Chapter 23: The Respiratory System

I. The Respiratory System: An Introduction, p. 814

Objectives:
1. Describe the primary functions of the respiratory system.
2. Explain how the delicate respiratory exchange surfaces are protected from pathogens, debris, and other hazards.

- Our cells produce energy for maintenance, growth, defense and division through mechanisms which require oxygen and produce carbon dioxide. We obtain oxygen from the air, which diffuses across delicate exchange surfaces on our lungs. Oxygen is carried to the cells by our cardiovascular system, which also returns carbon dioxide to the lungs.

Functions of the Respiratory System, p. 814

- The respiratory system has 5 basic functions:
  1. Providing an extensive surface area for gas exchange between air and circulating blood.
  2. Moving air to and from the exchange surfaces of the lungs.
  3. Protecting respiratory surfaces from the outside environment.
  4. Producing sounds.
  5. Participating in the olfactory sense.

Organization of the Respiratory System, p. 814

Figure 23-1
- The respiratory system is divided into the upper respiratory system, above the larynx, and the lower respiratory system, from the larynx down.
- The respiratory tract consists of a conducting portion (from the nasal cavity to the terminal bronchioles) and a respiratory portion (the respiratory bronchioles and alveoli).
- Alveoli are the air-filled pockets within the lungs where all gas exchange takes place.

Figure 23-2 The Respiratory Epithelium

- For gases to exchange efficiently, the walls of the alveoli must be very thin, and the surface area must be very great. The distance from the inside of an alveolus to and alveolar capillary is less than 1 micrometer. The surface area within the lungs is about 35 times the surface area of the body.
• The respiratory mucosa, consisting of an epithelial layer and an areolar layer, lines the conducting portion of the respiratory system.

• In the upper respiratory system, trachea and bronchi: The lamina propria, underlying the areolar tissue, contains mucous glands that secrete onto the epithelial surface.

• In the conducting portion of the lower respiratory system: The lamina propria contains smooth muscle cells that encircle the lumen of the bronchioles.

• The structure of the respiratory epithelium changes along the respiratory tract. The exchange surfaces of the alveoli are lined with alveolar epithelium: a very delicate, simple squamous epithelium containing scattered, specialized cells.

• The respiratory defense system consists of a series of filtration mechanisms that remove particles and pathogens:
  - Goblet cells and mucous glands produce mucus that bathes exposed surfaces.
  - Cilia sweep debris trapped in mucus toward the pharynx (mucus escalator).
  - Filtration in the nasal cavity removes large particles.
  - Small particles that reach the lungs can be engulfed by alveolar macrophages.

II. The Upper Respiratory System, p. 817

Objective:
1. Identify the organs of the upper respiratory system and describe their functions.

Figure 23-3 The Upper Respiratory System

The Nose and Nasal Cavity, p. 817

• Air enters the respiratory system through the nostrils or external nares into the nasal vestibule, which contains the first particle filtration system: nasal hairs.

• The nasal septum divides the nasal cavity into left and right.

• Mucous secretions from the paranasal sinus and tears keep the nasal cavity moist and clean. The superior portion of the nasal cavity is the olfactory region which provides the sense of smell.

• Air flows from the vestibule to the internal nares through the superior, middle and inferior meatuses. The meatuses are constricted passageways that produce air turbulence, giving incoming air time to warm and humidify, and particles to be
trapped.

- The hard palate forms the floor of the nasal cavity and separates it from the oral cavity. The soft palate extends posterior to the hard palate, dividing the superior nasopharynx form the rest of the pharynx. The nasal cavity opens into the nasopharynx through the internal nares.

- The nasal mucosa prepares inhaled air for arrival at the lower respiratory organs (warming and humidifying). Breathing through your mouth bypasses this important step.

*The Pharynx, p. 819*

- The pharynx is a chamber shared by the digestive and respiratory systems, extending from the internal nares to the entrances to the larynx and esophagus.

- The pharynx is divided into the nasopharynx, the oropharynx, and the laryngopharynx.

- The nasopharynx is the superior portion of the pharynx. It contains the pharyngeal tonsils and openings to the left and right auditory tubes.

- The oropharynx, the middle portion of the pharynx, communicates with the oral cavity.

- The laryngopharynx, the inferior portion of the pharynx, extends from the hyoid bone to the entrance to the larynx and esophagus.

**III. The Larynx, p. 819**

*Objective:*

1. Describe the structure of the larynx and discuss its role in normal breathing and in production of sound.

- Air from the pharynx enters the larynx, a cartilaginous structure that surrounds the glottis.

