It is a clear, crisp fall morning. The leaves are turning, and the air carries a hint of the chill to come. Many of the leaves have already fallen, and the last flowers of the season are in bloom. For Marie’s friends, the heat of the summer is past, and this is a time of energy and exuberance. But for Marie, it is a season fraught with threats because her very survival is in danger. The air is filled with mold spores, leaf dust, and tiny fragments of dead plants. For her, those piles of leaves are simply huge colonies of mold and heaps of dust that make breathing, the essential act of life, difficult. Most people don’t give a second thought to breathing, but not Marie, not in mold season. She has so little energy that she must stop to rest on a flight of stairs. Oxygen is so scarce in her blood that her lips and even her fingernails sometimes turn blue.

Marie is an asthmatic. Her lungs respond to mold and airborne dust with an inflammatory reaction that threatens her very survival during allergy season. Every minute, humans must transport oxygen to their cells and remove the carbon dioxide produced by cellular respiration. Human life depends on the integrated functioning of the cardiovascular and respiratory systems because neither system, by itself, can supply what we need to survive. And for Marie and millions of other asthmatics, this gas exchange process cannot be taken for granted. But to understand how asthma and other diseases affect the respiratory system, we must first get a grasp of the intricate anatomy and physiology of the airways and lungs.
The Respiratory System Provides Us With Essential Gas Exchange as Well as Vocalization

**LEARNING OBJECTIVES**

- Explore the overall function of the respiratory system.
- Identify the structures of the upper and lower respiratory tracts.
- Differentiate the conducting zone from the respiratory zone.
- Discuss the anatomy and physiology of the alveolar sac.

Thus far in our treatment of survival, we have talked about protecting ourselves from the environment, moving through the environment, and sensing and reacting to external and internal changes. We have explored how the cardiovascular system (Chapter 11) moves nutrients, gases, and waste through the body. But the cardiovascular system must cooperate with the respiratory system, which brings oxygen into the body and expels carbon dioxide. The respiratory system also filters incoming air, maintains blood pH, helps control fluid and thermal homeostasis, and produces sound. Otherwise, speech (and therefore biology lectures!) would be impossible.

The respiratory system has two anatomical divisions, the upper respiratory tract and the lower respiratory tract, with separate but related functions (Figure 12.1). The upper tract conditions air as it enters the body, and the lower respiratory tract allows oxygen to enter the blood, and waste gases to leave it.

**THE UPPER RESPIRATORY TRACT HAS AN INSPIRING ROLE**

The structures of the upper respiratory tract—the nose, pharynx, and larynx—warm, moisten, and filter the incoming air (Figure 12.2). The nose is one of the first body parts that small children can identify. We are familiar with the external portion of the nose, consisting of the nasal bone and hyaline cartilage, covered by skin and muscle. The division between the two nostrils, or external nares, is a plate of hyaline cartilage called the septum. The septum is attached to the vomer bone at its base. Both the septum and the cartilages that make up the sides of the nose...
serve to support the nasal openings. If a blow to the nose moves these cartilages to the side of the vomer, airflow is blocked. To treat this “deviated septum,” surgeons restore the septum into position and open both nasal passageways. Surgery on the nose (called rhinoplasty) can also be done for cosmetic reasons, usually by breaking the nasal bone and reshaping the nasal cartilages.

As mentioned, the nasal cavity warms, filters, and moistens incoming air, and does so far better than the mucous membranes of the mouth. Smells and ridges in the nasal cavity slow the air. As inhaled air moves through this convoluted space, it contacts the nasal epithelium. The epithelium in the upper respiratory tract is pseudostratiﬁed ciliated columnar epithelium. In the nasal region, this tissue is covered in mucus and constantly washed by tears draining from the eyes.

A large blood supply warms the nasal epithelium, and both the warmth and moisture are transferred to the inhaled air (Figure 12.3). If you have ever bumped your nose, you know of this large blood supply. Most of us have had a bloody nose at least once, and have been surprised by the remarkable quantity of blood that seems to leak out.

Filtering is a vital function of the nose because inhaled particles would seriously inhibit airflow in the lower respiratory tract. Coarse hairs in the nostrils filter out larger particles, and the mucus of the nasal passages further ﬁlters incoming air by trapping small particles. A ﬁnal function of the nasal epithelium is the sense of smell (as described in Chapter 8). To smell something more clearly, we often take deep breaths to ensure that airborne compounds reach the patch of sensory neurons.

The internal nares, the twin openings at the back of the nasal passageway, lead to the nasopharynx, or upper throat (Figure 12.4). The passageway between the nose and throat is normally open for breathing, but it must close when we swallow. The uvula, a ﬂeshy tab of tissue that hangs down in the back of the throat, contracts when touched by solids, moving upward and closing the internal nares. When your doctor asks you to say “Ahh” during a throat examination, you contract the uvula and move it up to allow the doctor to see the nasopharynx and the tonsils on the posterior wall of the pharynx. If you laugh or cough while drinking, the uvula may spasm, and liquids may leak past it. These liquids may be forced out the external nares, causing a burning sensation as they travel the nasal passages—and some slight embarrassment.

The eustachian, or auditory, tubes link the nasopharynx and the middle ear. When your ears “pop,” these tubes are opening to equalize air pressure between the middle and outer ear.

The oropharynx, the area directly behind the tongue, is covered by the uvula when it hangs down. This portion of the throat is devoted to activities of the mouth. Food and drink pass through the oropharynx with each swallow, so the mucous membrane and epithelium lining this region are usually thicker and more durable than elsewhere in the pharynx. The palatine and lingual tonsils are found in the oropharynx as well.

The lowest level of the pharynx, called the laryngopharynx, is the last part of the respiratory tract shared by the digestive and respiratory systems. The end of the laryngopharynx has two openings. The anterior opening leads to the larynx and the rest of the respiratory system. The posterior opening leads to the esophagus and the digestive system.

The larynx divides the upper and lower respiratory tracts. This structure, composed entirely of cartilage, holds the respiratory tract open, guards the lower tract against particulate matter, and produces the sounds of speech. The larynx is composed of nine pieces of hyaline cartilage: three single structures and three paired structures. The single pieces are the thyroid cartilage, the epiglottis, and the cricoid cartilage (Figure 12.5).
The Respiratory System Provides Us With Essential Gas Exchange as Well as Vocalization

CHAPTER 12

The Respiratory System: Movement of Air

Anterior view Posterior view

Epiglottis

Hyoid bone

Corniculate cartilage

Thyroid cartilage

(Adam’s apple)

Arytenoid cartilage

Cricoid cartilage

Thyroid gland

Tracheal cartilage

Larynx

Figure 12.5

Superior view of cartilages and muscles

A Movement of vocal folds apart (abduction)

B View through a laryngoscope

Vocal cords

A pair of cartilaginous cords stretched across the laryngeal opening that produce the tone and pitch of the voice.

