12 The Respiratory System

Everyone is anxiously waiting to hear that first breath as a baby is born. The parents may breathe a sigh of relief when they hear her first cry. It is the result of their baby's first intake of air from outside her body, but it certainly will not be her last. Her body will continue the process of breathing until death—24 hours a day, 365 days a year, for possibly 75 years or more. Rarely will she give her breathing conscious thought, yet day after day her respiratory anatomy will continue to perform the functions of the system. See Figure 12.1.

12.1 learning outcome

Use medical terminology related to the respiratory system.

learning outcomes

After completing this chapter, you should be able to:

12.1 Use medical terminology related to the respiratory system.

12.2 Trace the flow of air from the nose to the pulmonary alveoli and relate the function of each part of the respiratory tract to its gross and microscopic anatomy.

12.3 Explain the role of surfactant.

12.4 Describe the respiratory membrane.

12.5 Explain the mechanics of breathing in terms of anatomy and pressure gradients.

12.6 Define the measurements of pulmonary function.

12.7 Define partial pressure and explain its relationship to a gas mixture such as air.

12.8 Explain gas exchange in terms of the partial pressures of gases at the capillaries and the alveoli and at the capillaries and the tissues.

12.9 Compare the composition of inspired and expired air.

12.10 Explain the factors that influence the efficiency of alveolar gas exchange.

12.11 Describe the mechanisms for transporting O_2 and CO_2 in the blood.

12.12 Explain how respiration is regulated to homeostatically control blood gases and pH.

12.13 Explain the functions of the respiratory system.

12.14 Summarize the effects of aging on the respiratory system.

12.15 Describe respiratory system disorders.

word roots & combining forms

alveol/o: alveolus, air sac

bronch/o: bronchial tube

bronchi/o: bronchus

bronchiol/o: bronchiole

capn/o: carbon dioxide

cyan/o: blue

laryng/o: larynx

lob/o: lobe

nas/o: nose

pharyng/o: pharynx

phren/o: diaphragm

pneum/o, pneumon/o: air

pulmon/o: lung

rhin/o: nose

sinus/o: sinus

spir/o: breathing

thorac/o: chest

trache/o: trachea

pronunciation key

alveoli: al-VEE-oh-lye

arytenoid: ah-RIT-en-oyd

bronchi: BRONG-kye

bronchus: BRONG-kuss

conchae: KON-kee

corniculate: kor-NIK-you-late

laryngopharynx: lah-RING-oh-FAIR-inks

larynx: LAIR-inks

nares: NAH-reez

pharynx: FAIR-inks

trachea: TRAY-kee-ah

Overview

The word *respiration* has several usages. In Chapter 2, you studied *cellular respiration* as a cellular process performed by mitochondria to release energy from the bonds in a glucose molecule. In Chapter 5, you studied *aerobic* and *anaerobic respiration* as variations of cellular respiration. In this chapter, you will study **respiration** first as the movement of air into **(inspiration)** and out of the lungs **(expiration),** commonly called breathing. Then you will explore respiration as the exchange of gases in two areas—between the air in the lungs and the blood in capillaries and between the blood in the capillaries and the tissues out in the body. Once you understand how the exchange of gases takes place, you will be prepared to investigate how gases are transported in the blood.

As with all of the other human body systems you have covered so far, it is important to understand the anatomy of the system before tackling the physiology. So you will begin below by studying the anatomy of this system.

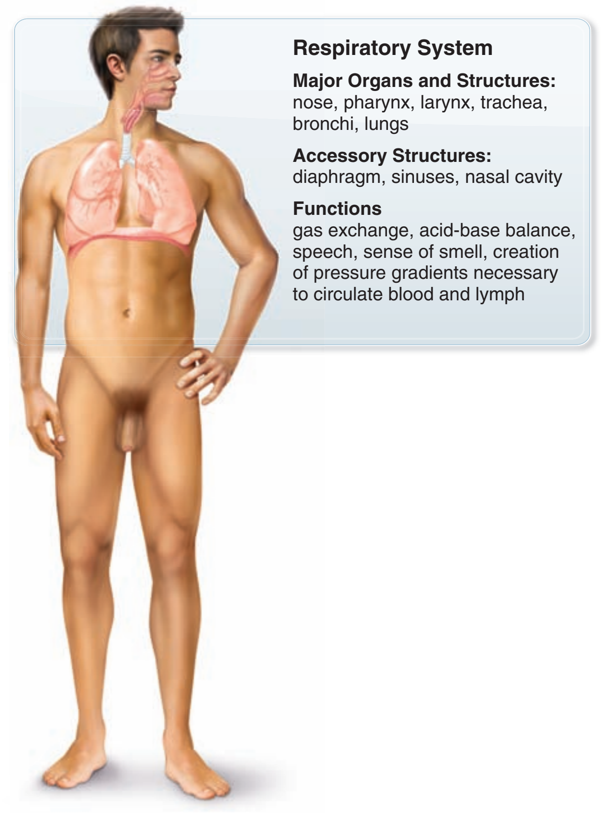

FIGURE 12.1 The respiratory system.

12.2 learning outcome

Trace the flow of air from the nose to the pulmonary alveoli and relate the function of each part of the respiratory tract to its gross and microscopic anatomy.

Anatomy of the Respiratory System

As you can see in Figure 12.2, the entire respiratory system's anatomy is housed in the head, neck, and thorax. In general, the anatomy in the head and neck is the **upper respiratory tract,** while the anatomy from the trachea through the lungs is the **lower respiratory tract.**

You have already studied some of this anatomy, such as the pleurae (serous membrane), in Chapter 1. To refresh your memory, a serous membrane is a double-walled, fluid-filled membrane. In the case of the pleurae, the visceral pleura is in contact with the lung's surface, while the parietal pleura is not. The parietal pleura lines the thoracic cavity and covers the diaphragm's superior surface. Fluid exists between the visceral and parietal pleurae. This anatomy will be important when you study the mechanics of breathing, later in the chapter.

Before you get started on the rest of the anatomy, consider the way air enters and moves through the body. Take a deep breath now with your mouth closed, and trace the air in that breath as it travels on its route (follow along with Figure 12.2). The air enters the **nasal cavity** through the **nose.** From there it goes to the **pharynx,** to the **larynx,** to the **trachea,** to the **bronchi** (where it enters the lungs), to the **bronchial tree,** and finally to the tiny air sacs called **alveoli** (not shown in the figure). At the alveoli, the second part of respiration—the exchange of gases—takes place.

pharynx: FAIR-inks

larynx: LAIR-inks

trachea: TRAY-kee-ah

bronchi: BRONG-kye

alveoli: al-VEE-oh-lye

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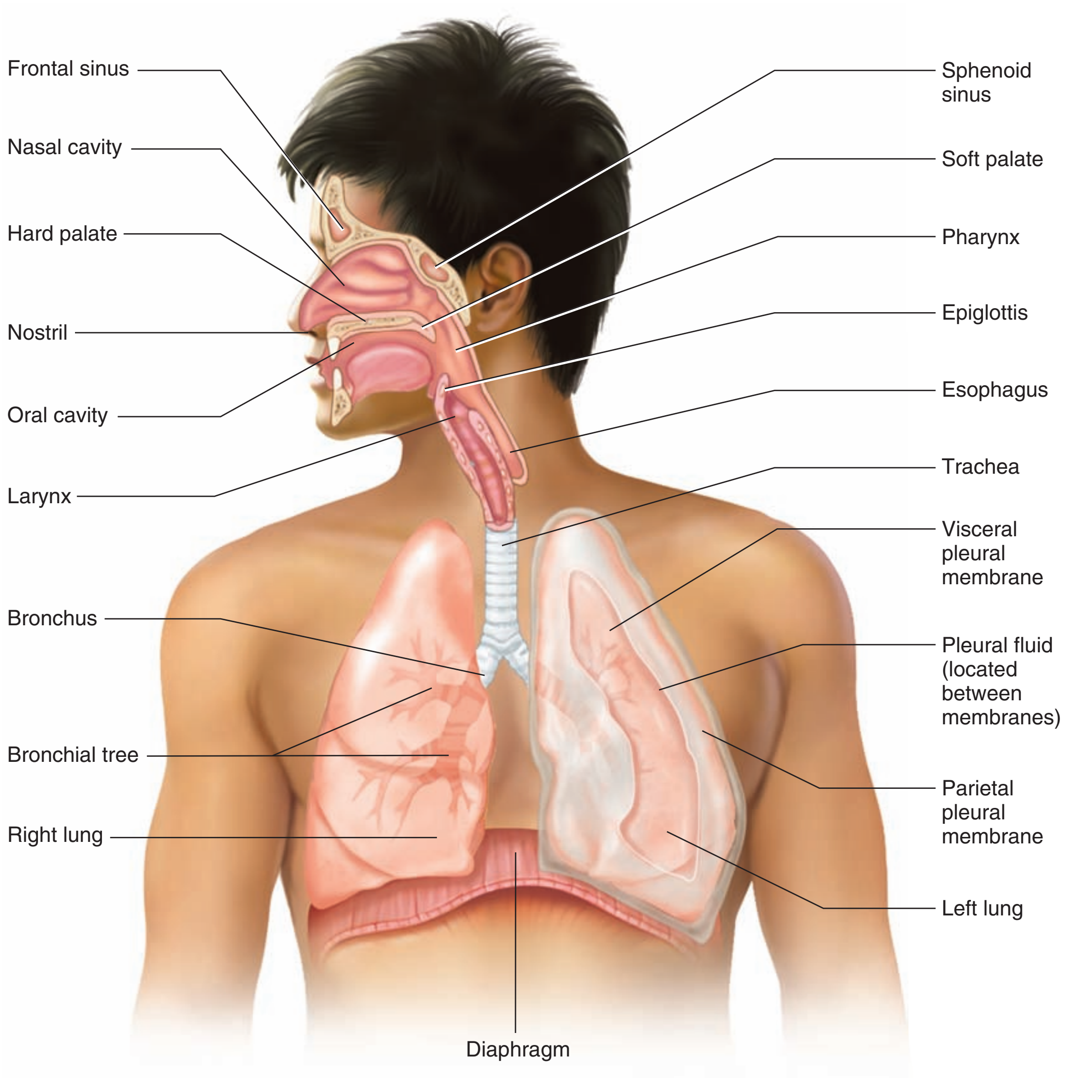

FIGURE 12.2 The respiratory system anatomy.

nares: NAH-reez

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Now you are ready to zoom in on all of the respiratory system's specific anatomy (mentioned above) in the order that the air traveled through it in your deep breath. You will need to become familiar with the gross and microscopic anatomy along the way because this is important in understanding precisely how the anatomy functions.