*Figure 23-4 Anatomy of the Larynx*

*Cartilages and Ligaments of the Larynx, p. 819*

- Three large, unpaired cartilages form the larynx:
  1. The thyroid cartilage (Adam’s apple):
     i. hyaline cartilage
     ii. forms anterior and lateral walls of larynx
     iii. ligaments attach to hyoid bone, epiglottis, laryngeal cartilages
2. The cricoid cartilage:
   iv. hyaline cartilage
   v. form posterior portion of larynx
   vi. ligaments attach to first tracheal cartilage
   vii. articulates with arytenoid cartilages

3. The epiglottis:
   viii. elastic cartilage
   ix. ligaments attach to thyroid cartilage and hyoid bone

- The thyroid and cricoid cartilages surround and protect the glottis and the entrance to the trachea. During swallowing, the larynx is elevated and the epiglottis folds back over the glottis, preventing entry of food and liquids into the respiratory tract.

- The larynx also contains 3 pairs of smaller hyaline cartilages:
  1. the arytenoid cartilages
  2. the corniculate cartilages
  3. the cuneiform cartilages

**Figure 23-5 The Glottis**

- The corniculate and arytenoid cartilages function in the opening and closing of the glottis and the production of sound.

- The vestibular ligaments and the vocal ligaments extend between the thyroid cartilage and the arytenoid cartilages, and are covered by folds of laryngeal epithelium that project into the glottis. The vestibular ligaments lie within the vestibular folds, which protect the delicate vocal folds.

*Sound Production, p. 821*

- Air passing through the glottis vibrates the vocal folds and produces sound waves. The sound produced is varied by tension on the vocal folds, and on voluntary muscles that position the arytenoid cartilage relative to the thyroid cartilage.

- Sound production at the larynx is called phonation, which along with articulation (modification of sound by other structures) produces speech.

*The Laryngeal Musculature, p. 821*

- The larynx is associated with:
  1. muscles of the neck and pharynx
  2. intrinsic muscles that control the vocal folds or open and close the glottis

**IV. The Trachea and Primary Bronchi, p. 821**
Objective:
1. Discuss the structure of the airways outside the lungs.

The Trachea, p. 821

Figure 23-6 Anatomy of the Trachea

- The trachea or “windpipe” extends from the cricoid cartilage into the mediastinum where it branches into the right and left pulmonary bronchi.
- Beneath the mucosa, the trachea has a submucosa that contains the mucous glands.
- The trachea has 15-20 tracheal cartilages that strengthen and protect the airway. The tracheal cartilages are discontinuous on the posterior side, where the trachea contacts the esophagus. An elastic ligament and the trachealis muscle connect the ends of each tracheal cartilage.

The Primary Bronchi, p. 822

- The right and left primary bronchi are separated by an internal ridge called the carina.
- The right primary bronchus is larger in diameter than the left, and descends at a steeper angle.
- Each primary bronchus travels to a groove (the hilus) along the medial surface of its lung, where pulmonary nerves, blood vessels and lymphatics enter, anchored in a meshwork of connective tissue. This complex, called the root of the lung, is anchored to the mediastinum.

V. The Lungs, p. 824

Objective:
1. Describe the superficial anatomy of the lungs, the structure of a pulmonary lobule, and the functional anatomy of the alveoli.

Figure 27-7 Gross Anatomy of the Lungs

- The left and right lungs are in the left and right pleural cavities. The inferior portion of each lung (the base) rests on the superior surface of the diaphragm.

Lobes and Surfaces of the Lungs, p. 824

- The lungs have lobes separated by deep fissures. The right lung has 3 lobes: the superior, middle and inferior, separated by horizontal and oblique fissures. The
left lung has 2 lobes: superior and inferior, separated by an oblique fissure.

**Figure 23-8** Relationship between Lungs and Heart

- The right lung is wider (displaced upward by the liver), and the left lung longer (displaced leftward by the heart, forming the cardiac notch).

*The Bronchi, 824*

- The primary bronchi and their branches form the bronchial tree. The left and right bronchi are outside the lungs (extrapulmonary bronchi). Branches within the lungs are intrapulmonary bronchi.
- Each primary bronchus branches to form secondary bronchi (lobar bronchi). One secondary bronchus goes to each lobe.

**Figure 23-9** Bronchi and Lobules

- Secondary bronchi branch to form tertiary bronchi (segmental bronchi), each of which supplies air to a single bronchopulmonary segment. The right lung has 10 bronchopulmonary segments, the left lung 8 or 9.
- The walls of the primary, secondary and tertiary bronchi contain progressively less cartilage and more smooth muscle, increasing muscular effects on airway constriction and resistance. Inflammation caused by bronchitis causes constriction and breathing difficulty.