Vocal folds

The closure by causing the epiglottis to rest against the top of the larynx. You can feel this movement by touching your “Adam’s apple” and swallowing. You will feel the entire larynx move up with your tongue.

The cricoid cartilage is the only complete ring of cartilage in the respiratory system. It is narrow in front but thick in the back of the larynx. The cricoid cartilage holds the respiratory system open. If it is crushed, airflow is impeded and breathing becomes nearly impossible. In an emergency, it may be necessary to surgically open the airway below a crushed cricoid cartilage.

The larynx is called the “voice box” because it is the location of the vocal cords (Figure 12.6). These are folds, covered by mucus membrane, and held in place by elastic ligaments stretched across the glottis. These folds vibrate as air moves past them, producing sound. High-pitched sounds occur when tension on the vocal folds increases, and low-pitched sounds occur when the tension is reduced. We unconsciously adjust tension on the vocal folds by moving the paired laryngeal cartilages. The arytenoid and cuneiform cartilages both pull on the vocal folds to alter pitch. The amplitude, or amount the cords are vibrating, determines sound volume.

As boys reach puberty and their testes produce more testosterone, their voices change. Testosterone stimulates the growth of cartilage in the larynx, altering the thickness of the vocal folds. Boys train their voices through daily use to adjust their vocal fold tension based on the size of the larynx. As the larynx grows, the tension needed to produce the same sounds changes. In effect, the male must retrain his voice to maintain vocal tone. When the larynx is growing quickly, the male voice will often “crack” or “squeak” due to his inability to adjust the tension on his changing vocal folds.

The lower respiratory tract routes air to the lungs. The main function of the lower tract is to move inhaled air to the respiratory membrane. Physiologically, the upper tract and the first portion of the lower tract make up the conducting zone of the respiratory system, which conducts air from the atmosphere to the respiratory zone deeper in the body, where the actual exchange of gases takes place (Figure 12.7).
The conducting zone includes all the structures of the upper respiratory tract, as well as the trachea, bronchi, bronchioles, and terminal bronchioles. The respiratory zone lies deep within the lungs, and includes only the respiratory bronchioles and the alveoli.

The trachea connects the larynx to the bronchi. Beyond the larynx, air enters the trachea, a 12-centimeter-long tube extending from the base of the larynx to the fifth thoracic vertebra (Figure 12.8). The trachea is approximately 2.5 centimeters in diameter, and is composed of muscular walls embedded with 16 to 20 “C”-shaped rings of hyaline cartilage. (Remember that the cricoid cartilage of the larynx is the only complete ring of cartilage in the respiratory system.) The opening of each “C” is oriented toward the back. You can easily feel the tracheal rings through the skin of your throat, immediately below your larynx.

These cartilage “C” rings support the trachea so that it does not collapse during breathing, while also allowing the esophagus to expand during swallowing. When you swallow a large mouthful of food, the esophagus pushes into the lumen of the trachea following. When you swallow a large mouthful of food, the esophagus pushes into the lumen of the trachea. This is called a tracheoesophagus. Another way to restore breathing is called intubation—the insertion of a tube through the mouth or nose, through the larynx and into the trachea. The tube pushes obstructions aside and/or helps suction them out.

At the level of the fifth thoracic vertebra, the trachea splits into two tubes called the primary bronchi, which lead to each lung. Despite their common function, the two bronchi are slightly different. The right primary bronchus is shorter, wider, and more vertical than the left. For this reason, inhaled objects often get lodged in the right primary bronchus. These two bronchi are constructed very much like the trachea and are held open with incomplete rings of cartilage in their walls. At the lower base of the trachea is an extremely sensitive area called the carina. The mucus membrane of the carina is more sensitive to touch than any other area of the larynx or trachea, so this spot triggers a dramatic cough reflex when any solid object touches it.

Once inside the lungs, the primary bronchi divide into the secondary bronchi (see Figure 12.7). The right bronchus divides into three secondary bronchi, whereas the left splits into two. This branching pattern continues like the branches of a tree, getting smaller and smaller as the tubes extend farther from the primary bronchi. The sequentially smaller tubes are called tertiary bronchi, bronchioles, terminal bronchioles, and respiratory bronchioles. The respiratory system looks like an upside-down tree, with the base at the nasal passages and the tiniest branches leading to the “leaves” deep within the lungs. The bronchial tree undergoes two major changes as it reaches deeper into the body:

1. The cells of the mucus membrane get smaller. The epithelium of the upper and beginning portion of the lower respiratory tract is pseudostratified ciliated columnar epithelium; these fairly large cells secrete mucus, while the cilia sweep the mucus upward and outward to remove dust and inhaled particles. The epithelium changes to the slightly thinner, ciliated columnar epithelium in the larger bronchioles. The smaller bronchioles are lined with smaller ciliated cuboidal epithelium. Terminal bronchioles have no cilia and are lined with simple columnar epithelium. If dust reaches all the way to the terminal bronchioles, it can be removed only by macrophages of the immune system.
2. The composition of the walls of the bronchi and bronchioles changes. Smaller tubes need less cartilage to hold them open, so the incomplete rings of cartilage supporting the bronchi are gradually replaced by plates of cartilage in the bronchioles. These plates diminish in the smaller bronchioles, until the walls of the terminal bronchioles have virtually no cartilage. As cartilage decreases, the percentage of smooth muscle increases. Without cartilage, these small tubes can...
be completely shut by contraction of this smooth muscle. In asthma and other constric- tive respiratory disorders, this smooth muscle becomes irritated and tightens, reducing the tube diameter, sometimes even effectively clos- ing it.

Epinephrine, a hormone that is released into the bloodstream when we exercise or feel fright, relaxes smooth muscle. In the lungs, epi- nephrine relaxes the smooth muscle of the termi- nal bronchioles, increasing the diameter of the lumen and allowing greater airflow. This in turn increases the oxygen content of the blood and allows the muscles to work more efficiently. Someone you know who has asthma probably carries an “inhaler” filled with “rescue med- ication.” If you get a look at the label, the active ingredient is probably epineph- rine, norepinephrine, or a derivative. Spraying these drugs on the walls of the bronchioles immediately relaxes the smooth muscle, dramatically increasing tubule diameter.

The thoracic cavity houses the two organs of respiration, the lungs (Figure 12.9). These light- weight organs extend from just above the clavicle to the twelfth thoracic vertebra and fill the rib cage. The base of the lungs is the broad portion sitting on the di-aphragm. The apex is the small point extending above the clavicles. Although the lungs are paired, they are not identical. The right lung is shorter and fatter, and it has three lobes, whereas the left lung has only two lobes. The left lung is thinner and has a depression for the heart, called the cardiac notch, on the medial side. The central portion of the thoracic cavity is called the medi- astinum; therefore, the medial portion of the lungs is

Hilum Site of entry and exit for the nerves, blood vessels, and lymphatic vessels on most organs.