Nose

Air enters the nasal cavity through the nose's two **nares** (nostrils). The nasal bones superiorly and the plates of hyaline cartilage at the end of the nose are responsible for the nose's shape. You can feel where the nasal bone ends and cartilage begins at the bridge of the nose. See Figure 12.3.

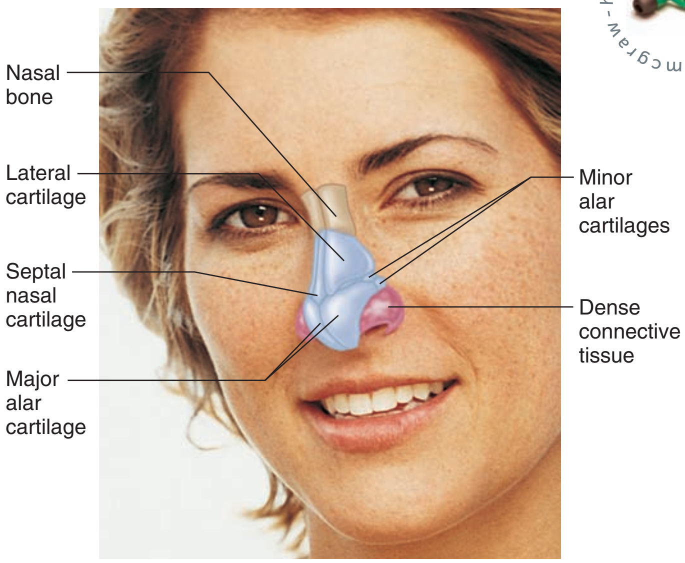
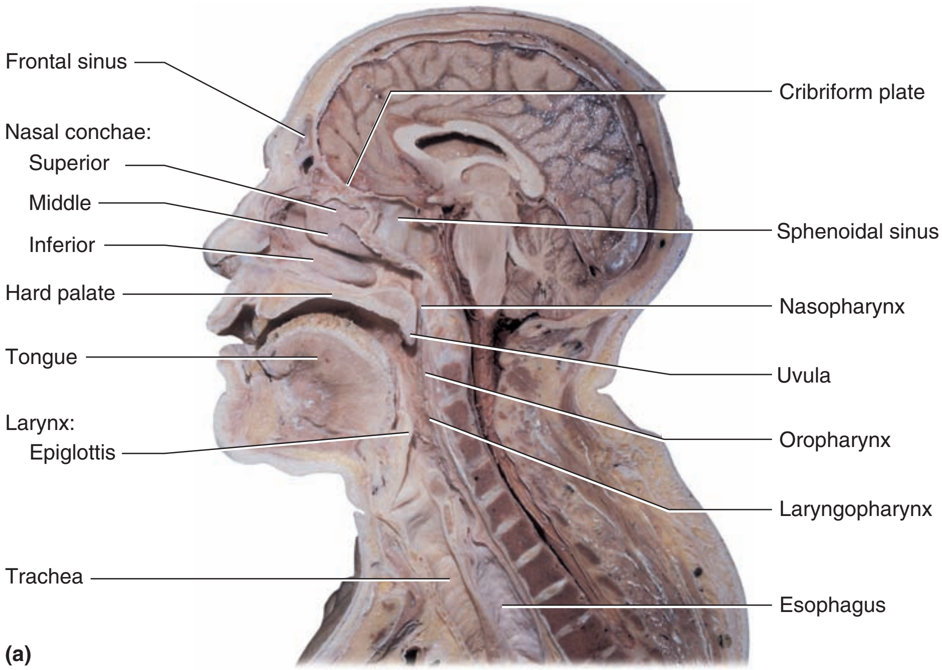


FIGURE 12.3 The nose.

Nasal Cavity

As you can see in Figure 12.4c, a septum divides the nasal cavity into right and left sides. The ethmoid bone (superiorly), the vomer (inferiorly), and a septal cartilage anteriorly form the septum. The anterior part of the nasal cavity (the **vestibule**) is lined by stratified squamous epithelial tissue with stiff **guard hairs** to block debris from entering the respiratory tract.

FIGURE 12.4 The anatomy of the upper respiratory tract: (a) sagittal view of cadaver, (b) sagittal section showing internal anatomy (nasal septum has been removed), (c) nasal septum and regions of the pharynx.



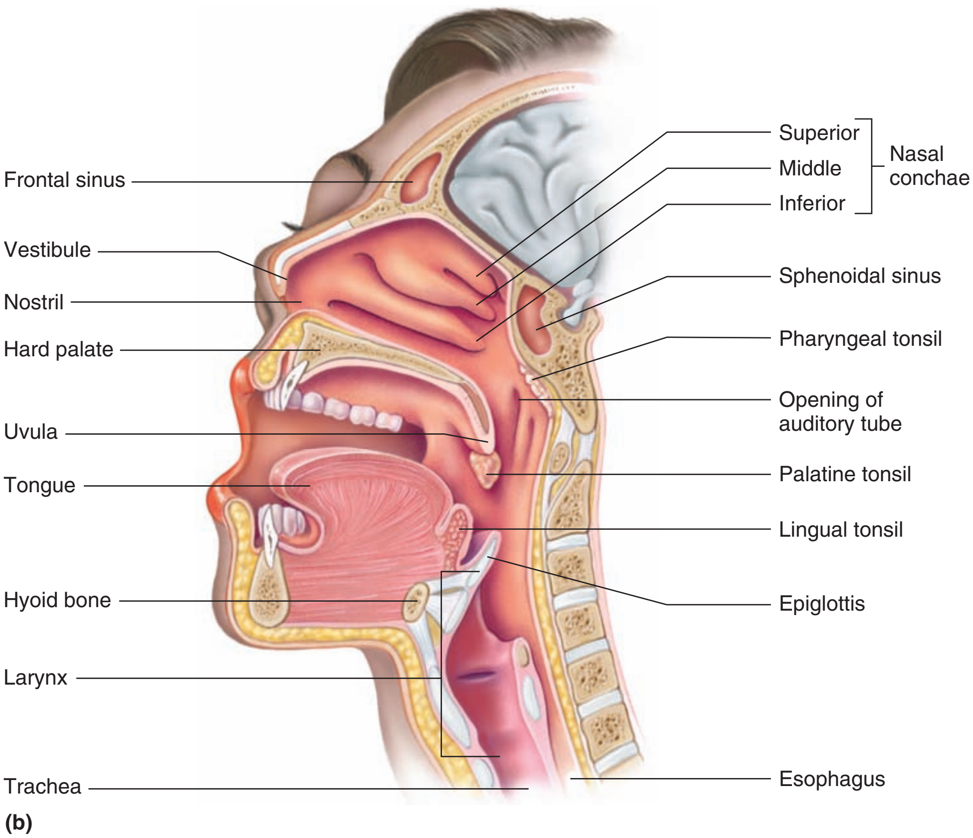
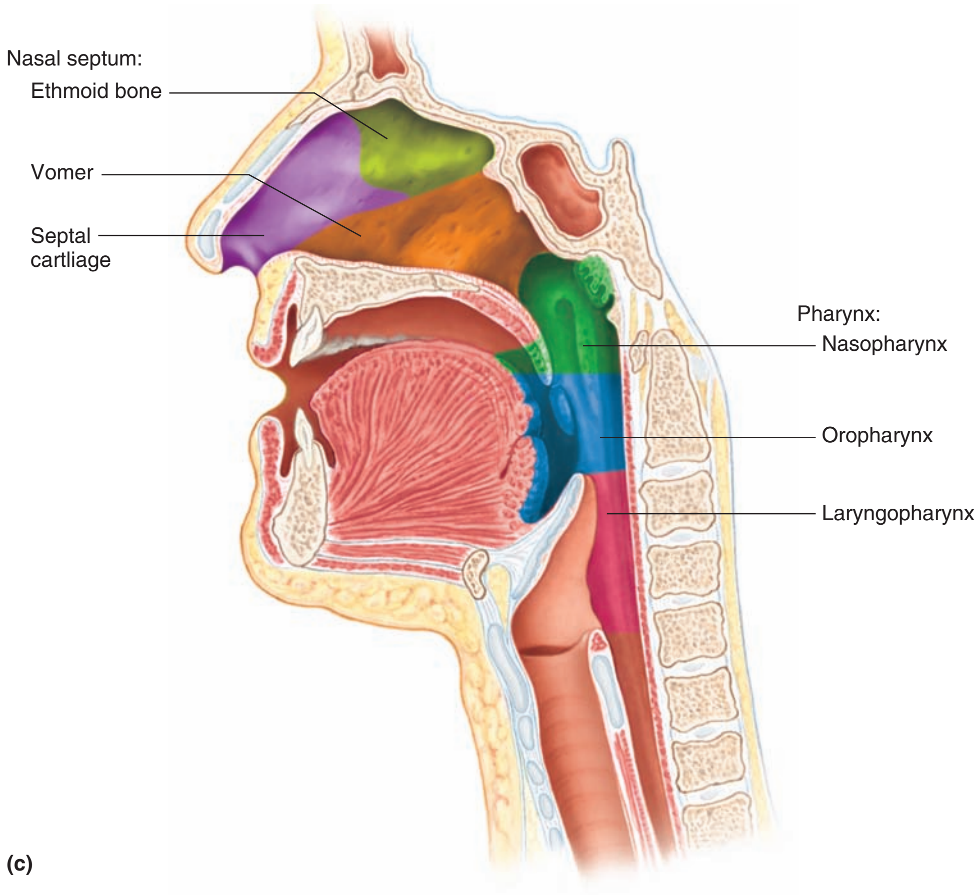