*The Bronchioles, p. 826*

**Figure 23-10**

- Each tertiary bronchus branches into multiple bronchioles, which branch further into the finest conducting branches, the terminal bronchioles. Each tertiary bronchus forms about 6500 tiny terminal bronchioles.
- Bronchioles have no cartilage and are dominated by smooth muscle. The autonomic nervous system regulates the smooth muscle, which controls the diameter of the bronchiole, which controls airflow and resistance in the lungs. Sympathetic activation causes bronchodilation; parasympathetic activation causes bronchoconstriction.
- Bronchoconstriction also occurs in response to histamine release in allergic reactions. Excessive stimulation (asthma) severely restricts airflow.

- **Pulmonary Lobules**
• Fibrous connective tissue partitions from the root of the lung (trabeculae), containing supportive tissues and lymphatic vessels, branch repeatedly to divide lobes into increasingly smaller compartments. The smallest partitions (interlobular septa) divide the lung into pulmonary lobules.

• Each terminal bronchiole delivers air to a single pulmonary lobule, which is supplied by pulmonary arteries and veins. Within the lobule the terminal bronchiole branches to form several respiratory bronchioles, where gas exchange takes place.

Alveolar Ducts and Alveoli, p. 826

Figure 23-11 Alveolar Organization

• Respiratory bronchioles are connected to alveoli along alveolar ducts, which end at alveolar sacs (common chambers connected to many individual alveoli).

• An extensive network of capillaries, surrounded by elastic fibers, is associated with each alveolus.

• The simple squamous alveolar epithelium consists of thin, delicate Type I cells. It is patrolled by alveolar macrophages (dust cells), and contains septal cells (Type II cells) that produce surfactant.

• Surfactant is an oily secretion, containing phospholipids and proteins, that coats the alveolar surfaces and reduces surface tension. If septal cells do not produce enough surfactant, alveoli collapse and respiration is difficult (respiratory distress).

• Gas exchange takes place across the thin respiratory membrane of the alveoli. The respiratory membrane consists of 3 parts:
  1. the squamous epithelial lining of the alveolus
  2. the endothelial cells lining an adjacent capillary
  3. the fused basal laminae between the alveolar and endothelial cells

• Diffusion across the respiratory membrane is very rapid because the distance is small and the gases (oxygen and carbon dioxide) are lipid soluble.

• Inflammation of the lobules of the lung (e.g. pneumonia) causes fluid to leak into the alveoli and compromises the function of the respiratory membrane.

The Blood Supply to the Lungs, p. 829

• The respiratory exchange surfaces receive blood from arteries of the pulmonary circuit. Each lobule receives an arteriole and a venule. A network of capillaries surrounds each alveolus as part of the respiratory membrane. Blood from alveolar
capillaries passes through pulmonary venules and veins, and returns to the left atrium.

• Capillaries supplied by bronchial arteries provide oxygen and nutrients to the tissues of conducting passageways of the lung. Venous blood bypasses the systemic circuit and flows into pulmonary veins.

• Blood pressure in the pulmonary circuit is low (30 mm Hg or less). Pulmonary vessels are easily blocked by blood clots, fat or air bubbles, causing pulmonary embolism.

The Pleural Cavities and Pleural Membranes, p. 829

Figure 23-8

• The 2 pleural cavities are separated by the mediastinum. Each lung occupies a pleural cavity lined with a serous membrane (the pleura). The pleura consists of 2 layers: the parietal pleura and the visceral pleura, lubricated by pleural fluid.

VI. An Overview of Respiratory Physiology, p. 830

Objectives:
1. Define and compare the processes of external respiration and internal respiration.
2. Describe the major steps involved in external respiration.

• The term respiration refers to 2 integrated processes: external respiration, including all processes involved in exchanging O2 and CO2 with the environment; and internal respiration, the uptake of O2 and production of CO2 by individual cells or cellular respiration.

• External respiration involves 3 processes:
  1. pulmonary ventilation or breathing
  2. gas diffusion across membranes and capillaries
  3. transport of oxygen and carbon dioxide between alveolar capillaries and capillary beds in other tissues

VII. Pulmonary Ventilation, p. 830

Objectives:
1. Summarize the physical principles governing the movement of air into the lungs.
2. Describe the origins and actions of the respiratory muscles responsible for respiratory movements.

• Pulmonary ventilation is the physical movement of air in and out of the respiratory tract, providing alveolar ventilation.
The weight of air, or atmospheric pressure, has several important physiological effects:

- **Boyle’s Law** defines the relationship between gas pressure and volume. In a gas, the molecules can be forced closer together by increasing pressure. In turn, the movement of gas molecules exerts pressure on their surroundings. The more molecules of gas there are in a given space, the greater pressure they exert on their container. This relationship is noted as $P = \frac{1}{V}$.