The pleura wraps the lungs The lungs are cov- ered in a serous membrane called the pleura that al- lows the lungs to expand and contract without tear- ing the delicate respiratory tissues (Figure 12.10). The pleura is anatomically similar to the pericardium around the heart in that they are com- posed of two membranous layers separated by serous fluid. The visceral pleura is snug against the lung tis- sue, and the parietal pleura lines the thoracic cavity. The pleural cavity between the two pleural mem- branes contains serous fluid. The surface tension of the fluid between these two membranes creates a slight outward pull on the lung tissue. Have you no- ticed that a thin layer of water on a glass table holds other glass objects to it? In the lungs, this same phe- nomenon causes adhesion between the visceral and parietal pleura. There is also a slight vacuum in the pleural space, created during development of the lungs and thoracic cavity. This vacuum is essential to proper lung functioning.
If the partial vacuum within the pleural space is lost, inhalation becomes difficult. This can happen if the thoracic cavity is punctured through injury or accident, causing either a pneumothorax (air in the pleural space) or a hemothorax (blood in the pleural space). If enough air or blood enters the pleural space, lung tissue in that area can collapse (Figure 12.11). The air or blood must be evacuated, and pleural integrity restored, to reinflate the lung and reestablish normal breathing. Pleurisy is less devastating and more common than a collapsed lung. In pleurisy, the pleural membranes swell after being inflamed or irritated, and they rub against each other. Every breath is painful, and deep breathing, coughing, or laughing may be excruciating. Anti-inflammatory drugs can reduce these symptoms.

The lobes of each lung are separate sections of the organ that can be lifted away from the others lobes, just as a butcher might separate lobes of beef liver. Air enters each lobe through one secondary bronchus. Despite having different numbers of secondary bronchi, each lung has ten terminal bronchioles, each supplying one bronchopulmonary segment.

Gases are exchanged in the respiratory zone
A bronchopulmonary segment looks somewhat like a grape on a grapevine (Figure 12.12). A single terminal bronchiole feeds all the respiratory membranes of each bronchopulmonary segment. One pulmonary arteriole runs to each segment, and one pulmonary venule returns from it. Small groups of respiratory membranes, called lobules, extend off the terminal bronchiole. These lobules are wrapped in elastic tissue and covered in pulmonary capillaries. Lobules are attached to the terminal bronchiole by a respiratory bronchiol.

The respiratory bronchiole leads to alveolar ducts, which finally conduct air to the alveoli, the respiratory membranes for the entire system. Only after traveling through the entire set of tubes in the conducting zone can gases diffuse in the alveoli. Diffusion takes place nowhere else in the respiratory system. It is here, and here alone, that oxygen enters the bloodstream and carbon dioxide exits.

The alveolus is a cup-shaped membrane at the end of the terminal bronchiole. Alveoli are clustered into an alveolar sac at the end of terminal bronchiole. The key to respiration is diffusion of gases, and diffusion requires extremely thin membranes. The walls of the alveolar sac are a mere two squamous epithelial cells thick—one cell from the alveolar wall and one from the capillary wall. As mentioned in the beginning of the chapter, asthma impedes air flow to these respiratory membranes. (See also the I wonder . . . feature, Why are asthma rates going up?"

Diffusion of gases across the cell membrane requires a moist membrane, but moist membranes have a tendency to stick together much like plastic food wrap (Figure 12.13). Septal cells, scattered through the lung, produce surfactant, a detergent-like fluid that moistens the alveoli and prevents the walls from sticking together during exhalation. (Imagine how a small layer of watery detergent would release the bonding of a ball of plastic wrap.) The surfactant also serves as a biological detergent, solubilizing oxygen gas to promote uptake. Because septal cells begin secreting surfactant only during the last few weeks of pregnancy, premature babies often have difficulty breathing. Every inhalation requires a gasp to reinflate the collapsed alveoli because their walls stick together. In the late 1980s, artificial surfactant was given to premature infants to enhance respiration before septal cells begin producing surfactant. Now this drug is routinely given to premature infants before birth to enhance respiration before septal cells begin producing surfactant.
Asthma, a constriction of the bronchi that causes wheezing and shortness of breath, has become an epidemic. An estimated 14 to 30 million Americans have asthma, including at least 6 million children, many in inner cities. The disease sends about 500,000 people to the hospital each year. Incredibly, the rate of diagnosed asthma patients has doubled since the 1980s.

Part of the increase may be due to better diagnosis, but is something else making this disease more common? The answer must lie in the environmental causes of asthma and/or in the human response to those causes. Asthma can result from exposure to irritants and allergens, including pollen, cockroaches, mold, cigarette smoke, air pollutants, respiratory infections, exercise, cold air, and some medicines. Researchers have examined these exposures and found some important clues to the asthma epidemic:

- Asthma hospitalizations peak just after school starts in the fall. In a Canadian study, schoolchildren aged 5 to 7 were going to emergency rooms a few days before preschoolers and adults. Of the wheezing schoolchildren, 80 to 85 percent had active rhinovirus (common cold) infections, as did 50 percent of adults. The research suggests that the common cold is spread by children partly because immune systems are still developing and that rhinovirus infections may trigger many asthma attacks.

- Poverty and environmental pollution both help to explain why inner-city African Americans have such high rates of asthma. One potent asthma allergen is the cuticle (shell) of a cockroach, an insect often found in crowded inner cities. Compounding this problem are the chaotic home lives characteristic of inner-city families, which can also interfere with timely administration of medicines to prevent asthma symptoms.

- Children who lived on a farm before age 5 have significantly lower rates of asthma, wheezing, and use of asthma medicine, compared to children who live in town. Although allergies play a key role in asthma, the farm children did not have lower rates of hay fever, an allergic reaction to pollen.

None of these studies exactly explains the surge in asthma diagnoses, but the last one does offer a clue. Some scientists suspect that early exposure to dirt and infectious disease somehow “tunes” the immune system to reduce the hyperactive reaction that contributes to the inflammation of asthma. Early exposure to endotoxin, a component of the cell wall of gram-negative bacteria, has been associated with low rates of asthma. But the picture is complicated: Endotoxin also inflames lung tissue in healthy people, and some studies have linked it to more wheezing, not less.

With the causes of the asthma epidemic still uncertain, the best take-home message is this: Most cases of asthma are controllable. If you suffer from it, know what triggers your disease and take action to reduce your exposure to your personal asthma triggers. Take your preventative medications as prescribed and get the suggested immunizations to prevent viral infections from triggering attacks.
The anatomy of the respiratory system eases the exchange of gases between the air and the body. But how is external air brought into the depths of the respiratory system during inhalation (or inspiration)? Inhalation (and the opposite movement, called exhalation or expiration) are governed by muscular movements of the thoracic cavity. Inhalation is an active process, requiring muscular contractions, but exhalation requires only that those muscles relax. The combined inflow and outflow of air between atmosphere and alveoli is called pulmonary ventilation. Pulmonary ventilation is governed by Boyle's law, which states that the volume of a gas varies inversely with its pressure (Figure 12.15). In other words, if you increase the size of a container of gas without adding gas molecules, the pressure must decrease.