FIGURE 12.4 concluded



The nasal cavity widens posterior to the vestibule to make room for three bony, lateral ridges called the **nasal conchae.** See Figure 12.4b. The ethmoid bone forms the superior and middle nasal conchae, while the inferior nasal concha is a separate bone. This portion of the nasal cavity is lined by mucous membranes that trap debris and warm and moisturize the incoming air. The nasal conchae provide extra surface area for the mucous membranes to function. The mucous membranes are composed of ciliated pseudostratified epithelial tissue. The cilia move mucus and any trapped debris posteriorly so that it can be swallowed. Olfactory neurons located in the roof of the posterior nasal cavity detect odors and provide the sense of smell.

conchae: KON-kee

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study **hint**

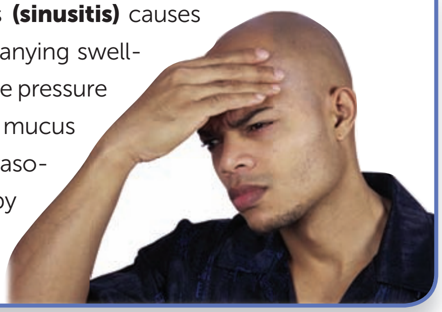
Take a look up your own nose by using a flashlight and a mirror. You can see the hairs in the vestibule and notice that the posterior nasal cavity appears very red and moist. These are the moist, mucous membranes, and their rich blood supply moisturizes and warms the air. You should also see that there is limited space for air to pass because of the protruding nasal conchae. This causes more air to come in contact with the mucous membranes, so they are better able to function.

spot check **1** Why do you think the vestibule is stratified epithelial tissue instead of mucous membranes?

Sinuses You studied the sinuses of the frontal, ethmoid, sphenoid, and maxilla bones in Chapter 4. The frontal and sphenoidal sinuses are shown in Figure 12.4. These cavities within the bones are also lined with respiratory epithelial tissue to warm and moisturize the air. The mucus produced in the sinuses is drained to the nasal cavity through small openings.

clinical point

Inflammation of the epithelium in the sinuses **(sinusitis)** causes increased mucus production, and the accompanying swelling may block its drainage to the nasal cavity. The pressure within the sinuses created by the buildup of mucus causes a *sinus headache.* Decongestants (vasoconstrictors) help reduce the swelling, thereby improving mucus drainage, which reduces the increased pressure.



At this point in your deep breath, the inspired air leaving the nasal cavity has been partially warmed and moistened, and some of its debris has been trapped. The structure the air encounters next—the pharynx—is explained below.

Pharynx

laryngopharynx: lah-RING-oh-FAIR-inks

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The **pharynx,** commonly called the *throat,* is divided into three regions based on location and anatomy—the **nasopharynx,** the **oropharynx,** and the **laryngopharynx.** You will explore these in the paragraphs that follow.

Nasopharynx As you can see in Figure 12.4c, the nasopharynx is located posterior to the nasal cavity and the soft palate. This passageway is also lined by ciliated pseudostratified columnar epithelial tissue whose cilia move mucus and trapped debris to the next region of the pharynx so that it can be swallowed. The pharyngeal tonsils and the opening to the auditory tube (eustachian tube) are located in this region.

Oropharynx This region of the pharynx (shown in Figure 12.4c) is inferior to the nasopharynx. The oropharynx is common to the respiratory and digestive systems as a passageway for air, food, and drink. For the oropharynx to withstand the possible abrasions caused by the passage of solid food, it must be lined with a more durable tissue—stratified squamous epithelial tissue. In addition, the palatine tonsils are located in this region to deal with any incoming pathogens.

Laryngopharynx This region of the pharynx extends from the level of the epiglottis to the beginning of the esophagus. Like the oropharynx, the laryngopharynx is lined by stratified squamous epithelial tissue to handle the passage of air, food, and drink. See Figure 12.4c. Solids and liquids continue on from the laryngopharynx to the esophagus, but inspired air moves through an opening **(glottis)** to the **larynx,** the next structure in the respiratory pathway.

Larynx

The **larynx** is a cartilage box (voice box) of nine separate cartilages, eight of which are composed of hyaline cartilage connective tissue. The **epiglottis** (the ninth cartilage of the larynx) is composed of elastic cartilage connective tissue. As you can see in Figure 12.4b, the epiglottis stands almost vertically over the glottis. Its function is to fold over the glottis during swallowing to prevent solids and liquids from entering the larynx. You will learn more about how this works in the next chapter. The epiglottis remains in its vertical position at all other times to ensure the easy passage of air from the laryngopharynx through the glottis to the larynx.

Figure 12.5 gives you a closer look at the larynx. Here you can see the **laryngeal prominence** ("Adam's apple") of the **thyroid cartilage.** It enlarges to be more visible in men than women due to the presence of testosterone. You can also see (in this figure) the two **arytenoid cartilages** and the two **corniculate cartilages** that operate the vocal cords.

arytenoid: ah-RIT-en-oyd

corniculate: kor-NIK-you-late

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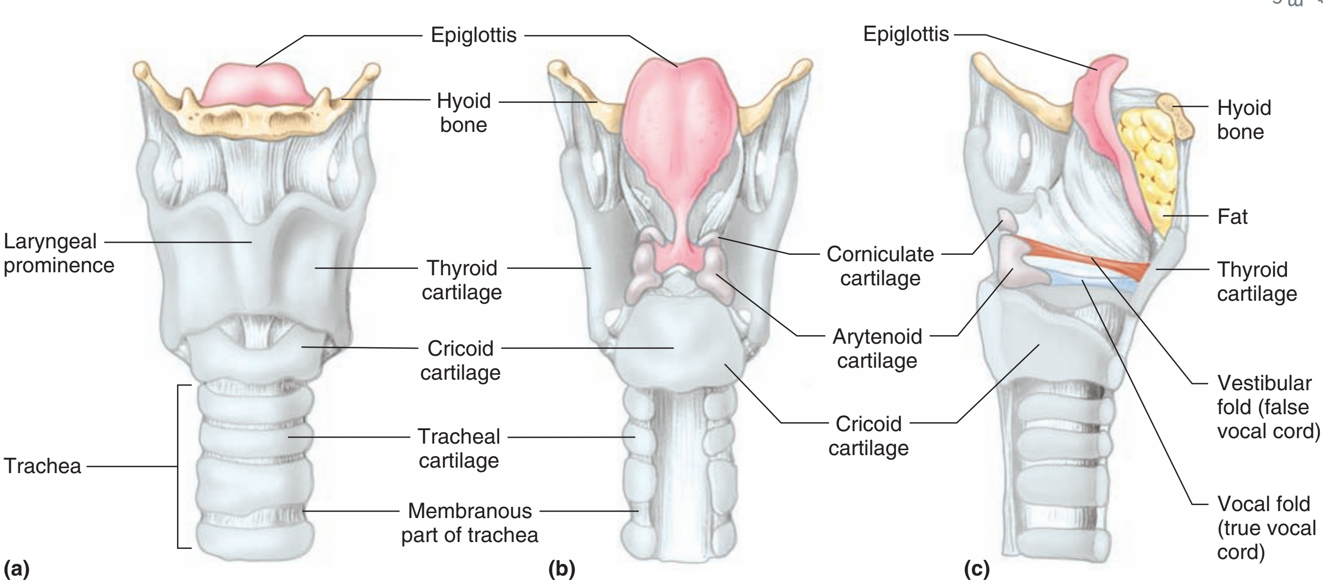

FIGURE 12.5 The larynx: (a) anterior view, (b) posterior view, (c) sagittal section.

Vocal Cords The walls of the larynx are muscular to operate the **vocal cords** shown in Figures 12.5c, 12.6, and 12.7. There are two sets of folds in the inner wall of the larynx—the **vestibular folds** and the vocal cords. The vestibular folds have no function in speech. They are important in closing the larynx during swallowing.

Figure 12.6 shows how the vocal cords are *abducted* (spread apart) and *adducted* (brought closer together) by muscles pulling on the arytenoid and corniculate cartilages. The opening formed by *abducting* the vocal cords is the glottis. Air passing through *adducted* vocal cords causes them to vibrate to make sounds of varying pitch depending on the tautness of the cords. So speech is a very active process, which involves muscles pulling on cartilages of the larynx to operate the vocal cords. The larynx at the vocal cords is lined with stratified squamous epithelial tissue to withstand the vibrations.

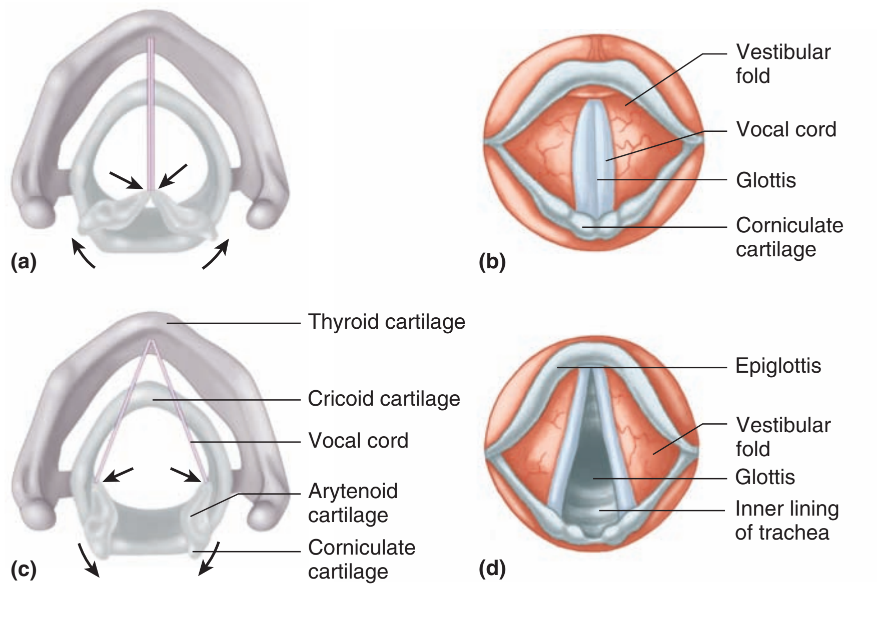

FIGURE 12.6 Action of laryngeal muscles on the vocal cords: (a) adduction showing just the cartilages and the vocal cords, (b) adduction as seen with all tissues present, (c) abduction showing just the cartilages and the vocal cords, (d) abduction as seen with all tissues present.