**Figure 23-14** Mechanisms of Pulmonary Ventilation

- Air flows from an area of higher pressure to an area of lower pressure.

- A single respiratory cycle consists of an inspiration or inhalation, and an expiration or exhalation, causing volume changes that create changes in pressure. The volume of the thoracic cavity changes with expansion or contraction of either the diaphragm or the rib cage.

- The **compliance** of the lungs is an indicator of their expandability. Low compliance requires greater force, high compliance requires less force.

- Several factors affect compliance:
  1. The connective tissue structure of the lungs
  2. The level of surfactant production
  3. The mobility of the thoracic cage

**Pressure Changes During Inhalation and Exhalation, p. 833**

- Gas pressure can be measured inside and outside the lungs.

**Table 23-1** lists the 4 most common methods of reporting gas pressure.

- Normal atmospheric pressure (1 atmosphere) at sea level is 760 mm Hg.

**Figure 23-15** Pressure and Volume Changes with Inhalation and Exhalation

- Intrapulmonary pressure (intra-alveolar pressure) is relative to atmospheric pressure. In relaxed, quiet breathing, the difference between atmospheric pressure and intrapulmonary pressure is small, about -1 mm Hg on inhalation, or +1 mm Hg on expiration. Straining to the maximum (a dangerous activity) can increase the range from -30 mm Hg to +100 mm Hg.
• **Intrapleural pressure** is the pressure in the space between the parietal and visceral pleura: averaging about -4 mm Hg, with a maximum of -18 mm Hg. Intrapleural pressure remains below atmospheric pressure throughout the respiratory cycle.

• Cyclical changes in intrapleural pressure operate the respiratory pump which aids in venous return to the heart.

• The amount of air moved in and out of the lungs in a single respiratory cycle is called **tidal volume**.

• An injury to the chest wall that allows air into the pleural cavity is called **pneumothorax**, which can result in a collapsed lung or **atelectasis**.

*The Mechanics of Breathing, p. 835*

**Figure 23-16** The Respiratory Muscles

• The most important skeletal muscles involved in respiratory movements are the diaphragm and the external intracostal muscles (of the ribs). Accessory respiratory muscles become active when respiration increases significantly.

• **Inhalation** involves the following muscles:
  1. The **diaphragm** contraction draws air into the lungs (75% of air movement).
  2. The **external intracostal muscles** assist inhalation (25% of air movement).
  3. The **accessory muscles** assist in elevating the ribs:
      - sternocleidomastoid
      - serratus anterior
      - pectoralis minor
      - scalene muscles

• **Exhalation** is largely passive; active exhalation involves the following muscles:
  1. **Internal intercostal and transversus thoracis** muscles depress the ribs.
  2. **Abdominal muscles** compress the abdomen and force the diaphragm upward.

- **Modes of Breathing**

• Respiratory movements are classified as **quiet breathing** or **forced breathing**, depending in the pattern of muscle activity:

• **Quiet breathing (eupnea)** involves active inhalation and passive exhalation:
  - diaphragmatic breathing or deep breathing is dominated by the diaphragm
  - costal breathing or shallow breathing is dominated by ribcage movements

• When inhalation muscles relax, elastic components of the muscles and lungs
recoil, returning structures to their original positions (elastic rebound).

- **Forced breathing** or hyperpnea involves active inhalation and exhalation, assisted by accessory muscles. Maximum levels of forced breathing occur in exhaustion.

*Respiratory Rates and Volumes, p. 837*

- The respiratory system adapts to changing oxygen demands by varying the number of breaths per minute (respiratory rate) and the volume of air moved per breath (tidal volume).

- The amount of air moved per minute (the respiratory minute volume) is calculated by multiplying the respiratory rate times the tidal volume.

- The respiratory minute volume measures pulmonary ventilation, but only a part of that air reaches the alveolar exchange surfaces. The volume of air that remains in the conducting passages is called the anatomic dead space.

- Alveolar ventilation is the amount of air reaching the alveoli each minute, which is calculated as the difference between tidal volume and anatomic dead space, multiplied by the respiratory rate.

- The air that reaches the alveoli (average 4.2 liters per minute) contains less oxygen and more carbon dioxide than atmospheric air, because it is mixed with exhaled air.

- Together, the respiratory rate and tidal volume determine the alveolar ventilation rate:
  - For a given respiratory rate, increasing tidal volume increases the alveolar ventilation rate.
  - For a given tidal volume, increasing the respiratory rate increases the alveolar ventilation.