When you inhale, your muscles expand your thoracic cavity (Figure 12.16). Your diaphragm contracts, dropping the bottom from the thoracic cavity. This dropping of the diaphragm alone causes most of the size increase in the thoracic cavity during an inhalation. The intercostal muscles also contract, raising the ribs slightly. (You can feel this by holding your sides as you breathe and feeling your ribs expand and contract.) The lungs are connected to the walls of the thoracic cavity through the pleura, so the lungs are dragged along with the moving walls of the thoracic cavity. The volume of the lungs thus increases during inhalation. The pressure inside them must therefore drop, causing gas molecules to rush in from the environment immediately outside your nostrils. Because air moves from high-pressure zones to low-pressure zones, air will move from the environment into your lungs to equilibrate this pressure gradient. This is how inhalation occurs.

Drowning occurs when water, which is too heavy to remove from the lungs, is pulled into the lungs. Our respiratory muscles cannot push out the water, and water carries too little oxygen to diffuse into our blood. In fact, oxygen will diffuse in the opposite direction, from the blood to the water!

When the muscles that expanded the thoracic cavity relax, the thoracic cavity returns to its original size. The diaphragm relaxes, the intercostals relax, and the thoracic cavity returns to its former size. The volume of the cavity decreases, increasing the pressure on the gases within the cavity. Decreased pressure within the lungs sets up a pressure gradient, where the atmosphere outside the nose has a higher pressure than that deep within the lungs. Air moves into the lower-pressure lungs to equalize the pressure. The diaphragm performs 75 percent of the work in normal respiration, with help from the intercostal, sternocleidomastoid, serratus anterior, pectoralis minor, and scalene muscles. You can identify these other muscles by watching in a mirror while inhaling deeply. Neck and shoulder muscles will appear as they contract.

The lungs increase in volume as they follow the walls of the thoracic cavity, causing the pressure within them to decrease. The diaphragm drops and volume increases. During inhalation, the ribcage moves upward and outward like the handle on a bucket.

Increases pressure within the lungs sets up a pressure gradient, where the atmosphere outside the nose has a higher pressure than that deep within the lungs. Air moves into the lower-pressure lungs to equalize the pressure. The diaphragm relaxes, the intercostals relax, and the thoracic cavity returns to its former size. The volume of the cavity decreases, increasing the pressure on the gases within the cavity.

The gases within the cavity rush outward through the nostrils to again equalize the pressure between the lungs and the outside environment. This is a complete cycle of pulmonary ventilation, including an inhalation and an exhalation.
size, which raises pressure in the thoracic cavity above that outside the nostrils (Figure 12.17). Again, because air moves toward areas of low pressure, the required air exits the respiratory tract. During exhalation, the lungs act like a bicycle pump. The container holding the air gets smaller, gas pressure rises, and as soon as it exceeds the pressure outside the pump, air leaves the container.

Exhalation is a passive process, mainly involving muscular relaxation. If we must forcibly exhale, as in sighing or yelling, we contract muscles that directly and indirectly shrink the thoracic cavity. The abdominal muscles are primarily involved in forcible exhalation. When these muscles contract, they push on the abdominal organs, pushing the diaphragm up. You can prove this by placing a hand on your abdomen and forcibly exhaling. You will feel these muscles contract as you force out the air.

Recall that the alveoli are thin and moist. Surface tension helps prevent these membranes from gumming up and sticking together during exhalation. A second factor is the vacuum between the two layers of the pleura. This vacuum forms during fetal development, when the walls of the thoracic cavity enlarge faster than the lungs. The parietal pleura is pulled outward with the expanding walls while the visceral pleura remains attached to the lungs. The resulting vacuum is essential to respiration because it prevents collapse of the thin alveoli during exhalation. The walls of the alveoli spring inward as the air leaves the respiratory tract, but the alveolar walls do not collapse and stick together, partly because of the outward pull of the vacuum between the pleura. In addition, the slight vacuum helps the lungs enlarge and fill with air on the next inhalation.

**YOUR BRAIN STEM IS SETTING YOUR RESPIRATORY RATE**

As you read this text, you are breathing at a steady rate. These constant, day-in, day-out breaths are called your resting rate. Respiratory rate is governed by the medulla oblongata and the pons. The respiratory center in the medulla oblongata causes rhythmic contractions of the diaphragm, stimulating contraction for two seconds and allowing three seconds of rest. This cycle repeats continuously unless overridden by higher brain function (Figure 12.18). You can override the medullary signal by holding your breath or by forcibly exhaling, but you cannot hold your breath until you die. Many small children use this threat to blackmail adults, but let them try! The pons in the brain stem will not let anybody “forget” to breathe. Once the carbon dioxide level builds to a critical point, the child will pass out, and the pons will regain control of breathing. You can bet that child will resume breathing.

The body can sense the levels of carbon dioxide and oxygen in the blood through chemoreceptors in the carotid arteries and aorta. High carbon dioxide levels immediately trigger an increase in the depth and rate of respiration. These chemoreceptors are quite sensitive to carbon dioxide and respond to a 10 percent increase in carbon dioxide levels by doubling the respiratory rate. In contrast, a much larger decrease in oxygen level is needed before these receptors will cause the respiratory rate to increase.

Different respiratory volumes describe different types of breath. During normal breathing, the volume of air inhaled per minute reflects the respiratory rate and the volume of each normal breath, called the tidal volume (TV). Tidal volume, approximately 500 ml is somewhat more than the amount of air that is actually exchanged because the trachea, larynx, bronchi, and bronchioles are “anatomic dead spaces” that do not participate in gas exchange. These dead spaces have a volume of about 150 ml. So each tidal breath delivers about 350 ml of air to the respiratory membranes, with 150 ml filling the conducting respiratory tract.

Just as you can consciously control your breathing rate, you can increase the volume of breath by contracting more muscles during inhalation. During a “forced inhalation,” the average adult male can inhale approximately 5,500 ml of additional air, and the average adult female can force in approximately 1,900 ml. This volume is called inspiratory reserve volume (IRV).
the to about 1,000 ml for males and 700 ml for females, in 500 ml tidal volume after a normal tidal inhalation, up air with which to celebrate birthdays!

Similarly, we can exhale much more than the 500 ml tidal volume after a normal tidal inhalation, up to about 1,000 ml for males and 700 ml for females, in the expiratory reserve volume (ERV). This volume is increased from approximately 500 ml to over 3,000 ml—plenty of space to blow out of you.” In our terms, your problem was a loss of residual volume. The force of falling momentarily shrunk the thoracic cavity beyond what muscular contractions could achieve and forced out a portion of the residual volume. Your first breath was painful and may even have produced awkward noises as you reinflated the empty alveoli to refill your RV. This is just what infants do with their first few gasps after birth (which are commonly mistaken for crying).