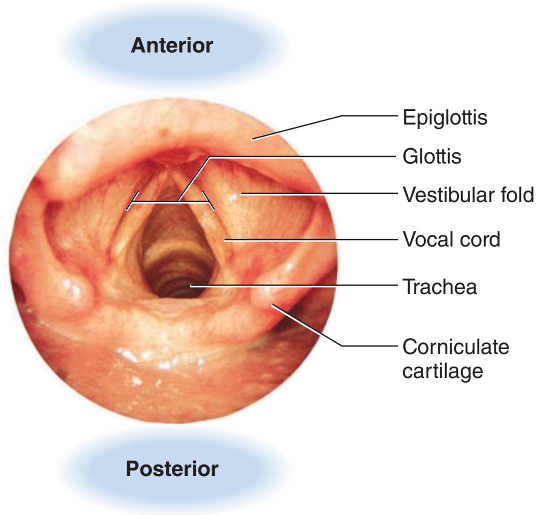

FIGURE 12.7 Endoscopic view of the vocal cords as seen with a laryngoscope.

Trachea

From the larynx, inspired air travels to the **trachea,** a rigid tube with 18 to 20 C-shaped cartilages composed of hyaline cartilage connective tissue. See Figure 12.8. These cartilages hold the trachea open for the easy flow of air. The C-shaped cartilages are open posteriorly with smooth muscle bridging the gap. This feature allows the esophagus (directly posterior to the trachea) room to expand into the tracheal space when swallowed food passes on its way to the stomach. If the cartilages were circular instead of C-shaped, a swallowed piece of meat could get hung up on each cartilage as it passed down the esophagus.

Like the nasal cavity and the nasopharynx, the trachea is lined with ciliated pseudostratified columnar epithelial tissue with goblet cells that secrete mucus. See Figures 12.8 and 12.9. The air you breathe is full of particles, such as dust, pollen, and smoke particles. You may have seen the dust in

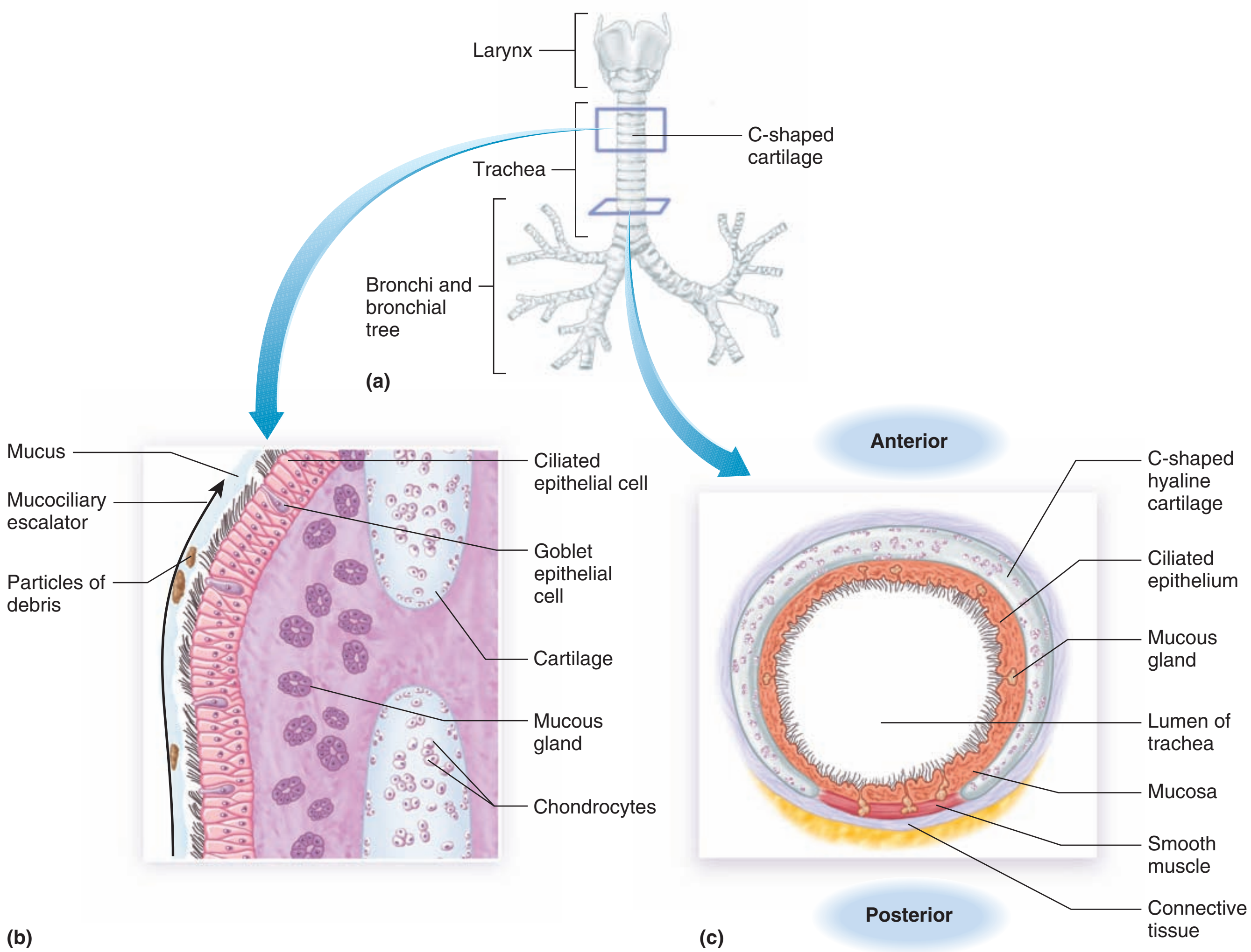

FIGURE 12.8 The trachea and bronchi: (a) anterior view, (b) longitudinal view of the trachea showing cilia moving mucus and debris, (c) transverse section of the trachea showing C-shaped cartilage.

FIGURE 12.9 Lining of trachea. Epithelial tissue of the trachea, showing ciliated cells and goblet cells.

the air as the sun shines through a window. Even during sleep, the cilia of the trachea move mucus and any trapped debris up (like an escalator) toward the pharynx to be swallowed. See Figure 12.8b. This prevents the accumulation of debris in the lungs.

clinical point

The smoke inhaled with each drag on a cigarette contains a lot of particles, but the respiratory anatomy is designed to prevent this debris from accumulating in the lungs. However, the increased amount of debris may, over time, cause the lining of a habitual smoker's trachea to go through metaplasia, changing from ciliated epithelial tissue to a more durable, nonciliated tissue. Without the ciliated escalator, the respiratory system resorts to coughing up the debris. As a result, the long-term smoker develops the *smoker's hack* each morning to move the debris inspired each night.

spot check 2 Compare the direction the cilia move debris in the nasopharynx to the direction they move debris in the trachea. How do they differ?

spot check 3 A patient on a ventilator has a tube inserted into the trachea through a procedure called a **tracheostomy.** What should be done to the air delivered through a ventilator considering the respiratory anatomy leading to the trachea has been bypassed?

The trachea splits to become the right and left main bronchi, each of which enters its respective lung. You will explore the lungs and bronchial tree together, looking first at their gross anatomy, as shown in Figure 12.10.

Lungs and the Bronchial Tree

As you can see in Figure 12.10b, the right and left main bronchi each enters its respective lung at an area on the medial surface of the lung called the **hilum.** This is the same location used by pulmonary arteries and veins to enter and leave the lung. The left **bronchus** is slightly more horizontal than the right bronchus due to the location of the heart. The main bronchi and all of their further branches make up the **bronchial tree.** See Figure 12.10c.

bronchus: BRONG-kuss

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Upon entering the lung, each main bronchus branches to become the **lobar bronchi,** each going to a separate lobe of the lung. The left lung has fewer lobes (two) than the right, again because of the position of the heart. The right lung has three lobes, and therefore three lobar bronchi.

