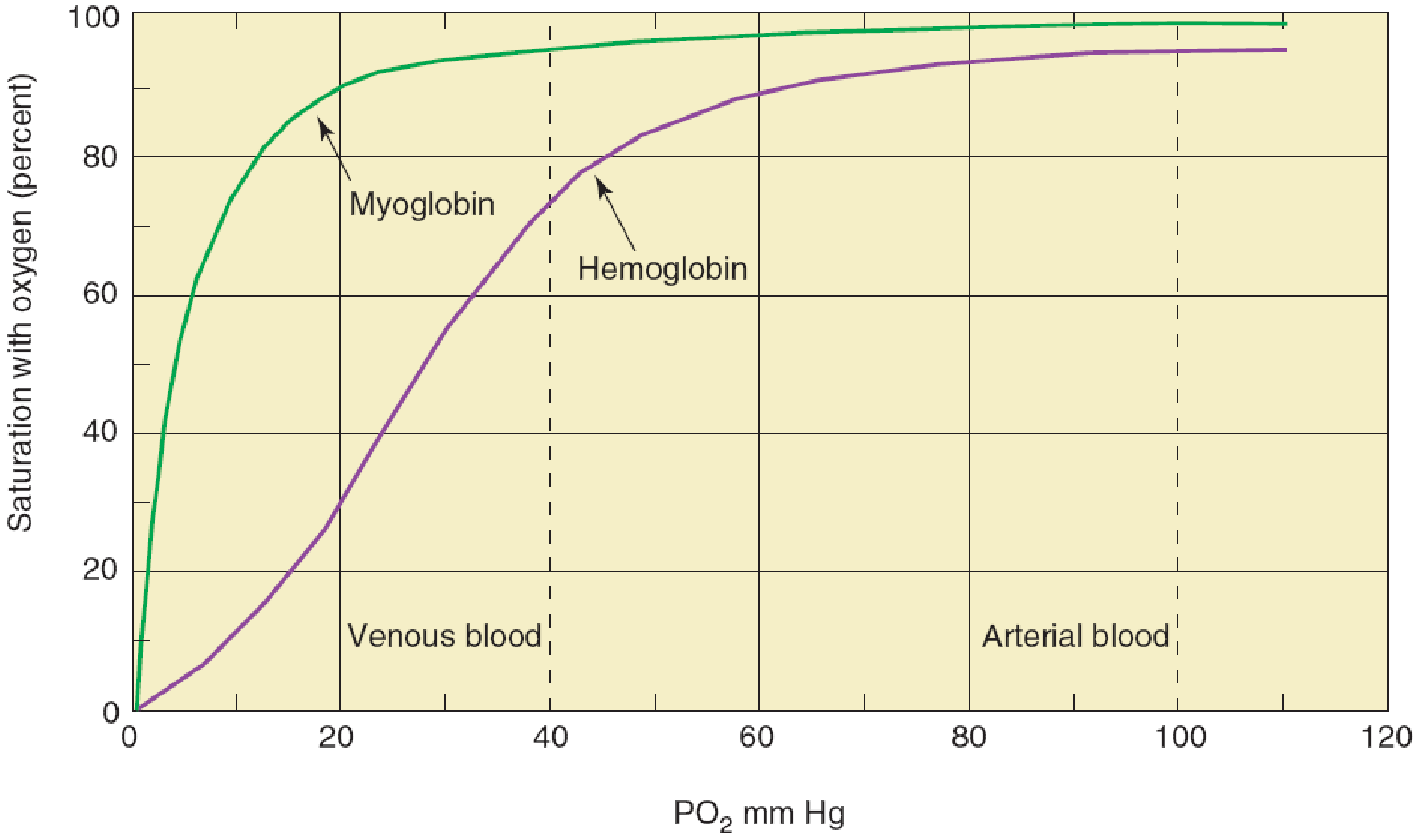
Dissociation Curves for Myoglobin and Hemoglobin



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CO_2 Transport in Blood

- **Dissolved in plasma (10%)**
- **Bound to Hb (20%)**
- **Bicarbonate (70%)**

$$CO_2 + H_2O \xrightarrow{\text{Carbonic anhydrase}} H_2CO_3 \longrightarrow H^+ + HCO_3^-$$

- At the tissue:
  - H^+ binds to Hb
  - HCO_3^- diffuses out of RBC into plasma
  - Cl^- diffuses into RBC (chloride shift)
- At the lung:
  - O_2 binds to Hb (drives off H^+)
  - Reaction reverses to release CO_2

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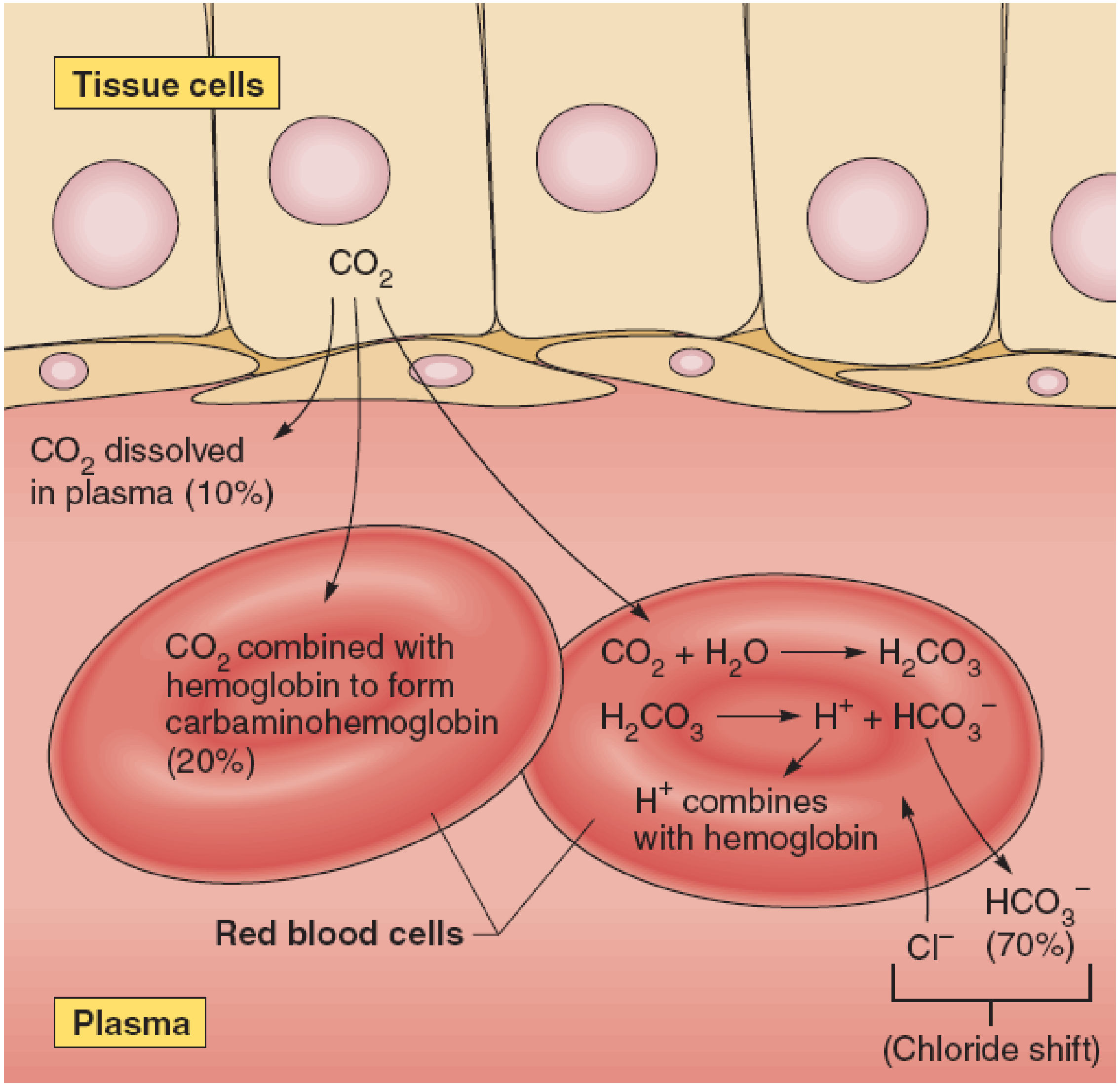
CO_2 Transport in the Blood at the Tissue