External Respiration Brings Supplies for Internal Respiration

The exchanges of both external and internal respiration are driven by the partial pressures of oxygen and carbon dioxide. In external respiration, the driving force lies between the partial pressures of the gases in the alveolar air and the capillary blood. In internal respiration, it is the partial pressure differences between the gases in the capillary blood and the tissue fluid that cause diffusion of those gases.

The air we breathe is composed of many gases. Nitrogen is the most common, making up 78.1 percent of the atmosphere by volume. Oxygen is the second most common gas, occupying 20.9 percent of the total volume. Water vapor varies by location and weather, ranging from 0 to 4 percent of volume. And finally, carbon dioxide makes up a measly 0.4 percent of air by volume. The air pressure in any mass of air is a sum of the partial pressures of each constituent gas, and the pressure exerted by each gas is directly related to its proportion in the atmosphere. In air, 78.1 percent of the pressure is generated by nitrogen molecules, 20.9 percent by oxygen, and 0.4 percent by carbon dioxide. Knowing that atmospheric pressure is usually close to 760 mm Hg, we can calculate the partial pressures of each gas.
The heart is about 40 mm Hg. Blood picks up carbon dioxide in the blood returning to the left side of the heart's left atrium, its carbon dioxide partial pressure has dropped to 40 mm Hg. The difference between 40 and 45 mm Hg tells us how much of this waste gas was removed from the body.

**INTERNAL RESPIRATION SUPPLIES OXYGEN TO THE CELLS AND REMOVES THEIR GASEOUS WASTE**

Internal respiration is the exchange of gases between the blood and the cells (see Figure 12.22). For survival, oxygen in the arteries must reach the tissues, and carbon dioxide generated in the cells must leave the body. In the capillaries of the systemic circulation, the two gases again diffuse in opposite directions. Oxygen enters the tissues, and carbon dioxide diffuses out, again based on partial pressure. The partial pressure of oxygen in the capillary beds of the systemic circuit is approximately 95 mm Hg whereas the partial pressure of oxygen in most tissues is about 40 mm Hg. This gradient allows oxygen to leave the blood and enter the respiring cells without requiring energy from the body. Cellular respiration produces carbon dioxide, and the partial pressure of carbon dioxide in the tissues is about 45 mm Hg. Blood in the capillary beds has a carbon dioxide partial pressure of 40 mm Hg. This smaller gradient is still enough to cause carbon dioxide to diffuse from the cells to the blood, which carries it off to the lungs and releases it into the alveolar air.

### Atmospheric pressure

Atmospheric pressure is the sum of the pressures of all these gases:

\[
P_{\text{atm}} = P_{\text{N}_2} + P_{\text{O}_2} + P_{\text{CO}_2} + P_{\text{H}_2\text{O}}
\]

We can determine the partial pressure exerted by each component in the mixture by multiplying the percentage of the gas in the mixture by the total pressure of the mixture. Atmospheric air is 78.6% nitrogen, 20.9% oxygen, 0.04% carbon dioxide, and 0.0% other gases; a variable amount of water vapor is also present, about 0.4% on a cool, dry day. Thus, the partial pressures of the gases in inhaled air are as follows:

- \( P_{\text{N}_2} = 0.786 \times 760 \text{ mm Hg} = 597.4 \text{ mm Hg} \)
- \( P_{\text{O}_2} = 0.209 \times 760 \text{ mm Hg} = 158.8 \text{ mm Hg} \)
- \( P_{\text{CO}_2} = 0.004 \times 760 \text{ mm Hg} = 3.0 \text{ mm Hg} \)
- \( P_{\text{H}_2\text{O}} = 0.0006 \times 760 \text{ mm Hg} = 0.5 \text{ mm Hg} \)
- Total: 760 mm Hg

### Dalton’s law

Each gas in the atmosphere exerts a different partial pressure. Together they all add up to atmospheric pressure. As these gases float around in the environment, they independently diffuse from areas of high concentration to areas of low concentration.

**Figure 12.21**

Why discuss partial pressure? Because it explains the movement of oxygen and carbon dioxide in respiration. **Dalton’s law** states that gases move independently down their pressure gradients, from higher to lower pressure (Figure 12.21). So oxygen will diffuse from the air in the alveoli, whereas carbon dioxide will diffuse from blood to the alveoli. Each gas independently moves toward an area of lower pressure without affecting any other gas.

The partial pressure of oxygen in the air of the alveoli is approximately 100 mm Hg, whereas the partial pressure of oxygen in the tissues hovers near 40 mm Hg. Through simple diffusion, oxygen moves from the air in the alveoli through the thin respiratory membrane and into the blood. By the time blood in the respiratory capillaries completes its journey through the lungs, the partial pressure of oxygen in the blood has equilibrated with that of the air. Blood returning to the heart’s left atrium carries oxygen with a partial pressure of 100 mm Hg ready to be pumped to the tissues (Figure 12.22).

While oxygen is diffusing into the blood, carbon dioxide is leaving it. The partial pressure of carbon dioxide in the blood returning to the left side of the heart is about 40 mm Hg. Blood picks up carbon dioxide as it courses through the tissues, and by the time it reaches the alveoli, the partial pressure of carbon dioxide is 45 mm Hg higher than the 40 mm Hg in the alveolar air. This CO2 pressure gradient causes carbon dioxide to diffuse from the blood to the alveolar air. When the blood leaves the lungs and enters the left atrium, its carbon dioxide partial pressure has dropped to 40 mm Hg. The difference between 40 and 45 mm Hg tells us how much of this waste gas was removed from the body.

### Summary of the events of external and internal respiration

**Figure 12.22**

Most oxygen is transported by the hemoglobin of the RBCs. Carbon dioxide is transported in the blood plasma as bicarbonate ions.
Transport of Oxygen and Carbon Dioxide Requires Hemoglobin and Plasma

**LEARNING OBJECTIVES**

Understand the role of hemoglobin in respiration.
Recognize the role of carbon dioxide in maintaining blood pH.

Respiration involves not only the structures of the respiratory system, but also the functioning of the cardiovascular system. The respiratory system moves the gases in and out of the body, while the cardiovascular system transports them within the body. The pulmonary capillaries exchange gases in the lungs, while the systemic capillaries exchange gases in the body. The final piece to this puzzle is to determine how these gases are carried through the cardiovascular system between these two capillary beds.

**HEMOGLOBIN TRANSPORTS OXYGEN**

As we know, the **hemoglobin** molecule carries oxygen in the bloodstream (Figure 12.23). Hemoglobin picks up oxygen through a bond between the oxygen molecule and the iron atom of the heme molecule. Hemoglobin has a high affinity for oxygen under some conditions but will release it under other conditions. The oxygen–hemoglobin dissociation curves discussed in Chapter 11 and reviewed below demonstrate hemoglobin’s unique characteristics.