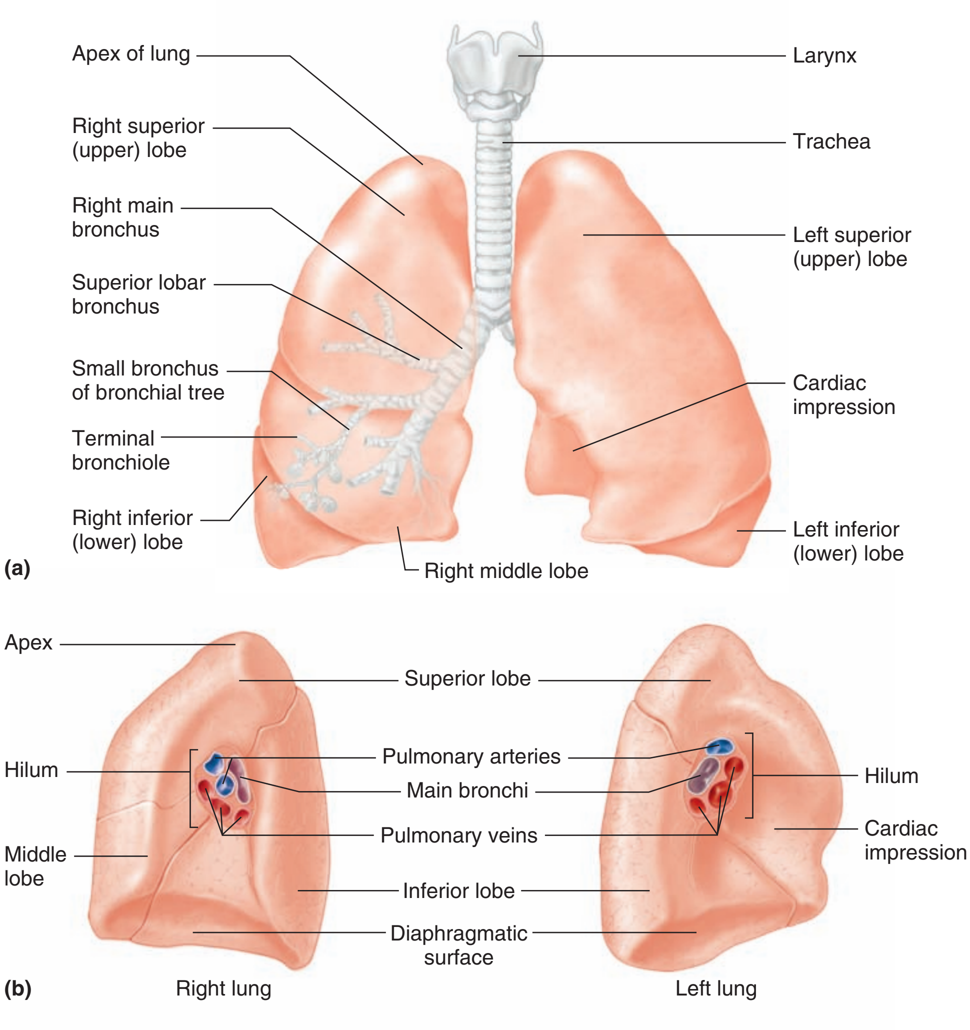
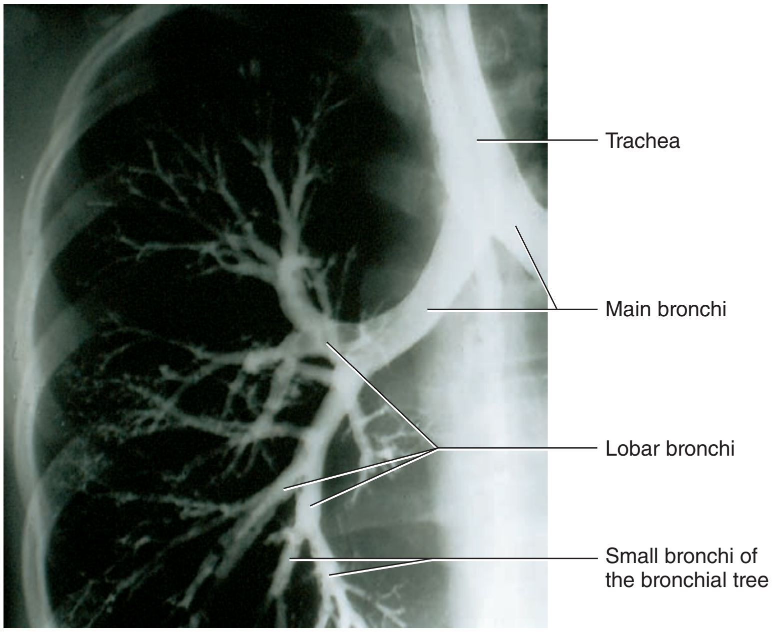


FIGURE 12.10
Gross anatomy of the lungs and bronchial tree:
(a) anterior view, (b) medial views of the right and left lungs, (c) bronchogram (radiograph of the bronchial tree), anterior view.



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warning

The lungs fill with air, but they are not hollow like a balloon. A cross section of a lung appears solid—more like Styrofoam composed of tiny beads. Each of the tiny beads is a tiny, hollow air sac that can fill with inspired air. See Figure 12.11.

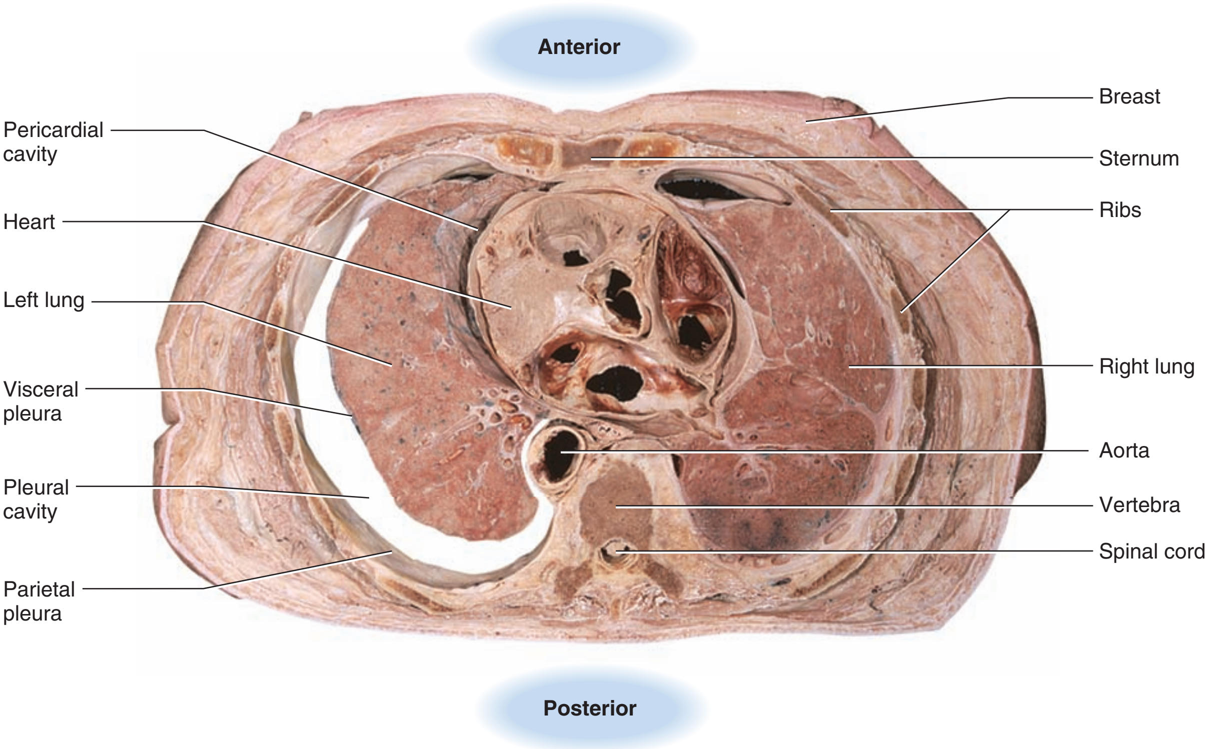


FIGURE 12.11 Cross section of a cadaver through the thoracic cavity.

Lobar bronchi further divide to smaller and smaller bronchi that branch to form the bronchial tree. See Figure 12.10c. All of the bronchi are supported by cartilage plates, which hold them open for the easy passage of air. The smallest bronchi further branch to form bronchioles. These small tubes do not have cartilage in their walls. Instead, their walls have smooth muscle that allows them to dilate or constrict to adjust airflow. You will learn more about this later in the chapter. Each bronchiole supplies air to a **lobule** (subsection of a lobe) of the lung composed of tiny air sacs called *alveoli*. See Figure 12.12a.

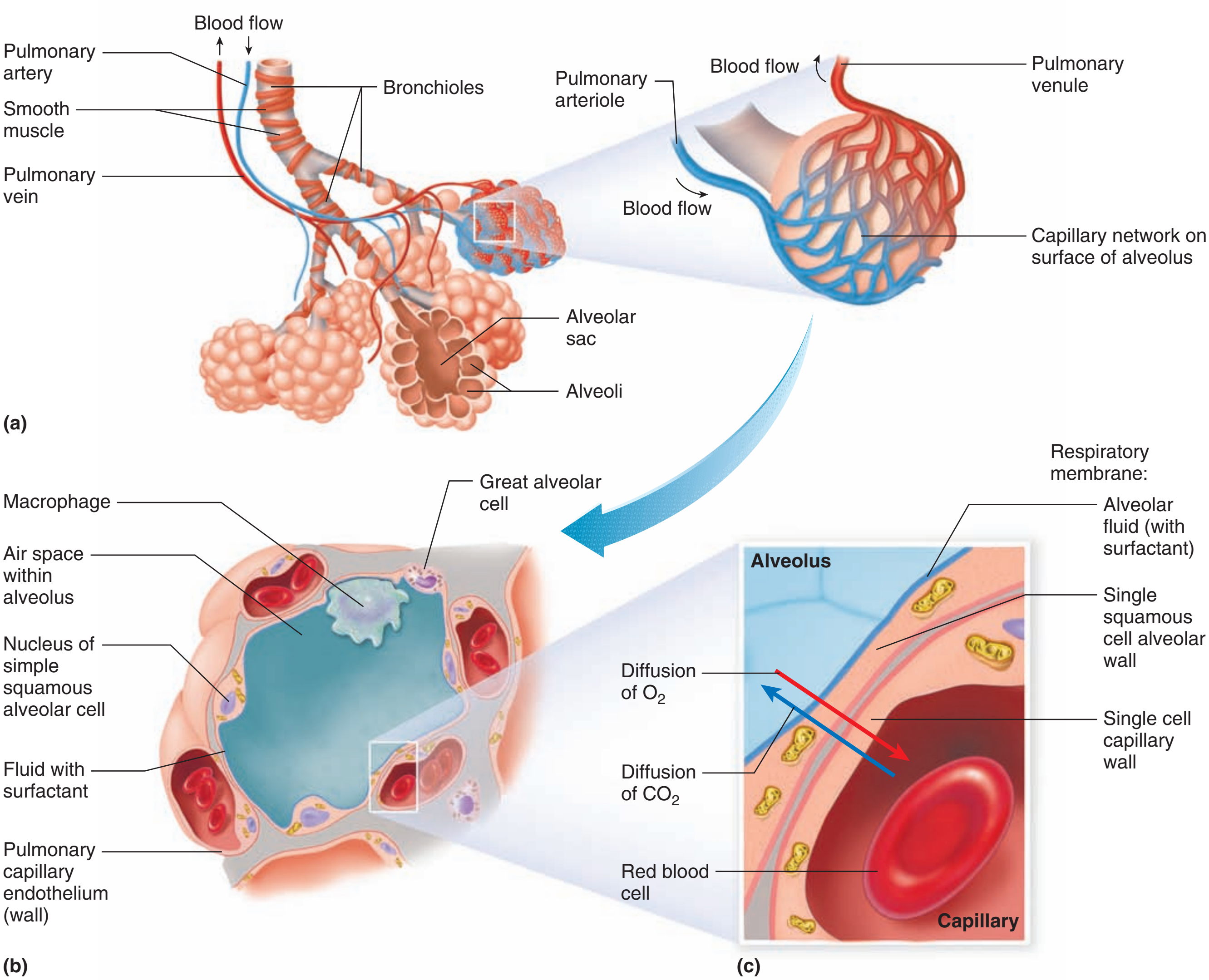


FIGURE 12.12 **Bronchiole, alveoli, and the respiratory membrane:** (a) clusters of alveoli at the end of a bronchiole and the network of capillaries covering them, (b) cells of the alveoli, (c) respiratory membrane.

spot check 4 Penny is an inquisitive 18-month-old girl who likes to see what fits into what. One morning, she put a small, metal washer that she found on the floor into her nose just as her mother entered the room. Her mother gasped when she saw what Penny had done. This scared Penny, so she gasped, too, and the metal washer was gone. She had inhaled it. What route do you think the metal washer will take (trace the pathway)?

spot check 5 In which lung will the doctor at the clinic find the metal washer? Explain.