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CO_2 Transport in the Blood at the Lung

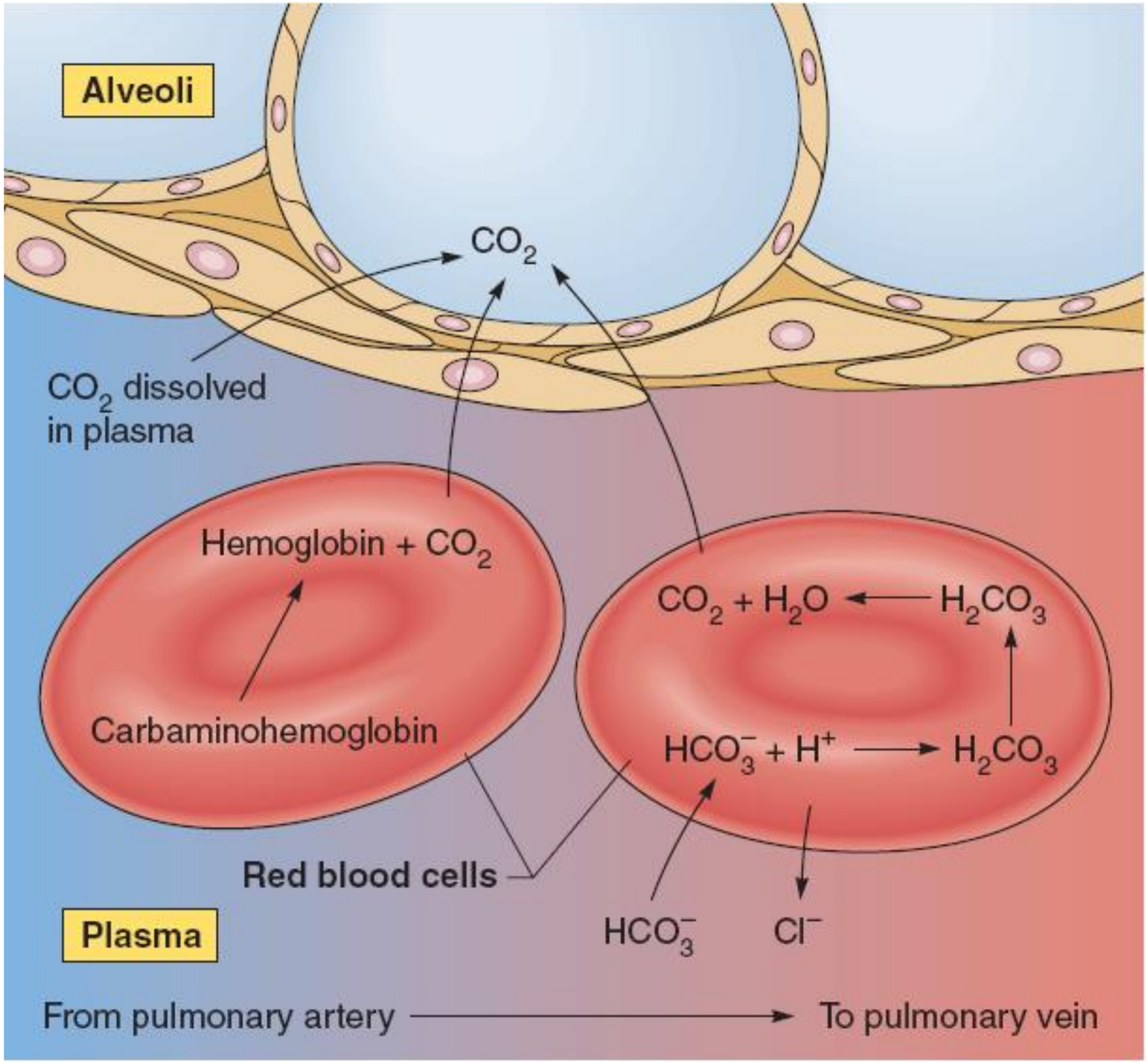

Figure 10.20

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In Summary

- Over 99% of the O_2 transported in blood is chemically bonded with hemoglobin. The effect of the partial pressure of O_2 on the combination of O_2 with hemoglobin is illustrated by the S-shaped O_2-hemoglobin dissociation curve.
- An increase in body temperature and a reduction in blood pH results in a right shift in the O_2-hemoglobin dissociation curve and a reduced affinity of hemoglobin for O_2.

hts Reserved.

In Summary

- Carbon dioxide is transported in blood three forms: (1) dissolved CO_2 (10% of CO_2 is transported in this way), (2) CO_2 bound to hemoglobin (called carbamino-hemoglobin; about 20% of blood CO_2 is transported via this form), and (3) bicarbonate (70% of CO_2 found in the blood is transported as bicarbonate [HCO_3^-]).

s Reserved.

Ventilation and Acid-Base Balance

- **Pulmonary ventilation removes H^+ from blood by the HCO_3^- reaction**

Lung ←

$$CO_2 + H_2O \xleftrightarrow{\text{Carbonic anhydrase}} H_2CO_3 \longleftrightarrow H^+ + HCO_3^-$$

Muscle →

  - Increased ventilation results in CO_2 exhalation
    - Reduces PCO_2 and H^+ concentration (pH increase)
  - Decreased ventilation results in buildup of CO_2
    - Increases PCO_2 and H^+ concentration (pH decrease)

Reserved.