The bond between oxygen and hemoglobin is reversible. Oxygen binds to the iron atom in the hemoglobin molecule when the partial pressure of oxygen is high, the pH is high, and the temperature is low. In areas where these conditions do not exist, hemoglobin releases oxygen. Even minute changes in temperature or pH will cause hemoglobin to release oxygen (Figure 12.24). Such differences exist in active tissue—muscles generate lactic acid and heat while contracting. Contraction requires oxygen to fuel ATP production, which produces lactic acid. An increase in lactic acid, in turn, lowers the pH. Waste heat warms the muscle, and all of these factors increase oxygen delivery to the muscle cells.

Several mechanisms transport carbon dioxide. Hemoglobin is best known for carrying oxygen, but it also conveys about 23 percent of total carbon dioxide through the bloodstream. This carbon dioxide binds to the protein portion of hemoglobin, forming **carbaminohemoglobin** (see Figure 12.23).

Another 7 percent of the blood-borne carbon dioxide is carried as dissolved CO₂ gas. The major share of blood-borne carbon dioxide (about 70 percent of total carbon dioxide) is carried as **bicarbonate ion** in plasma. Bicarbonate ion is produced in steps. First, carbon dioxide and water combine to form carbonic acid inside red blood cells. The enzyme **carbonic anhydrase** speeds this reaction, allowing red blood cells to remove most of the carbon dioxide from the blood. This carbonic acid then dissociates into a hydrogen ion and a bicarbonate ion. The hydrogen ion is picked up by hemoglobin, forming reduced hemoglobin. The bicarbonate ion is transferred out of the RBC in exchange for a chloride ion coming in to the RBC. The large transport of chloride ions into the RBCs, called the chloride shift, is an exchange reaction that requires no ATP because it merely switches the positions of the anions. The bicarbonate in the plasma then serves as a

**CONCEPT CHECK**

*What is the difference between external and internal respiration?*
*Explain how Dalton’s law governs the movement of oxygen and carbon dioxide in the body.*
*How does the blood transport oxygen and carbon dioxide?*
blood is due to a high concentration of oxyhemoglobin. But blood inside your body is never as crimson as what is spilled when you cut yourself. The partial pressure of oxygen in the atmosphere is far higher than anywhere in your body, so hemoglobin quickly picks up more oxygen when you bleed.

**Buffer**
A compound that absorbs hydrogen ions or hydroxide ions, stabilizing pH.

**Oxyhemoglobin**
Hemoglobin molecule with at least one oxygen molecule bound to the iron center.

**CONCEPT CHECK**

- How is oxygen carried in the blood?
- What is the role of hemoglobin in gas transport?
- What is one positive role of carbon dioxide in the blood?

**Sinuses**
Cavities in the skull, lined with the same type of mucus membrane as the nasal passages (Figure 12.26). Sinuses exist in the frontal bone, ethmoid, sphenoid, and maxillary bones, but the largest are in the frontal sinus.

Leaky capillaries allow blood to squeeze out and spread over the surfaces of tissues in the lung. From there, the oxygen of the blood moves into the alveoli and the carbon dioxide of the alveoli moves into the blood. The exchange of gases takes place in the pulmonary capillaries of the alveoli. In the capillaries, oxygen combines with hemoglobin and is transported to the tissues. Carbon dioxide diffuses from the tissues into the capillaries and is transported to the lungs.

**Respiratory Health is Critical to Survival**

The previous chapter introduced cardiovascular disorders and outlined their obvious impact on respiration. If the blood does not circulate properly, or if it does not carry enough oxygen, external and internal respiration are impaired.

The upper respiratory tract is susceptible to infection and inflammation of the nasal passages, sinuses, and larynx. One of the most common upper respiratory diseases is sinusitis, an inflammation or swelling of the sinuses (“-itis” means inflammation). Sinuses are cavities in the skull, lined with the same type of mucous membrane as the nasal passages (Figure 12.26). Sinuses exist in the frontal bone, ethmoid, sphenoid, and maxillary bones, but the largest are in the frontal sinus.

In A, the bicarbonate ion is being absorbed from the blood into the RBC, where it is converted to carbon dioxide and passed out to the alveoli. Oxygen is seen coming into the RBC at the alveoli as well. In B, carbon dioxide is passing from the tissues to the capillaries. Here it is picked up by the RBC. Inside the RBC, the carbon dioxide is converted to bicarbonate ions that are then pumped back out to the blood where they serve as a buffer. Oxygen is seen leaving the RBC and diffusing into the tissues, where it is used to drive cellular activities.

**Process Diagram**

**Carbon dioxide transport in blood**

**Figure 12.25**

In A, exchange of $O_2$ and $CO_2$ in pulmonary capillaries (external respiration).

In B, exchange of $O_2$ and $CO_2$ in systemic capillaries (internal respiration).
Histamine
A compound involved in allergic reactions that causes capillary leakage and increased fluid movement to affected tissues.

Acute sinusitis
Inflammation of the sinuses that results in sudden onset and usually of short duration.

Chronic sinusitis
Inflammation of the sinuses that persists for long periods of time.

Bone. When you succumb to the common cold or flu, viruses swell the nasal membranes. Histamines are released, and mucus production increases as the membranes try to rid the body of the virus. If the membrane lining a sinus swells, the opening can shut, preventing mucus produced in the sinus from draining and causing it to build up pressure in the closed sinus. Resident populations of streptococcus or staphylococcus bacteria can also grow unchecked in the closed sinus. Acute sinusitis is usually caused by a common cold and goes away on its own within two to three weeks. Chronic sinusitis, in contrast, is more severe and its causes are less clear. Most people who suffer from chronic sinusitis also have allergies, asthma, or a compromised immune system owing to a disease like AIDS. Treating this type of sinusitis is also more difficult; antibiotics, inhaled steroids, or even oral steroids may be used depending on the case.

If you have a young child, you probably know about otitis media (Figure 12.27). This inflammation of the middle ear fills the middle ear with fluid, distending the eardrum. A stretched eardrum can cause severe pain, and the eardrum can rupture as bacteria within the trapped fluid multiply. Otitis media is usually caused by a bacterial infection that can be treated with antibiotics. The pathogens most often arrive through the eustachian tube, with its open connection between the middle ear and the nasopharynx. In small children, the tube is almost horizontal, so fluids in the mouth can easily travel to the middle ear, especially since the bottom of the tube opens with each swallow. As we age, our facial bones expand, tilting the eustachian tubes toward the vertical, so fluids do not flow so readily to the middle ear. For this reason, ear infection rates drop with age.

Diseases of the lower respiratory tract are usually either obstructive, meaning that something is obstructing the normal flow of gases through the lungs, or constrictive, indicating that the airways have been narrowed in some way.