Alveoli The alveoli are clustered like grapes at the end of the bronchiole. As you can see in Figure 12.12, a network of capillaries covers the alveoli. This is vital for gas exchange, as you will read shortly. Figure 12.13 shows the histology of the alveoli with respect to the bronchioles and blood supply to the capillaries. There are approximately 150 million alveoli in each human lung. Each alveolus is a tiny air sac with two types of cells in its walls—simple squamous cells and **great alveolar cells.** Most of the alveolar wall is composed of one layer of thin squamous cells that allow for rapid gas exchange across their surface. The great alveolar cells (shown in Figure 12.12b) are important because they secrete a fluid called **surfactant.** Below, you will find out why this fluid is so important.

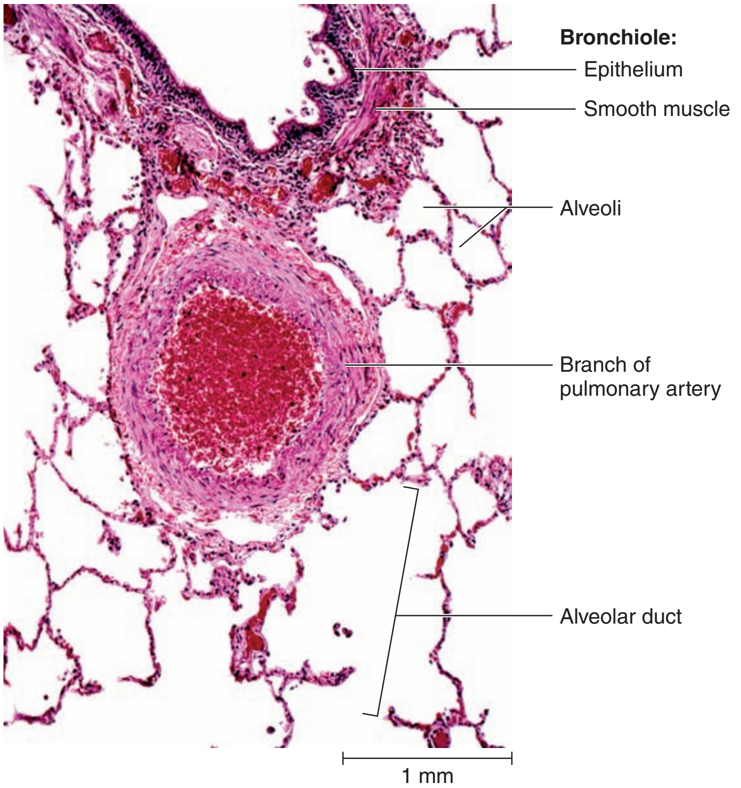


FIGURE 12.13 Histology of the lung: micrograph of alveoli, a bronchiole, and a branch of a pulmonary artery.

spot check 6 Why must the vessel represented in this figure be an artery and not a capillary, and why must the tube be a bronchiole and not a bronchus of the bronchial tree? (*Hint:* Look at the histology.)

12.3 learning outcome

Explain the role of surfactant.

Surfactant To understand the importance of surfactant, you must first understand a property of water: high surface tension. This basically means that water will always try to have the smallest surface area to volume ratio possible. In other words, water forms beads or drops because a sphere has a smaller surface area to volume ratio than a flat sheet. This is why water forms beads or drops on smooth surfaces like glassware in your dishwasher.

Surfactant reduces the surface tension of water much like the rinse agent you may add to your dishwasher to avoid water spots. The rinse agent reduces the surface tension of water (sheeting action), so water sheets off your glassware instead of forming beads that leave water spots as the glasses dry. Surfactant also causes water to form a thin sheet instead of a bead. Why is this important? By the time air has entered the alveoli, it has been thoroughly moisturized by all the mucous membranes it has passed along the respiratory route. If a bead of water were to form inside the tiny alveoli, the plump bead might touch the wall on the opposite side of the air sac and cause the thin, delicate walls of the alveoli to stick together, and this would cause the alveoli to collapse. A thin sheet of water in the alveoli (instead of a plump bead) reduces the chance of the alveoli walls collapsing on each other. Collapsed alveoli do not easily fill with air.

clinical point

A fetal respiratory system does not mature until late in pregnancy. The alveoli in infants born before the lungs are mature often collapse because of the lack of sufficient surfactant. This condition, called **respiratory distress syndrome (hyaline membrane disease),** is a common cause of neonatal death. Oxygen under positive pressure can be administered along with surfactant to keep the lungs (alveoli) inflated between breaths.

12.4 learning outcome

Describe the respiratory membrane.

Respiratory Membrane

So far, you have seen in Figure 12.12a and b the relationship of the alveoli to the bronchioles and the cells that make up the alveoli. In Figure 12.12c, you can see the structure formed by the capillary network adjacent to the alveoli—the respiratory membrane. This is a very important structure because it is the location of gas exchange in the lung. Take a closer look at this figure. The respiratory membrane is composed of the thin layer of water with surfactant in the alveoli, the single squamous cell alveolar wall, and the single cell capillary wall. If all of the respiratory membrane in one lung were laid out in a single layer, it would cover approximately 70 square meters (m^2), equivalent to the floor of a room 25 feet by 30 feet.

You have now covered all of the anatomy that the air of your deep breath encountered along its way to the respiratory membrane. It is time to explore the way this respiratory anatomy functions, starting with how you took the deep breath in the first place.

12.5 learning outcome

Explain the mechanics of breathing in terms of anatomy and pressure gradients.

Physiology of the Respiratory System

Mechanics of Taking a Breath

Air moves (but is not pushed) along the respiratory passageways on its way to the lungs because of pressure differences within the chest. This is much like the syringe example you became familiar with while studying blood flow through the heart (see Figure 10.11 in Chapter 10). The syringe example explained the relationship between volume, pressure, and flow. If the volume of space in the syringe is increased, the pressure inside the syringe is decreased, so air flows into the syringe to equalize the pressures inside and outside the syringe. Likewise, if the volume of space in the syringe is decreased, the pressure inside the syringe is increased, so air flows out of the syringe to equalize the pressures. As a result, pushing or pulling on the plunger changes the volume of the syringe.

How does the body change the volume of the chest? See Figure 12.14. Concentrate on the major muscles for breathing shown in bold in this figure. As you can see in Figure 12.14 (a and b), during inspiration the external intercostal, pectoralis minor, and sternocleidomastoid muscles contract to expand the rib cage, and the diaphragm contracts to flatten its dome shape. The combined effect of these contractions is an increase in the size (volume) of the chest cavity. All that needs to be done for normal expiration is to have the same muscles relax. Then the rib cage returns to its normal position and the diaphragm becomes dome-shaped again due to the recoil of abdominal organs. See Figure 12.14c. The volume of the chest is decreased, and air flows from the body. Expiration during normal breathing is a passive process (no energy required) involving the relaxation of muscles. But you can also see in Figure 12.14d that forced expiration involves the contraction of muscles too. The internal intercostals and abdominal wall muscles do contract in *forced expiration;* however, these muscles are not used for expiration during normal breathing. Forced expiration is intentionally forcing air out of the lungs, which happens when blowing out a candle or inflating a balloon. In this case, energy for muscle contraction is required.

So far in this explanation of the mechanics of breathing, you have seen how the muscles of the chest can increase the volume of the chest, but what about the volume of each lung? How is the volume of the lungs increased? This involves the pleural membranes and the pleural fluid. The parietal pleura is attached to the thoracic