*Figure 23-17* Respiratory Volumes and Capacities

- We can divide the total volume of the lungs into a series of volumes and capacities useful in diagnosis.

- Pulmonary volumes include:
  1. resting tidal volume in a normal respiratory cycle
  2. expiratory reserve volume (ERV) after a normal exhalation
  3. residual volume after maximal exhalation
     - minimal volume (in a collapsed lung)
  4. inspiratory reserve volume (IRV) after a normal inspiration
• Calculated **respiratory capacities** include:
  1. **inspiratory capacity** = tidal volume + inspiratory reserve volume
  2. **functional residual capacity (FRC)** = expiratory reserve volume + residual volume
  3. **vital capacity** = expiratory reserve volume + tidal volume + inspiratory reserve volume
  4. **total lung capacity** = vital capacity + residual volume

• **Pulmonary function tests** measure rates and volumes of air movements.

**VIII. Gas Exchange, p. 839**

**Objectives:**
1. Summarize the physical principles governing the diffusion of gases into and out of the blood.
2. Explain the important structural features of the respiratory membrane.
3. Describe the partial pressure of oxygen and carbon dioxide in alveolar air, blood, and the systemic circuit.

• The actual process of gas exchange occurs between blood and alveolar air across the respiratory membrane. This process depends on:
  1. the **partial pressures** of the gases, and
  2. the **diffusion** of molecules between a gas and liquid

**The Gas Laws, p. 839**

• Diffusion occurs in response to **concentration gradients**. The rate of diffusion depends on physical principles known as **gas laws** (including Boyle’s law).

**Diffusion and Respiratory Function, p. 840**

• Air is a mixture of gases. The most important are:
  - nitrogen (N2) about 78.6%
  - oxygen (O2) about 20.9%
  - water vapor about 0.5%
  - carbon dioxide (CO2) about 0.04%

• Atmospheric pressure (760 mm Hg) is produced by the air molecules bumping into each other. Each gas contributes to the total pressure in proportion to its number of molecules (Dalton’s law). The **partial pressure** is the pressure contributed by a single gas. All the partial pressures together add up to 760 mm Hg.

*Table 23-2 Partial Pressures*
Henry’s Law

- Henry’s law states that, at a given temperature, the amount of a particular gas in solution is directly proportional to the partial pressure of that gas. When a gas under pressure comes in contact with a liquid, the gas tends to dissolve in the liquid until equilibrium is reached.

- The actual amount of a gas in a solution (gas content) at a given partial pressure and temperature depends on the solubility of that gas in that particular liquid. In body fluids, CO2 is very soluble, O2 less soluble, and N2 has very low solubility.

- Normal partial pressures in plasma in a pulmonary vein:
  - PCO2 = 40 mm Hg
  - PO2 = 100 mm Hg
  - PN2 = 573 mm Hg

**Diffusion and Respiratory Function**

- Different partial pressure and solubilities determine the direction and rate of diffusion of gases across the respiratory membrane. Alveoli contain more carbon dioxide and less oxygen than atmospheric air.

- Gas exchange at the respiratory membrane is efficient because:
  1. The differences in partial pressure across the respiratory membrane are substantial.
  2. The distances involved in gas exchange are small.
  3. The gases are lipid soluble.
  4. The total surface area is large.
  5. Blood flow and air flow are coordinated.

**Respiratory Processes and Partial Pressure**

- Blood arriving in pulmonary arteries has a low PO2 and a high PCO2 compared to air. O2 enters the blood and CO2 leaves it by the concentration gradient. The exchange is rapid and allows blood to reach equilibrium with the alveolar air.

- The oxygenated blood mixes with unoxygenated blood from conducting passageways, lowering PO2 of blood entering the systemic circuit to about 95 mm Hg.

- Interstitial fluid normally has a PO2 of about 40 mm Hg and a PCO2 of about 45 mm Hg, so the concentration gradient in capillaries of peripheral tissues is in the opposite direction from the lungs: CO2 diffuses out of the tissues, and into the blood; O2 diffuses out of the blood, into the tissues.
IX. Gas Pickup and Delivery, p. 842

Objectives:
1. Describe how oxygen is picked up, transported, and released in the blood.
2. Discuss the structure and function of hemoglobin.
3. Describe how carbon dioxide is transported in the blood.

- Blood plasma can’t transport enough oxygen or carbon dioxide to meet physiological needs. This function is served by red blood cells (RBCs). Because RBCs remove O2 and CO2 from plasma, gases continue to diffuse into the blood.