CONSTRUCTIVE DISEASES ARE SERIOUS BUT OFTEN SPORADIC
As the name implies, constrictive respiratory diseases constrict the airways. One common constrictive disease of the lower respiratory tract is bronchitis, an inflammation of the mucous membrane lining the bronchi. When this membrane swells, the lumen of the bronchi constricts. Often these infected bronchial tubes also produce more mucus, which can block air passages. The most common symptom of bronchitis is a deep, often painful, cough. Acute bronchitis can be caused by viruses and occasionally bacteria. Chronic bronchitis is most often caused by smoking and can last from months to years, depending on the severity of the reaction to smoke and the duration of the smoking habit. The main symptom of acute bronchitis is a productive cough. In acute bronchitis, shortness of breath, tightness of the chest, and a general feeling of illness often accompany the cough. Treatment for bronchitis, antibiotics, inhaled steroids, or even oral steroids may be used depending on the case.

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Asthma is a constrictive pulmonary disease that can be life-threatening. During an asthma attack, the smooth muscle of the bronchi contracts. Pressure builds in these tubes, and the bronchi swell, interfering with the passage of air. Breathing becomes labored, and wheezing is common during exhalation. Breathing grows laborious, and the bronchi swell, interfering with the passage of air. Breathing becomes labored, and wheezing is common during exhalation.

Asthma attacks are usually triggered by an external source, such as exercise, viral infection, or inhalation of cold air or an allergen, or by high levels of ozone in the air (see the I wonder . . . box on the increasing prevalence of asthma).

Asthma may result from an overactive immune system, and to many people, inhaling an allergen can cause an immediate and life-threatening constriction of the airways. Many asthma patients carry inhalers containing bronchodilator drugs to quickly open the airways during an acute attack. As a preventative measure between attacks, many chronic asthmatics inhale bronchodilator drugs to reduce the number and severity of asthma attacks. Despite these medicines, however, asthma still kills up to 5,000 people every year in the United States.

**OBSTRUCTIVE DISEASES CAUSE PERMANENT LUNG DAMAGE**

Although asthma is a serious disease, it does not permanently damage lung tissue. In contrast, the chronic obstructive pulmonary diseases, including emphysema and fibrosis, do damage or destroy the terminal and respiratory bronchioles. The most common obstructive pulmonary diseases are pneumonia, tuberculosis, emphysema, and lung cancer (see Health, Wellness, and Disease box). After exhalation in all of these diseases, the tubes of the airway do not spring back open because the elastic tissue is destroyed. Pressure builds in the lungs as the patient tries to force air through the collapsed tubes, damaging the delicate alveoli and reducing the respiratory surface area. The most common cause of emphysema is smoking, but environmental pollutants and even genetic factors can also be to blame. Pulmonary fibrosis, a destructive increase in collagen that also makes the lungs less elastic, often results from occupational exposure to silicon or other irritants.

Lung tissue must remain warm and moist because gases cannot diffuse across a dry membrane. Unfortunately, these same conditions are perfect for bacterial growth. Bacteria living in the warm, moist, lung tissue cause two of the most common obstructive respiratory diseases: pneumonia and tuberculosis.

**I nhalers contain bronchodilator drugs**

In 1964, the U.S. Surgeon General issued an influential Report on Smoking and Health. The report looks tame given how much we now know about the toxicity of tobacco smoke, but it was an early acknowledgment that smoking causes lung cancer. Today, smoking-related lung cancer kills an estimated 174,000 people in the United States per year, and the number is rising.

Some of the approximately 4,000 compounds in tobacco smoke attack the delicate epithelial cells lining the respiratory tract and allow them to grow without control—the hallmark of cancer. Because early tumors are invisible, lung cancer is not usually detected until it has spread; therefore, the five-year survival rate is only 15 percent. Smoking and tobacco smoke also:

- are the major cause of emphysema.
- increase the risk of acute myeloid leukemia, and cancer of the throat, mouth, bladder, kidney, stomach, cervix, and pancreas, according to the American Cancer Society.
- impair several functions of the uterine tube, which conducts both gametes and the embryo, and alters female hormone effectiveness. Both effects could explain why smoking women have higher rates of reproductive problems, including undersized and/or premature infants.
- kill nerve cells, interfering with smell and taste.
- elevate pulse and body temperature.
- increase the risk of heart disease by a factor of 2 to 4.
- raise the level of carbon monoxide and reduce the level of oxygen in the blood, which in turn reduces the ability to exercise or even comfortably move about.
- destroy cilia in the airways, reducing the ability to expel mucus.
- promote heartburn and peptic ulcers by increasing stomach acid production.

Nicotine causes its own set of problems. Nicotine is a vasoconstrictor, which forces the heart to work harder. Nicotine’s neurological effects include increased concentration, a reduction in hunger, and a subtle boost in mood. Nicotine triggers the release of dopamine, a “feel-good” neurotransmitter, making “cuffin nails,” or cigarettes, highly addictive.

The tobacco industry is expert at promoting the delusion that smoking is “cool.” Many of their campaigns are targeted, subtly or not, at young people. It’s only logical. With so many customers dying each year, they need to replace them with young, healthy smokers.

But many people are quitting, and fewer people are starting. The number of cigarettes smoked per capita has declined 59 percent from 1963 to 2004. Still, an estimated 45 million Americans smoke. Smoking causes about 30 percent of all cancers and an estimated 438,000 premature deaths.
Pneumonia is a general term for a buildup of fluid in the lung, often as a response to bacterial or viral infection. When the delicate membranes in the alveoli become inflamed, they secrete fluid in an attempt to eradicate the pathogen, but this fluid inhibits gas exchange across the membrane. Symptoms of pneumonia include a productive cough, lethargy, fever, chills, and shortness of breath. Treatment depends on the underlying cause of the fluid buildup. Although pneumonia usually can be treated, it can be fatal, especially in patients with weak immunity owing to other serious illnesses.

Tuberculosis (TB) is a disease caused by Mycobacterium tuberculosis infection. This tiny bacterium can pass from person to person in airborne droplets generated by a sneeze and cough. The inhaled bacteria multiply from one small region of the infected organ, called the “focus.” Because it is airborne, the focus in humans is usually in the lung tissue. If the immune system can combat the disease, scar tissue may form at the focus. In those rare instances where the body does not eliminate the infection, the bacteria can enter the lymphatic system and infect just about any organ. The bacterium can also remain dormant for years and then reappear in the lungs without warning. Symptoms of TB resemble those of pneumonia, including a productive (and often bloody) cough, fever, chills, and shortness of breath. TB also causes weight loss and night sweats. TB is usually diagnosed if a focus appears on a chest X-ray. Previous exposure can be detected with a simple skin test, which is mandatory for children entering U.S. public schools (Figure 12.29).

A century ago, TB was a major deadly health threat, but antibiotics have reduced the incidence in industrialized nations. Unfortunately, TB is on the rise again because antibiotic-resistant strains have now appeared, and many patients must take multiple antibiotics for many months to clear the infection. TB is one of several cases where bacteria are starting to evade antibiotics that once controlled them. This shows how misuse of antibiotics, combined with their widespread use in animal agriculture, may help breed antibiotic-resistant strains of bacteria.