In Summary

- An increase in pulmonary ventilation causes exhalation of additional CO_2, which results in a reduction of blood PCO_2 and a lowering of hydrogen ion concentration (i.e., pH increases).

eserved.

Rest-to-Work Transitions

- **At the onset of constant-load submaximal exercise:**
  - Initially, ventilation increases rapidly
    - Then, a slower rise toward steady state
  - PO_2 and PCO_2 are relatively unchanged
    - Slight decrease in PO_2 and increase in PCO_2

erved.

The Transition From Rest to Exercise

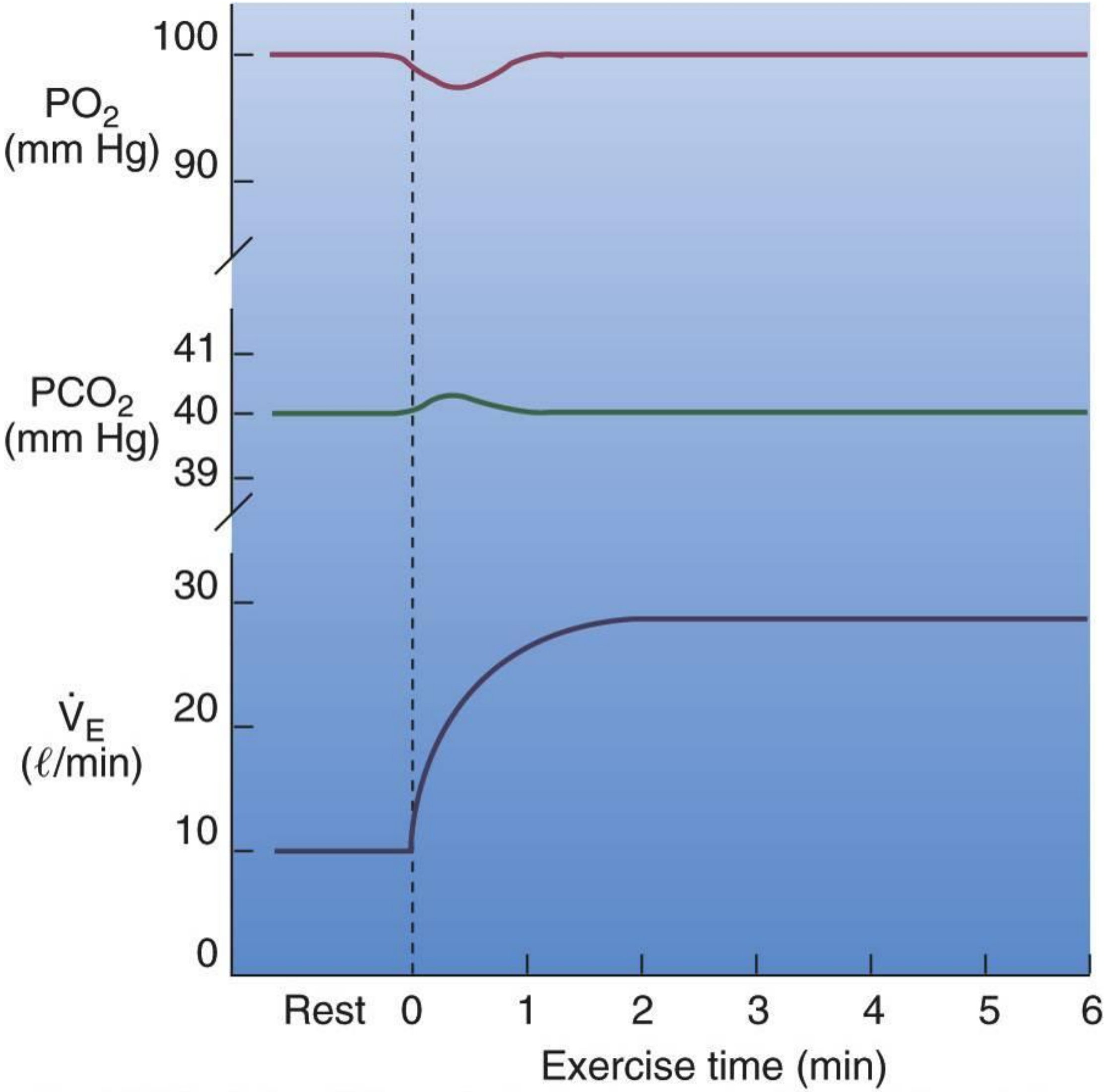


Figure 10.21

ved.

Prolonged Exercise in a Hot Environment

- **During prolonged submaximal exercise in a hot/humid environment:**
  - – Ventilation tends to drift upward
    - Increased blood temperature affects respiratory control center
  - – Little change in PCO_2

ed.