Oxygen Transport, p. 842

- Oxygen molecules bind to the iron ions in hemoglobin (Hb) molecules, in a reversible reaction. Each RBC has about 280 million hemoglobin molecules, each of which can bind 4 oxygen molecules. The percentage of heme units containing bound oxygen is called hemoglobin saturation.

- The most important environmental factors affecting hemoglobin are:
  1. the PO2 of blood
  2. blood pH
  3. temperature
  4. metabolic activity within RBCs

Figure 23-20 An Oxyhemoglobin Saturation Curve

- An oxyhemoglobin saturation curve is a graph that relates the saturation of hemoglobin to the partial pressure of oxygen. The higher the PO2, the greater the hemoglobin saturation. The relationship is a curve rather than a straight line because the hemoglobin molecule changes shape each time a molecule of oxygen is bound, making each successive oxygen molecule easier to bind. This allows hemoglobin to bind oxygen even when alveolar oxygen levels are low.

- When oxygenated blood arrives in the peripheral capillaries, O2 diffuses into the interstitial fluid, which has a low PO2. The amount of O2 released depends on how low the interstitial PO2 is. Up to 3/4 may be retained by the RBCs as reserves.

- Carbon monoxide (CO) from burning fuels binds strongly to hemoglobin, taking the place of O2, and can result in carbon monoxide poisoning.

Figure 23-21 pH, Temperature and Hemoglobin Saturation

- The oxyhemoglobin saturation curve is standardized for normal blood with a pH of 7.4 and temperature of 37 degrees C. When pH drops, or temperature rises, more oxygen is released, shifting the curve to the right. When pH rises, or
temperature drops, less oxygen is released, shifting the curve to the left.

- The effect of pH on hemoglobin saturation is called the Bohr effect. Carbon dioxide is the primary cause of this effect. When CO2 diffuses into an RBC, an enzyme (carbonic anhydrase) catalyzes a reaction with H2O that produces carbonic acid (H2CO3), a molecule that dissociates into a hydrogen ion (H+) and a bicarbonate ion (HCO3-). The hydrogen ions diffuse out of the RBC and lower the pH.

- Temperature effects are generally significant only in active tissues that are generating a lot of heat.

- RBCs have no mitochondria; they generate ATP only by glycolysis, in which lactic acid and 2,3-biphosphoglycerate (BPG) are formed. BPG has a direct effect on oxygen binding and release: the more BPG, the more oxygen is released. BPG levels rise when pH increases, or when stimulated by certain hormones. If BPG levels are too low, hemoglobin will not release oxygen.

**Figure 23-22** Fetal and Adult Hemoglobin

- The structure of fetal hemoglobin differs from that of adult hemoglobin. At the same PO2, fetal hemoglobin binds more oxygen than adult hemoglobin, which allows the fetus to take oxygen from maternal blood.

**Key**

- Hemoglobin within RBCs carries most of the oxygen in the bloodstream, and it releases O2 in response to changes in the oxygen partial pressure in the surrounding plasma.
- If the PO2 increases, hemoglobin binds oxygen; if the PO2 decreases, hemoglobin releases oxygen.
- At a given PO2, hemoglobin will release additional oxygen if the pH decreases or the temperature increases.

*Carbon Dioxide Transport, p. 845*

**Figure 23-23**

- Carbon dioxide (CO2) is generated as a byproduct of aerobic metabolism (cellular respiration) in peripheral tissues. After entering the bloodstream, a CO2 molecule is either:
  1. converted to carbonic acid
  2. bound to the protein portion of hemoglobin, or
  3. dissolved in plasma
• Most (70%) of the carbon dioxide in blood is transported as carbonic acid (H2CO3) which dissociates into H+ and bicarbonate (HCO3-). The bicarbonate ions are moved into the plasma by an exchange mechanism (called the chloride shift) that takes in Cl- ions without using ATP.

• 23% of the carbon dioxide in blood is bound to the amino groups of globular proteins of the Hb molecule, forming carbaminohemoglobin.

• The remainder of the carbon dioxide (about 7%) is transported as CO2 dissolved in plasma.

Key
• Carbon dioxide travels in the bloodstream primarily as bicarbonate ions, which form through dissociation of the carbonic acid produced by carbonic anhydrase inside RBCs.
• Lesser amounts of CO2 are bound to hemoglobin or dissolved in plasma.

Summary: Gas Transport, p. 846

Figure 23-24 summarizes oxygen and carbon dioxide transport mechanisms.

X. Control of Respiration, p. 847

Objectives:
1. Describe the factors that influence the respiration rate.
2. Identify and discuss the reflex respiratory activity and the brain centers involved in the control of respiration.