Cancer can attack just about any organ system, but lung cancer causes one-third of all cancer deaths in the United States. Lung cancer is primarily due to tobacco smoking; nearly 90 percent of all patients in the United States are current or former smokers. The Ethics and Issues box on page 00 discusses this in greater detail. Lung cancer takes years to develop, but the risk of lung cancer increases with each year of smoking. The good news is that quitting smoking reduces the risk, even for long-term smokers. As with other respiratory illnesses, the symptoms include a chronic cough, possibly with bleeding, wheezing, and chest pain. Treatment may include surgical removal of the tumor, or destruction of the cancer with radiation or chemotherapy. Unlike other cancers, lung cancer is relatively easy to prevent. Avoid smoking and exposure to environmental carcinogens such as radon gas, coal dust, and radon gas.

Cystic fibrosis (CF) results from a defective gene that controls the consistency of mucus in the lungs. The CF version of this gene causes thick, sticky mucus to be produced, rather than thin, fluid mucus that is conducive to diffusion. This thick mucus traps bacteria and slows airflow through the bronchial tree, and it may also block the pancreas and bile duct. Treatment for the lung obstruction includes physical therapy to dislodge the mucus (Figure 12.30), and new drugs that may make the mucus more fluid. Approximately 30,000 people in the United States are currently living with cystic fibrosis. Another 1,000 are diagnosed yearly, usually before age 3. One promising line of research would use gene therapy to correct the defect that causes CF.
CHAPTER SUMMARY

1. The Respiratory System Provides Us with Essential Gas Exchange as well as Vocalization

   The respiratory system delivers oxygen and removes carbon dioxide, helps balance blood pH, sustains fluid and thermal homeostasis, and produces speech in the larynx. The upper respiratory tract warms, moistens, and filters incoming air. The lower tract exchanges gas with the environment. The bronchial tree reaches into the lobes of the lungs. To the end of the respiratory bronchioles are the alveoli, the thin membranous sacs where gas exchange occurs. Septal cells produce surfactant to prevent the alveolar membranes from sticking together. Dust cells patrol the respiratory membranes to remove foreign particles.

2. In Order to Breathe, Air Must Be Moved into and out of the Respiratory System

   Pulmonary ventilation is the movement of air into and out of the lungs, based on Boyle’s law of gases. Tidal volume is the amount of air you inspire during a normal quiet inhalation. Your vital capacity, the total amount of air you can move in and out during one breath, is the sum of tidal volume, inspired respiratory volume, and expired respiratory volume. Residual volume is the volume of air that you cannot remove from the lungs.

3. External Respiration Brings Supplies for Internal Respiration

   External respiration is the exchange of gases between air in the alveoli and blood in the pulmonary capillaries. Oxygen enters the red blood cells, while carbon dioxide moves out. Internal respiration is the transfer of gases between systemic capillaries and body cells. Oxygen diffuses into the cells, while carbon dioxide diffuses into the blood. The diffusion in both types of respiration is based on Dalton’s law of partial pressures.

4. Transport of Oxygen and Carbon Dioxide Requires Hemoglobin and Plasma

   Oxygen is carried bound to iron in hemoglobin molecules inside red blood cells. Most carbon dioxide is moved as bicarbonate ion in plasma. Bicarbonate also serves as a buffer that stabilizes pH in the blood. Some carbon dioxide is carried by the protein portion of hemoglobin, turning venous blood blue.

5. Respiratory Health is Critical to Survival

   In constrictive respiratory diseases like asthma and bronchitis, airway diameter is reduced. Obstructive diseases, including emphysema, fibrosis, tuberculosis, pneumonia, and lung cancer, feature a physical obstruction to airflow. The death toll due to lung cancer in the United States is high, but the disease is preventable because most cases are caused by smoking.

CRITICAL THINKING QUESTIONS

1. We know humans cannot breathe under water, and yet fishes can. One difference between fish gills and human lungs is that the blood in the gill flows in a countercurrent pattern. This means that the water and blood flow across the respiratory surface in opposite directions. How might this speed oxygen removal from the water? Draw a schematic of this arrangement with arrows to show how countercurrent flow works. What else are humans lacking in terms of breathing under water? How might our physiology be “improved” to allow us to extract oxygen from water?

2. Although lung cancer is the most common cancer associated with smoking, the larynx is also susceptible to tobacco smoke. When cancer is detected in the larynx, the affected area is removed. What problems would you expect if the entire larynx must be removed? Often the tumors appear on the vocal folds. How might removal of these growths affect vocalization? What alternative methods of sound production might be available to victims of laryngeal cancer?

3. In Chapter 11, we discussed carbon monoxide poisoning. How does activation of the “flight-or-flight” nervous system affect the respiratory system? What neurotransmitter is released, and does activation of the “flight-or-flight” nervous system affect the respiratory system? What neurotransmitter is released, and how does it affect the functioning of the upper and lower respiratory tracts? What happens to pulmonary ventilation when the sympathetic nervous system is in control? Is there any change in external or internal respiration?
11. The function of the entire area depicted in the figure at the bottom of the previous page is
   a. diffusion of gases into and out of the blood.
   b. infection fighting within the lungs.
   c. movement of air into the deeper tissues of the respiratory system.
   d. thermal homeostasis.

12. During inspiration, the diaphragm
   a. contracts, increasing
   b. contracts, decreasing
   c. relaxes, increasing
   d. relaxes, decreasing

13. True or False: The gas law that dictates the differential movement of carbon dioxide and oxygen into and out of the tissues of the body is Boyle’s law.

14. Identify the volume indicated as A on this diagram:
   a. Vital capacity
   b. Tidal volume
   c. Expiratory reserve volume
   d. Inspiratory reserve volume

15. The movement of oxygen from the blood into the tissues is referred to as
   a. internal respiration.
   b. external respiration.
   c. Dalton’s law.

16. Carbon dioxide moves from the tissues of the body into the blood because
   a. the partial pressure of oxygen is lower in the tissues.
   b. the partial pressure of carbon dioxide is lower in the blood.
   c. the volume of carbon dioxide decreases in the blood.
   d. carbon dioxide floats in the blood, and will always travel upwards.

17. Oxygen is carried on the
   a. plasma proteins of the blood.
   b. protein portion of the hemoglobin molecule.
   c. iron portion of the hemoglobin molecule.
   d. white blood cells.

18. Hemoglobin binds oxygen more tightly when oxygen concentrations are _______ and pH is _______.
   a. low, low
   b. high, low
   c. high, high
   d. low, high

19. The structures indicated by the letter A are often susceptible to
   a. flooding with mucus.
   b. bronchitis.
   c. otitis media.
   d. sinusitis.

20. True or False: Bronchitis is an example of a constrictive disease.