Exercise in a Hot/Humid Environment

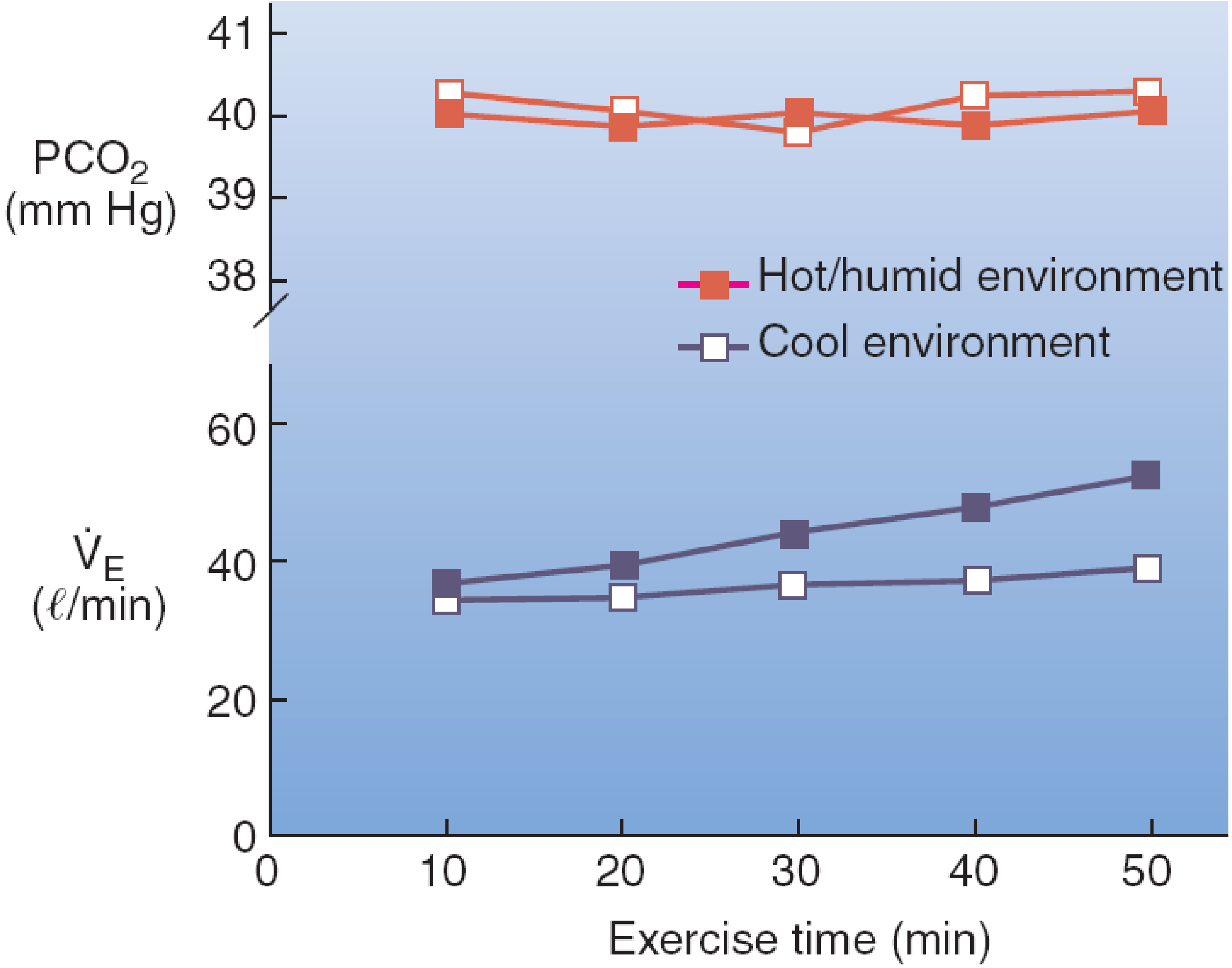


Figure 10.22

Incremental Exercise in an Untrained Subject

- **Ventilation**
  - – Linear increase up to ~50–75% VO_2 max
  - – Exponential increase beyond this point
  - – Ventilatory threshold (Tvent)
    - ▪ Inflection point where V_E increases exponentially
- **PO_2**
  - – Maintained within 10–12 mmHg of resting value

Incremental Exercise in an Elite Athlete

- **Ventilation**
  - Tvent occurs at higher % VO_2 max
- **PO_2**
  - Decrease of 30–40 mmHg at near-maximal work
    - Hypoxemia
  - Due to:
    - Ventilation/perfusion mismatch
    - Short RBC transit time in pulmonary capillary due to high cardiac output

Ventilatory Response to Incremental Exercise

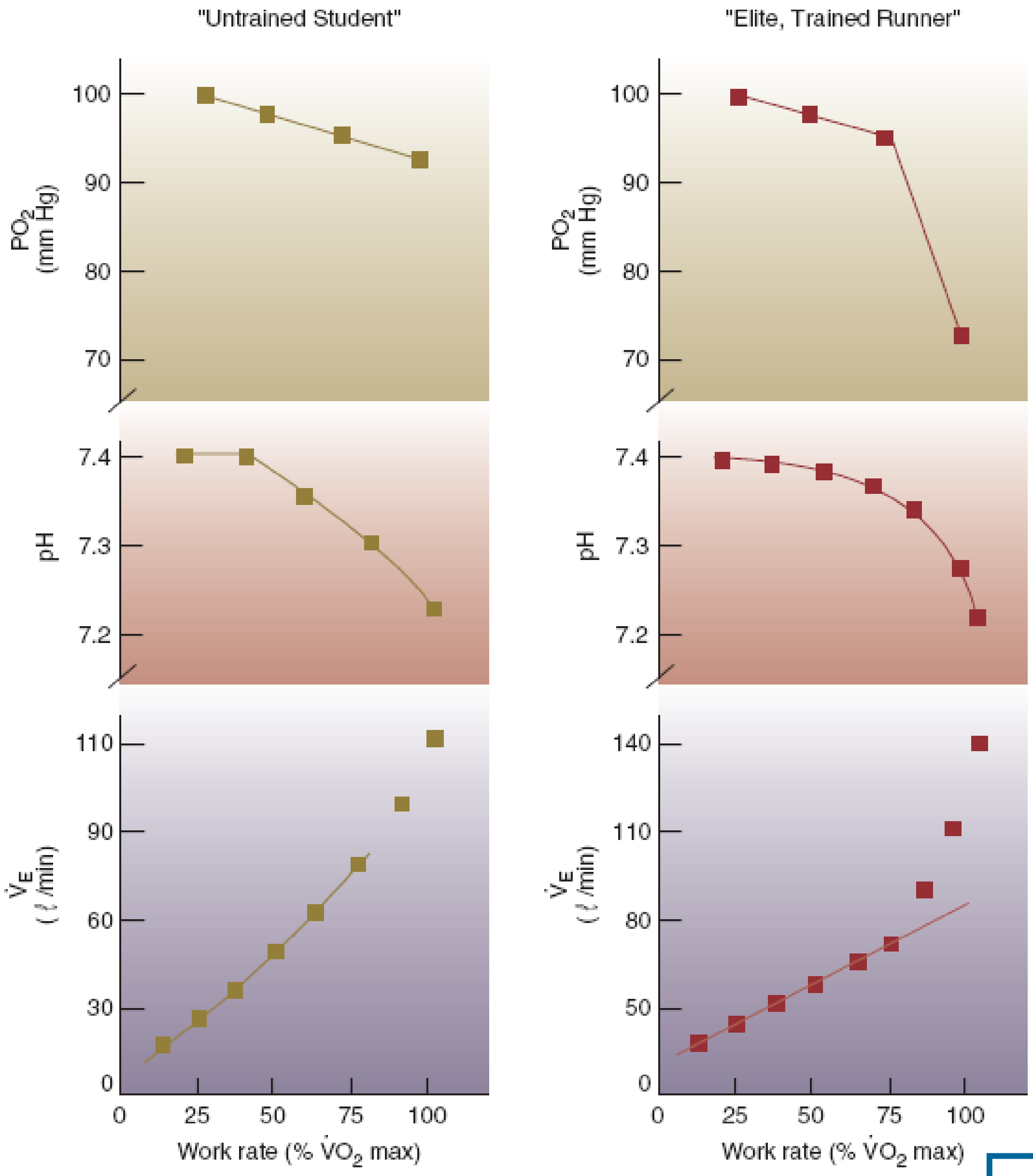


Figure 10.23

In Summary

- At the onset of constant-load submaximal exercise, ventilation increases rapidly, followed by a slower rise toward a steady-state value. Arterial PO_2 and PCO_2 are maintained relatively constant during this type of exercise.
- During prolonged exercise in a hot/humid environment, ventilation “drifts” upward due to the influence of rising body temperature on the respiratory control center.
- Incremental exercise results in a linear increase in V_E up to approximately 50% to 70% of O_2 max; at higher work rates, ventilation begins to rise exponentially. This ventilatory inflection point has been called the ventilatory threshold.