• Normally, diffusion of gases at the peripheral and alveolar capillaries are balanced, maintaining homeostasis. The body maintains this equilibrium by:
  1. changes in blood flow and oxygen delivery
  2. changes in depth and rate of respiration

Local Regulation of Gas Transport and Alveolar Function, p. 848

• The rate of oxygen delivery in each tissue and the efficiency of oxygen pickup at the lungs are largely regulated at the local level:
  1. Rising PCO2 levels cause relaxation of smooth muscle in arterioles and capillaries, increasing blood flow
  2. Coordination of lung perfusion and alveolar ventilation, shifting blood flow.
  3. PCO2 levels control bronchoconstriction and bronchodilation.

- IP: Respiratory System/Gas Exchange

The Respiratory Centers of the Brain, p. 848
• When oxygen demand rises, cardiac output and respiratory rates increase under neural control.

• The respiratory centers of the brain have both voluntary and involuntary components: Involuntary centers regulate respiratory muscles in response to sensory information. Voluntary control in the cerebral cortex affects the respiratory centers of the pons and medulla oblongata, or the motor neurons that control respiratory muscles.

• The respiratory centers are 3 pairs of nuclei in the reticular formation of the medulla oblongata and pons.

• The respiratory rhythmicity centers of the medulla oblongata set the pace of respiration. Each center can be divided into:
  1. a dorsal respiratory group (DRG):
     - inspiratory center
     - functions in quiet and forced breathing
  2. a ventral respiratory group (VRG):
     - inspiratory and expiratory center
     - functions only in forced breathing

Figure 23-24a
• During quiet breathing:
  - Brief activity in the DRG stimulates inspiratory muscles
  - DRG neurons become inactive, allowing passive exhalation

Figure 23-24b
• During forced breathing:
  - Increased activity in DRG stimulates VRG, which activates accessory inspiratory muscles.
  - After inhalation, neurons of expiratory center stimulate active exhalation

• The apneustic and pneumotaxic centers of the pons are paired nuclei that adjust the output of the respiratory rhythmicity centers, regulating the respiratory rate and depth of respiration. Each apneustic center provides continuous stimulation to its DRG center. The pneumotaxic centers inhibit the apneustic centers and promote passive or active exhalation.

Figure 23-26 Respiratory Centers and Reflex Controls

• Interactions between the VRG and DRG establish the basic pace and depth of respiration. The pneumotaxic center modifies the pace.

• SIDS (sudden infant death syndrome) may result from a problem with connections between the pacemaker complex and respiratory centers that disrupts
the normal respiratory reflex pattern.

Respiratory Reflexes, p. 850

- The activities of the respiratory centers are modified by sensory information from:
  1. Chemoreceptors sensitive to the PCO2, PO2, or pH of blood or cerebrospinal fluid.
  2. Baroreceptors in the aortic or carotic sinuses sensitive to changes in blood pressure.
  3. Stretch receptors that respond to changes in the volume of the lungs.
  4. Irritating physical or chemical stimuli in the nasal cavity, larynx or bronchial tree.
  5. Other sensations including pain, changes in body temperature, and abnormal visceral sensations.

- Changes in patterns of respiration induced by these sensations are called respiratory reflexes.

-The Chemoreceptor Reflexes

- The respiratory centers are strongly influenced by chemoreceptor input from:
  1. Cranial nerve IX (the glossopharyngeal nerve)
     - from carotid bodies
     - stimulated by changes in blood pH or PO2
  2. Cranial nerve X (the vagus nerve):
     - from aortic bodies
     - stimulated by changes in blood pH or PO2
  3. Receptors that monitor cerebrospinal fluid:
     - on ventrolateral surface of medulla oblongata
     - respond to PCO2 and pH of CSF

- Stimulation of chemoreceptors leads to increased depth and rate of respiration.

- Chemoreceptors are subject to adaptation (a decrease in sensitivity due to chronic stimulation).

Figure 23-27 Chemoreceptor Responses to Changes in PCO2

- Hypercapnia is an increase in the PCO2 of arterial blood, which stimulates chemoreceptors in the medulla oblongata to restore homeostasis. The most common cause of hypercapnia is hypoventilation, an abnormally low respiration rate that allows CO2 to build up in the blood.

- Excessive ventilation (hyperventilation) results in abnormally low PCO2 or hypocapnia, which stimulates chemoreceptors to decrease the respiratory rate and restore homeostasis.
The Baroreceptor Reflexes

- Carotid and aortic baroreceptor stimulation affect blood pressure (Chapter 21) and the respiratory centers. When blood pressure falls, respiration increases; when blood pressure increases, the respiratory rate falls.