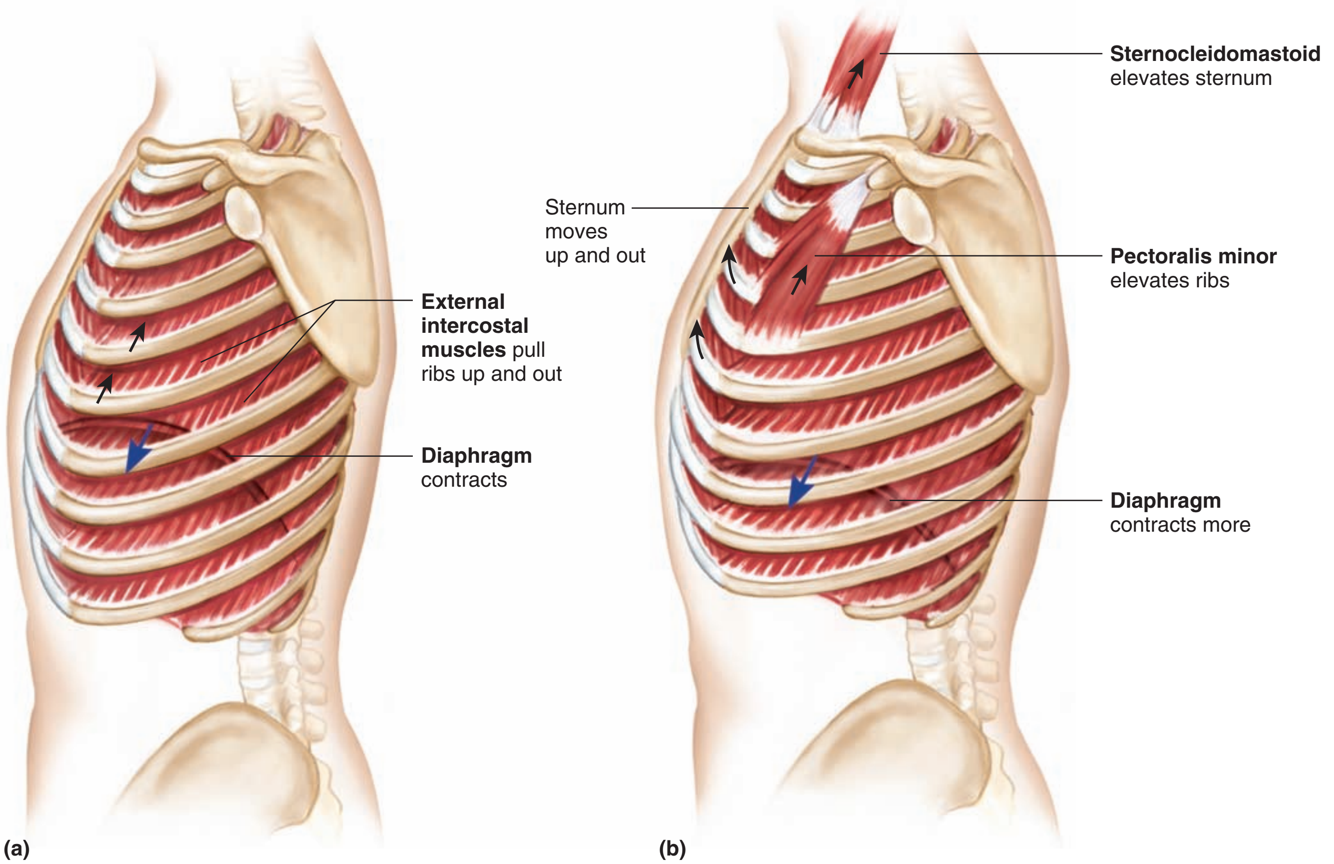
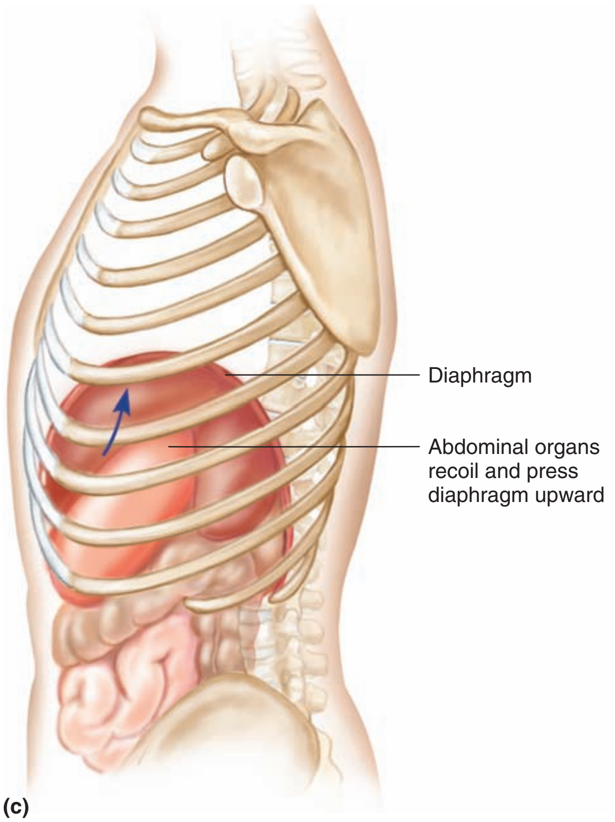


FIGURE 12.14 **Respiratory muscles:** (a) external intercostal muscles and diaphragm at the beginning of inspiration, (b) additional muscle action to continue inspiration, (c) recoil of abdominal organs, causing diaphragm to dome when it relaxes, (d) muscle actions during forced expiration.



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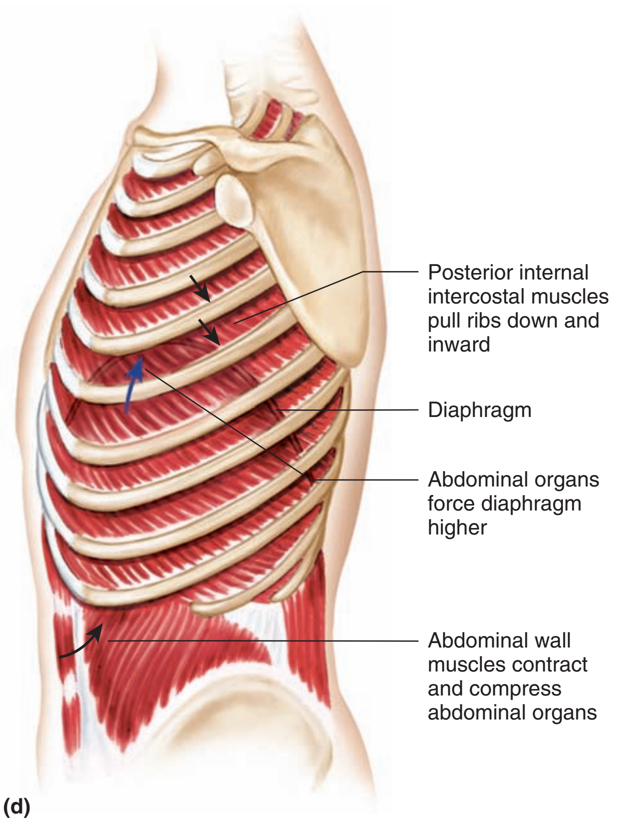

(d)

FIGURE 12.14 concluded

wall and diaphragm, while the visceral pleura is attached to the lung. The pleural fluid between the parietal and visceral pleurae cause the two pleurae to stick together and move as one. As the respiratory muscles expand the thoracic wall and flatten the diaphragm, the parietal pleura moves with the wall and diaphragm. As the parietal pleura moves with the thoracic wall and diaphragm, the visceral pleura and the lung move with it—expanding the lung along with the thoracic cavity. As the lung expands, the pressure within the lung (intrapulmonary pressure) decreases, so air moves in until the pressure inside the lung is equal to the pressure outside the body. The intrapulmonary and atmospheric pressures are then equal. When inspiration ends, the thoracic wall returns to its original position and its volume is diminished. The pressure is now greater in the lung than outside the body, so air flows from the body until the intrapulmonary and atmospheric pressures are again equal. Figure 12.15 shows the muscle action and the pressure changes during inspiration and expiration.

clinical point

A **pneumothorax** (collapsed lung) occurs if air is introduced in the pleural cavity between the pleural membranes. Just as fluid holds the parietal and visceral pleurae together, air between the pleurae allows them to separate. Normally, there is tension on the lung, keeping it partially inflated at all times. However, in a pneumothorax, the pleurae separate, so the lung may recoil and separate from the thoracic wall. The air in a pneumothorax may be introduced by a penetrating trauma like a knife wound or broken rib, medical procedures such as inserting a needle to withdraw pleural fluid, or even a disease like emphysema (covered later in this chapter). In mild cases, the pneumothorax may correct itself without medical intervention. In more severe cases, a chest tube may need to be introduced into the pleural space to remove the air to inflate the lung, and surgery may be required to repair the opening into the pleural space.

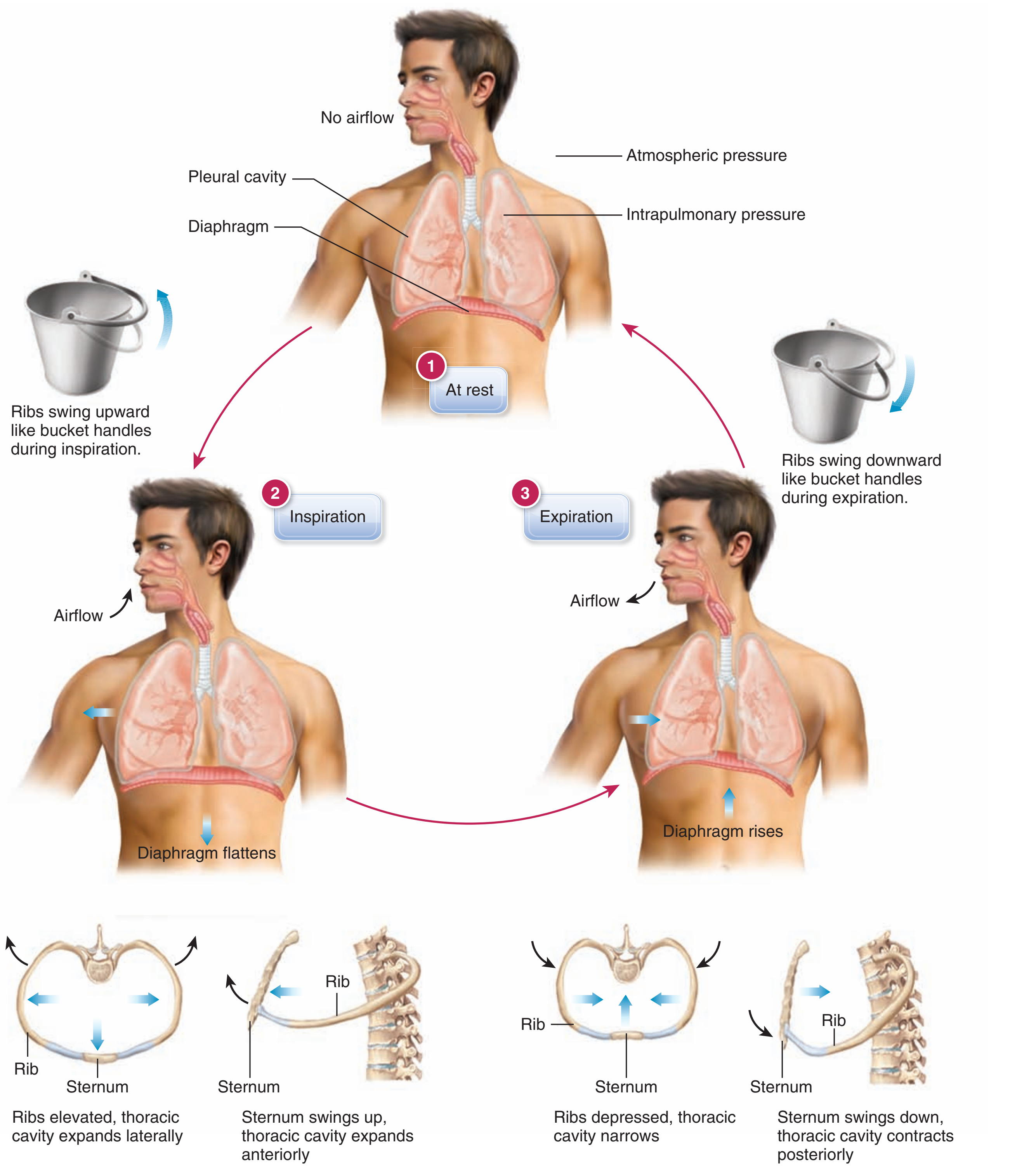

FIGURE 12.15 **A respiratory cycle of inspiration, expiration, and rest:** 1. At rest, atmospheric and intrapulmonary pressures are equal, and there is no airflow. 2. In inspiration, the thoracic cavity expands laterally, vertically, and anteriorly; intrapulmonary pressure falls below atmospheric pressure; and air flows into the lungs. 3. In expiration, the thoracic cavity contracts in all three directions, intrapulmonary pressure rises above atmospheric pressure, and air flows out of the lungs. There is a rest between breaths. The handles of the pails represent ribs.