Control of Ventilation at Rest

- **Inspiration and expiration**
  - Produced by contraction and relaxation of diaphragm
- **Controlled by somatic motor neurons in the spinal cord**
  - Controlled by respiratory control center
    - In medulla oblongata

Respiratory Control Center

- **Stimulus for inspiration comes from four respiratory rhythm centers**
  - In Medulla
    - preBötzinger Complex and retrotrapezoidal nucleus
  - In Pons
    - Pneumotaxic center and caudal pons

Input to the Respiratory Control Center

- **Humoral chemoreceptors**
  - Central chemoreceptors
    - Located in the medulla
    - PCO_2 and H^+ concentration in cerebrospinal fluid
  - Peripheral chemoreceptors
    - Aortic and carotid bodies
    - PO_2, PCO_2, H^+, and K^+ in blood
- **Neural input**
  - From motor cortex and skeletal muscle mechanoreceptors

The Brain Stem Respiratory Control Centers

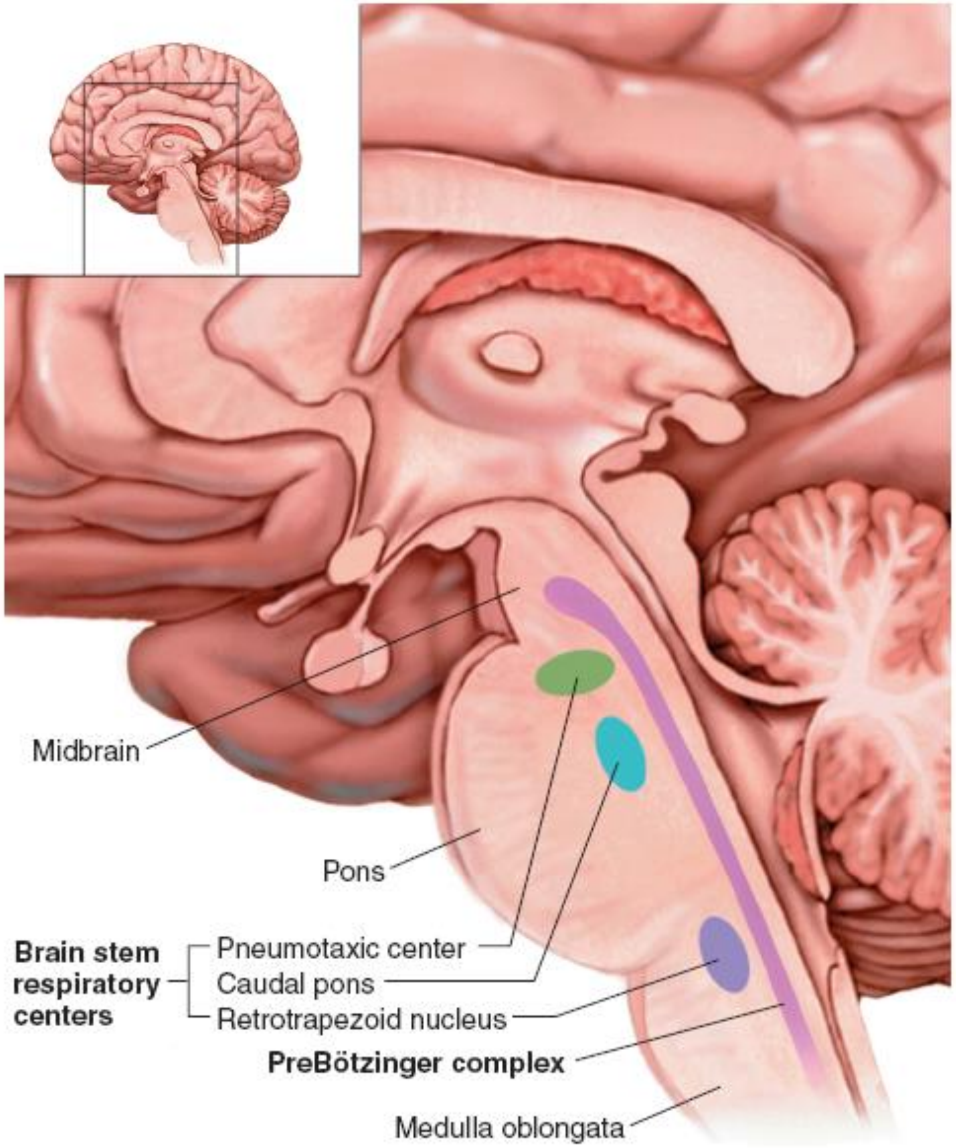


Figure 10.24

The Location of the Peripheral Chemoreceptors

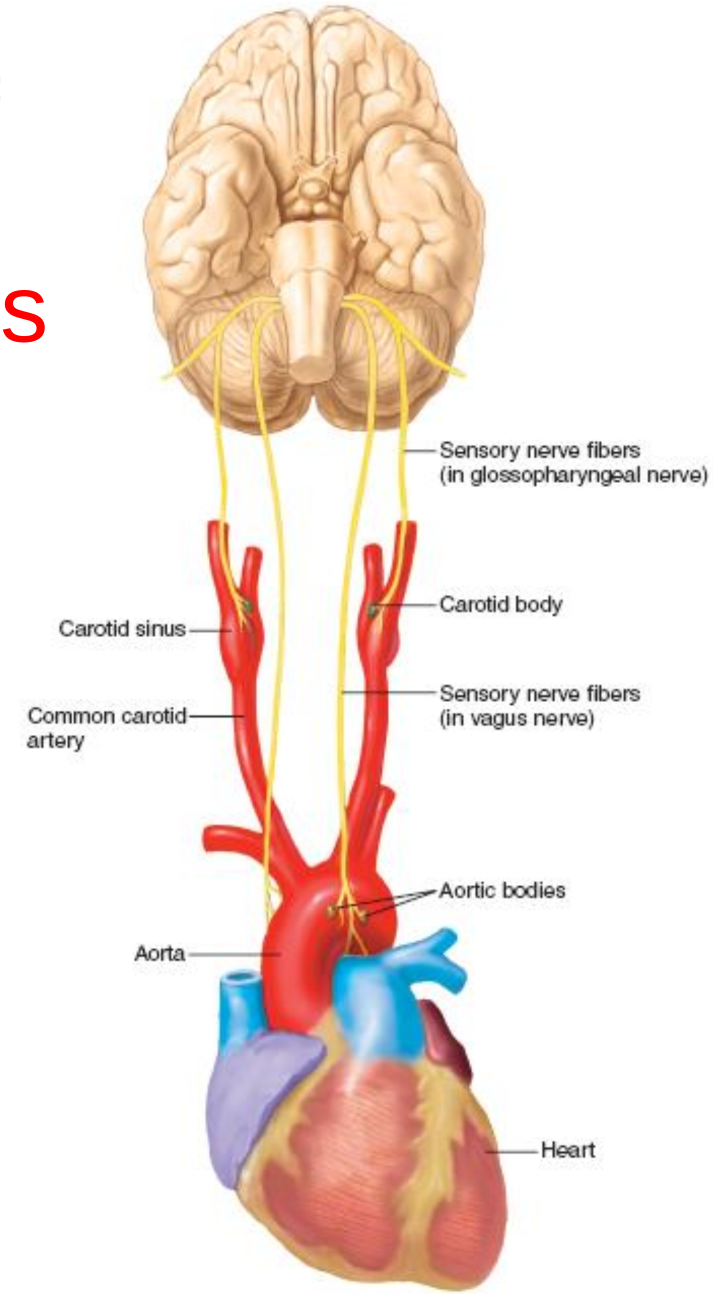


Figure 10.25

Effect of Arterial PCO_2 on Ventilation

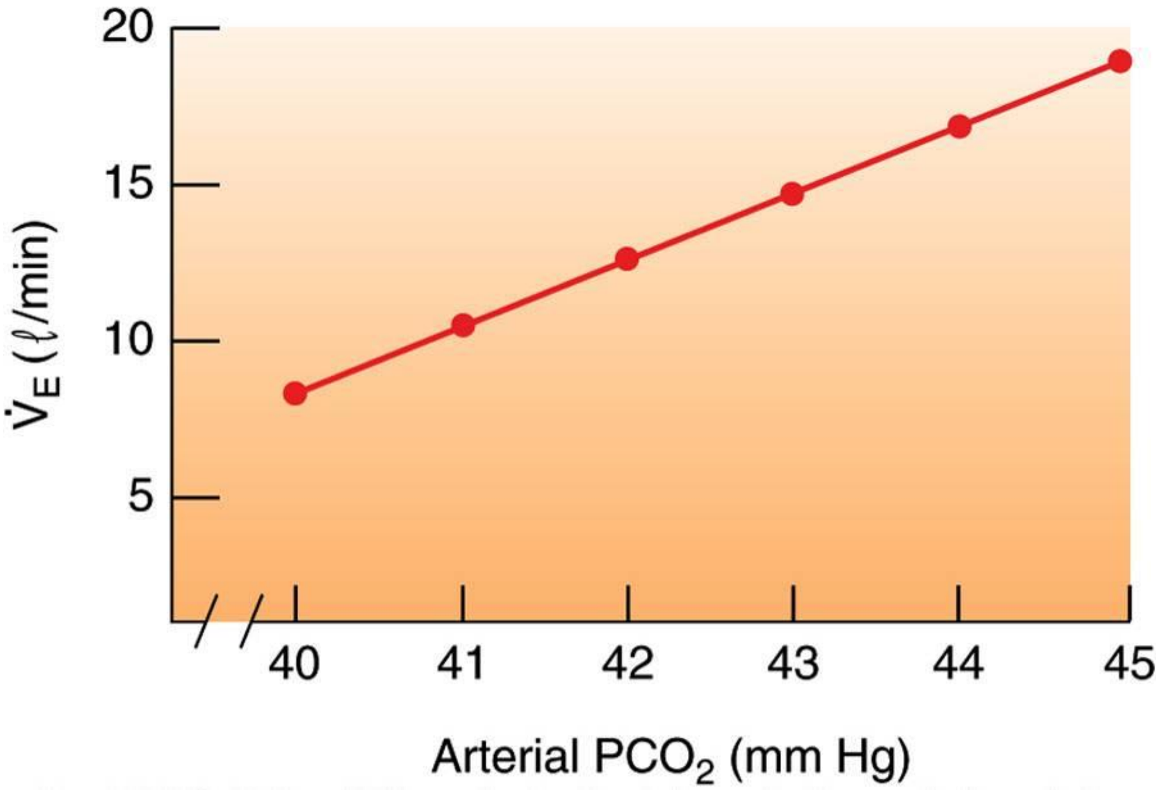


Figure 10.26

Effect of Arterial PO_2 on Ventilation

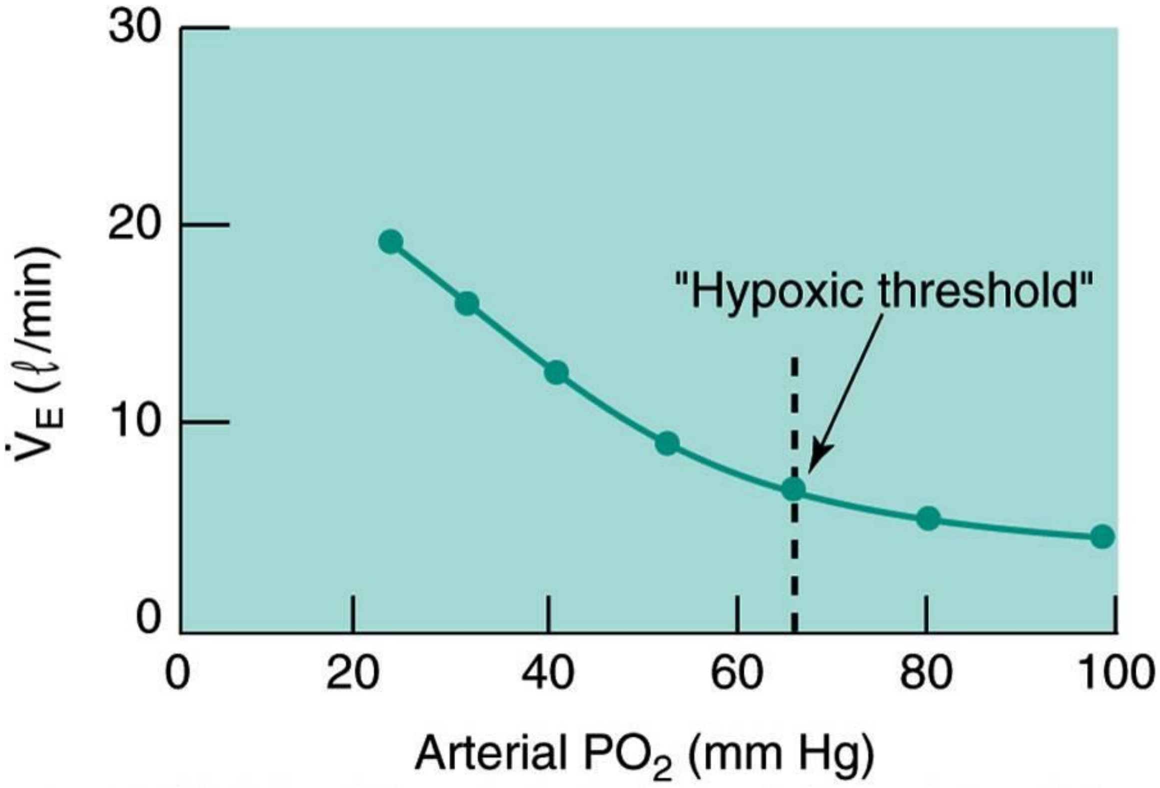
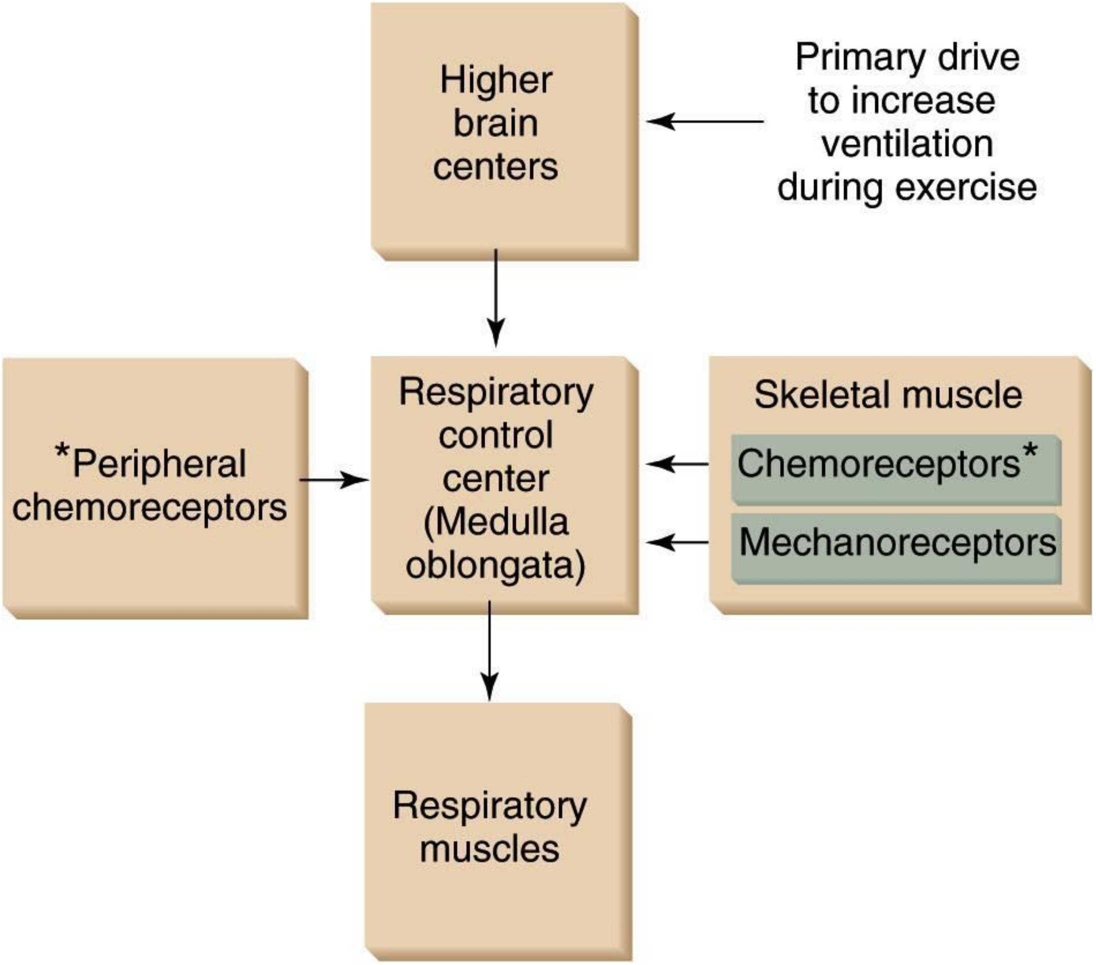


Figure 10.27

Ventilatory Control During Exercise

- **Submaximal exercise**
  - Primary drive:
    - Higher brain centers (central command)
  - “Fine tuned” by:
    - Humoral chemoreceptors
    - Neural feedback from muscle
- **Heavy exercise**
  - Alinear rise in V_E
    - Increasing blood H^+ (from lactic acid) stimulates carotid bodies
    - Also K^+, body temperature, and blood catecholamines may contribute

A Summary of Respiratory Control During Submaximal Exercise



*Act to fine-tune ventilation during exercise

Figure 10.27

A Closer Look 10.2

Training Reduces the Ventilatory Response to Exercise

- **No effect on lung structure**
- **Ventilation is lower during exercise following training**
  - Exercise ventilation is 20–30% lower at same submaximal work rate
- **Mechanism:**
  - Changes in aerobic capacity of locomotor muscles
    - Result in less production of lactic acid
    - Less afferent feedback from muscle to stimulate breathing