- There are 2 baroreceptor reflexes involved only in forced breathing (the Hering-Breuer reflexes):
  1. The inflation reflex prevents overexpansion of the lungs during forced breathing
  2. The deflation reflex inhibits the expiratory centers and stimulates the inspiratory centers when the lungs are deflating.

- When the lungs are exposed to toxic vapors, chemicals irritants or mechanical stimulation, receptors in the epithelium of the respiratory tract trigger protective reflexes such as sneezing, coughing and laryngeal spasm.

- Sneezing and coughing involve apnea (a period in which respiration is suspended), followed by an explosive exhalation to clear the air passageways.

- Laryngeal spasm temporarily closes the airway to prevent foreign substances from entering.

Voluntary Control of Respiration, p. 852

- The cerebral cortex can indirectly affect the respiratory centers:
  1. Strong emotions can stimulate respiratory centers in the hypothalamus.
  2. Emotional stress can activate sympathetic or parasympathetic division of the ANS, causing bronchodilation or bronchoconstriction.
  3. Anticipation of strenuous exercise can increase respiratory rate and cardiac output by sympathetic stimulation.

Key

- A basic pace of respiration is established by the interplay between respiratory centers in the pons and medulla oblongata.
- That pace is modified in response to input from chemoreceptors, baroreceptors, and stretch receptors.
- In general, carbon dioxide levels, rather than oxygen levels, are the primary drivers of respiratory activity.
- Respiratory activity can also be interrupted by protective reflexes and adjusted by the conscious control of respiratory muscles.

XI. Changes in the Respiratory System at Birth, p. 853

- The respiratory systems of fetuses and newborns differ significantly:
1. Before birth, pulmonary vessels are collapsed, and the lungs contain no air.
2. During delivery, the placental connection is lost:
   - blood PO2 falls, PCO2 rises
3. At birth, the newborn must overcome the force of surface tension to inflate the bronchial tree and alveoli and take its first breath.
4. The large drop in pressure required to take the first breath also pulls blood into the pulmonary circulation, closing the foramen ovale and the ductus arteriosus.
   - fetal blood circulation patterns are redirected
5. Subsequent breaths fully inflate the alveoli.

XII. Aging and the Respiratory System, p. 853

**Figure 23-28** Respiratory Performance and Age

- Many factors reduce the efficiency of the respiratory system with age:
  1. Elastic tissue deteriorate, reducing lung compliance and lowering vital capacity.
  2. Arthritic changes restrict chest movements, limiting respiratory minute volume.
  3. Emphysema affects individuals over the age of 50, depending on exposure to respiratory irritants such as cigarette smoke.

XIII. Integration with Other Systems, p. 854

- The maintenance of homeostatic O2 and CO2 levels in peripheral tissues requires coordination between several systems. The respiratory and cardiovascular systems work together to:
  1. Improve the efficiency of gas exchange by controlling lung perfusion.
  2. Increase respiratory drive through chemoreceptor stimulation.
  3. Raise cardiac output and blood flow through baroreceptor stimulation.

- The respiratory system is linked to all other systems as well:

**Figure 23-29** Relationships between the Respiratory System and Other Systems

SUMMARY

In chapter 23 we learned about:
- The 5 functions of the respiratory system
  - gas exchange between air and circulating blood
  - moving air to and from exchange surfaces
  - protection of respiratory surfaces
  - sound production
- facilitating olfaction
- The structures and functions of the respiratory tract
  - alveoli
  - respiratory mucosa
  - lamina propria
  - the respiratory defense system
- The structures and functions of the upper respiratory system
  - the nose and nasal cavity
  - the pharynx
- The structures and functions of the larynx:
  - cartilages and ligaments
  - sound production
  - the laryngeal musculature
- The structures and functions of the trachea and primary bronchi
- The structures and functions of the lungs:
  - lobes and surfaces
  - the bronchi
  - the bronchioles
  - alveoli and alveolar ducts
  - blood supply to the lungs
  - pleural cavities and membranes
- Respiratory physiology
  - external respiration
  - internal respiration
- Pulmonary ventilation
  - air movement
  - pressure changes
  - the mechanics of breathing
  - respiratory rates and volumes
- Gas exchange
  - the gas laws
  - diffusion and respiration
- Gas pickup and delivery
  - partial pressure
  - oxygen transport (RBCs and hemoglobin)
  - carbon dioxide transport
- Control of respiration
  - local regulation (lung perfusion, alveolar ventilation)
  - respiratory centers of the brain
  - respiratory reflexes
  - voluntary control of respiration
- Changes in the respiratory system at birth
- Aging and the respiratory system