Effects of Endurance Training on Ventilation During Exercise

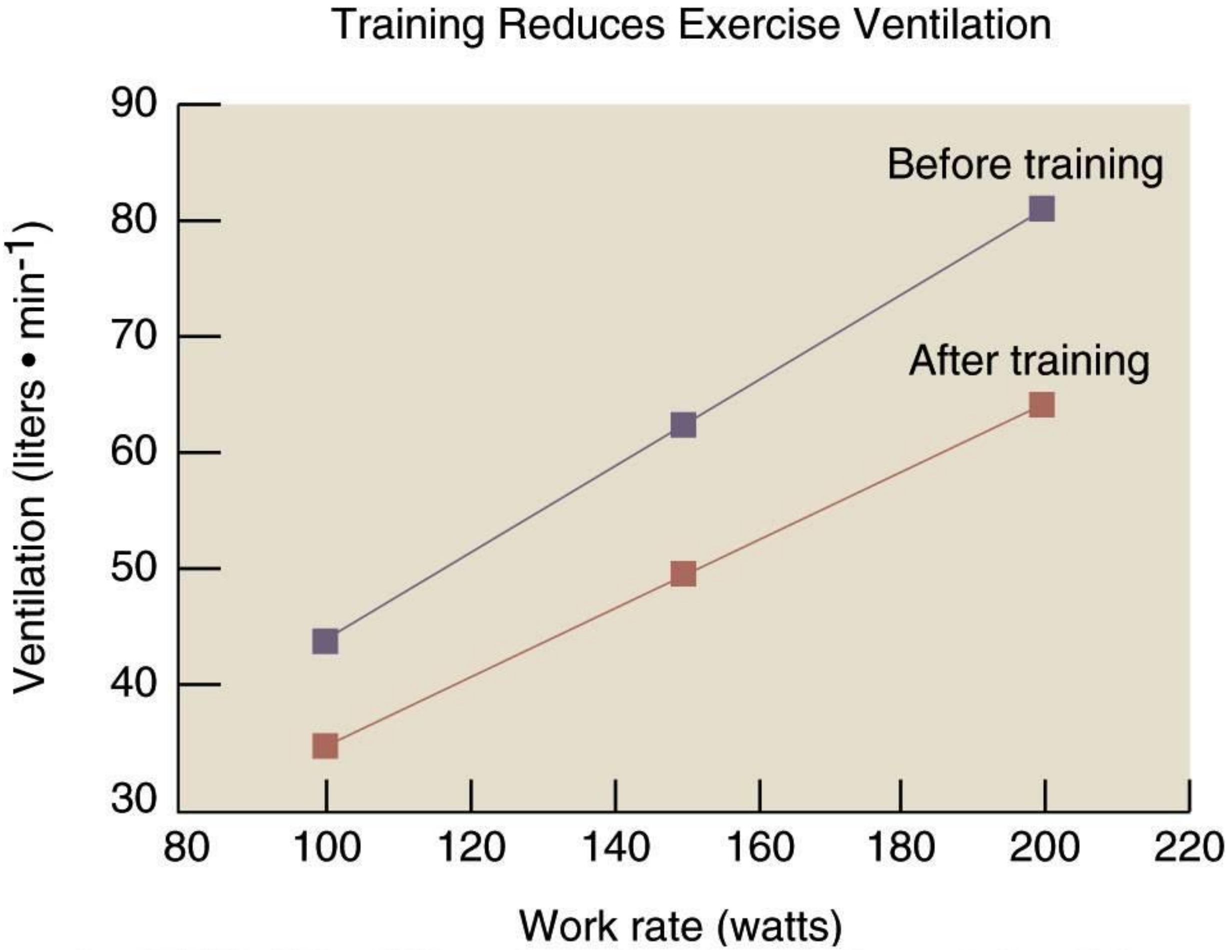


Figure 10.29

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In Summary

- Current evidence suggests that the normal rhythm of breathing is generated by the interaction between four separate respiratory rhythm centers located in the medulla oblongata and the pons. At rest, the breathing rhythm is dominated by pacemaker neurons in the preBötzinger Complex. During exercise, however, the preBötzinger Complex interacts with the retrotrapezoidal nucleus along with two additional regulatory centers in the Pons to regulate breathing. The coupling of these respiratory control centers to regulate breathing involves both positive and negative feedback to achieve tight control.

In Summary

- Input into the respiratory control center to increase ventilation can come from both neural and humoral sources. Neural input may come from higher brain centers, or it may arise from receptors in the exercising muscle. Humoral input may arise from central chemoreceptors , peripheral chemoreceptors, and/or lung CO_2 receptors. The central chemoreceptors are sensitive to increases in PCO_2 and decreases in pH. The peripheral chemoreceptors (carotid bodies are the most important) are sensitive to increases in PCO_2 and decreases in PO_2 or pH. Receptors in the lung that are sensitive to an increase in PCO_2 are hypothesized to exist.

In Summary

- The primary drive to increase ventilation during exercise probably comes from higher brain centers (central command). Also, humoral chemoreceptors and neural feedback from working muscles act to fine-tune ventilation.
- Controversy exists concerning the mechanism to explain the alinear rise in ventilation (ventilatory threshold) that occurs during an incremental exercise test. However, it appears that the rise in blood H^+ concentration that occurs during this type of exercise provides the principal stimulus to increase ventilation via stimulation of the carotid bodies.

Effect of Training on Ventilation

- **No effect on lung structure and function at rest**
- **Normal lung exceeds demand for gas exchange**
  - Adaptation is not required for the lung to maintain blood-gas homeostasis
- **One exception: Elite endurance athletes**
  - Failure of lung to adapt to training results in hypoxemia

Does the Pulmonary System Limit Exercise Performance?

- **Low-to-moderate intensity exercise**
  - – Pulmonary system not seen as a limitation
- **Maximal exercise**
  - – Historically not thought to be a limitation in healthy individuals at sea level
    - New evidence that respiratory muscle fatigue does occur during high intensity exercise (>90% VO_2 max)
  - – May be limiting in elite endurance athletes
    - 40–50% experience hypoxemia

Research Focus 10.1

Do Nasal Strips Improve Athletic Performance?

- **The purpose of nasal strips**
  - Reduce nostril airway resistance
- **Theoretically, would increase airflow into lungs**
  - No evidence of increased ventilation or performance
- **Potential psychological advantage**

In Summary

- The pulmonary system does not limit exercise performance in healthy young subjects during prolonged submaximal exercise (e.g., work rates <90% VO_2 max).
- In contrast to submaximal exercise, new evidence indicates that the respiratory system (i.e., respiratory muscle fatigue) may be a limiting factor in exercise performance at work rates >90% VO_2 max. Further, incomplete pulmonary gas exchange may occur in some elite athletes and limit exercise performance at high exercise intensities.

Study Questions

1. **What is the primary function of the pulmonary system? What secondary function does it serve?**
2. **List and discuss the major anatomical components of the respiratory system.**
3. **What muscle groups are involved in ventilation during rest? During exercise?**
4. **What is the functional significance of the ventilation-perfusion ratio? How would a high V/Q ratio affect gas exchange in the lung?**
5. **Discuss the factors that influence the rate of diffusion across the blood-gas interface in the lung.**

Study Questions

6. Graph the relationship between hemoglobin-O_2 saturation and the partial pressure of O_2 in the blood. What is the functional significance of the shape of the O_2-hemoglobin dissociation curve? What factors affect the shape of the curve?
7. Discuss the modes of transportation for CO_2 in the blood.
8. Graph the ventilatory response in the transition from rest to constant-load submaximal exercise. What happens to ventilation if the exercise is prolonged and performed in a hot/humid environment? Why?
9. Graph the ventilatory response to incremental exercise. Label the ventilatory threshold. What factor(s) might explain the ventilatory threshold?

Study Questions

10. **List and identify the functions of the chemoreceptors that contribute to the control of breathing.**
11. **What neural afferents might also contribute to the regulation of ventilation during exercise?**
12. **Discuss the control of ventilation during exercise.**