12.6 learning outcome

Define the measurements of pulmonary function.

Measurements of Pulmonary Function

How well the respiratory system functions to move air into and out of the lungs can be measured in pulmonary function **(spirometry)** tests. A **spirometer** is a device used to measure the volume of air moved. Figure 12.16 shows a photo of Gabe, who is breathing into the spirometer to determine his various **lung volumes** and **lung capacities** (capacities are determined by adding two volumes). Table 12.1 defines the various values, and Figure 12.17 shows a graph of Gabe's values.

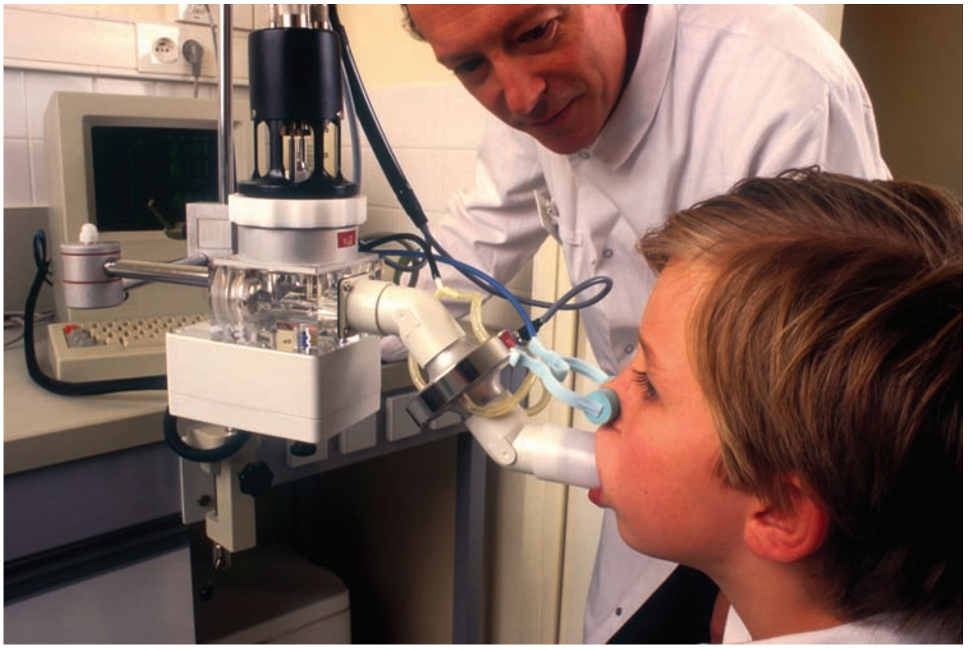

FIGURE 12.16 Spirometry. A spirometer is used to measure lung volumes and capacities.

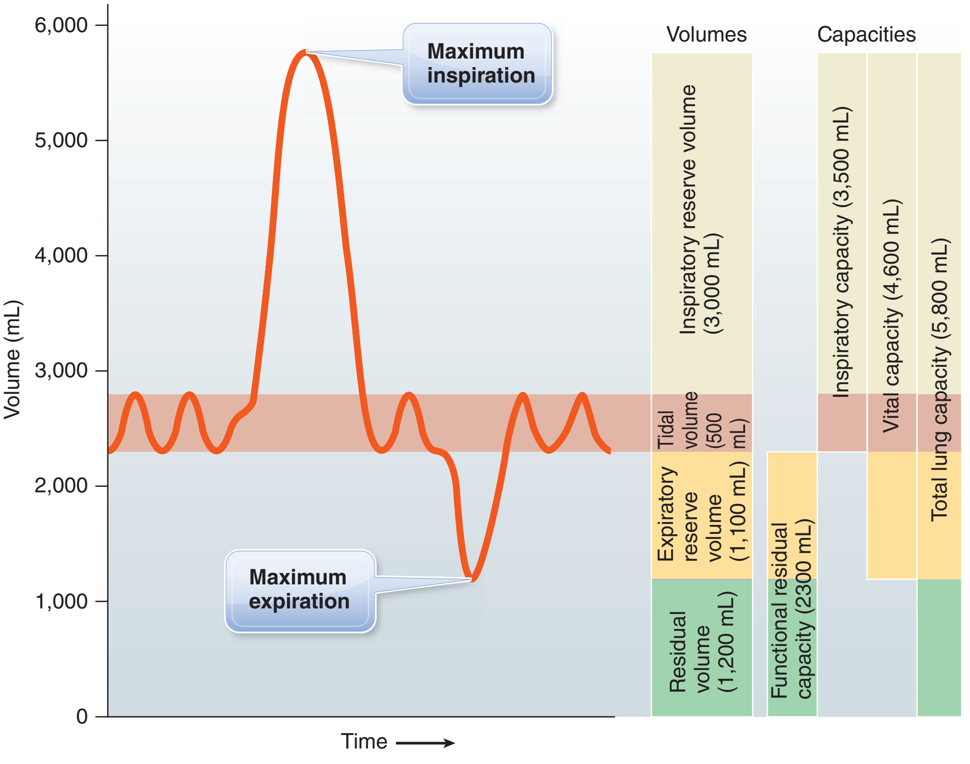

FIGURE 12.17 Graph of pulmonary volumes and capacities.

TABLE 12.1 Lung volumes and capacities

Volume or capacity	Definition	Typical value
Tidal volume (TV)	The tidal volume is the amount of air moved in a normal breath (inspired or expired) at rest.	500 mL
Inspiratory reserve volume (IRV)	The inspiratory reserve volume is the amount of air that can be forcefully inspired beyond the amount inspired in a normal breath at rest.	3,000 mL
Expiratory reserve volume (ERV)	The expiratory reserve volume is the amount of air that can be forcefully expired beyond the amount expired in a normal breath at rest.	1,100 mL
Residual volume (RV)	The residual volume is the amount of air in the lungs that cannot be moved.	1,200 mL
Functional residual capacity (FRC)	The functional residual capacity is the amount of air remaining in the lungs after the expiration of a normal breath at rest. FRC = ERV + RV.	2,300 mL
Inspiratory capacity (IC)	The inspiratory capacity is the maximum amount of air that can be inspired after the expiration of a normal breath at rest. IC = TV + IRV.	3,500 mL
Vital capacity (VC)	Vital capacity is the maximum amount of air that can be moved. VC = IC + FRC.	4,600 mL
Total lung capacity (TLC)	The total lung capacity is the maximum amount of air the lung can hold. TLC = VC + RV.	5,800 mL

Exercise may temporarily increase the tidal volume for an individual, but this does not mean that all of the other values will increase. The maximum amount of air the respiratory system can move (vital capacity) does not change on a temporary (minute-by-minute) basis. So if there is an increase in tidal volume during a workout, there must be a decrease in the inspiratory and expiratory reserve volumes.

Lung volumes and capacities vary from one individual to another due to gender, size, age, and physical condition. In general, a woman's vital capacity is less than a man's; a tall, thin person has a greater vital capacity than someone short and obese; and a trained athlete has a greater vital capacity than someone who has a sedentary lifestyle.

Compliance is another measurement of pulmonary function. It measures how well the lung can expand and return to shape (elasticity). It is harder to expand the lungs and the thorax if there is decreased compliance. This may be due to the buildup of scar tissue in the lung (pulmonary fibrosis), collapse of the alveoli (respiratory distress syndrome), skeletal disorders (scoliosis or kyphosis), or **chronic obstructive pulmonary disorders (COPDs),** such as asthma, chronic bronchitis, emphysema, and lung cancer (discussed later in the chapter).

At this point, you have become familiar with the anatomy of the respiratory system and how it works to deliver air into and out of the lungs. You can now begin to explore the second part of respiration—the exchange of gases—by looking at the gases present in the air you breathe.

12.7 learning outcome

Define partial pressure and explain its relationship to a gas mixture such as air.

Composition of Air

Gases diffuse across membranes from high concentration to low concentration until the concentrations are equal. So it is important to be able to talk about quantities of gases. The air you breathe is a mixture of gases—78.6 percent nitrogen, 20.9 percent oxygen, 0.04 percent carbon dioxide, and variable amounts of water vapor depending on humidity levels. Gases fill whatever space is available to them and can be compressed, so volume is not a good measure of the amount of a gas. For example, an open scuba tank (of a given volume) will fill with air, but more air can be pumped under pressure into the same tank before it is sealed (compressed air). Therefore, the amount of a gas is expressed not as volume but in terms of the pressure a gas exerts. In the case of a mixture of gases, like air, the amount of each gas is expressed as a **partial pressure**—the amount of pressure an individual gas contributes to the total pressure of the mixture. So, if the total pressure of the air (atmospheric pressure) is 760 mmHg, then the partial pressure of nitrogen (P_{N_2}) is 78.6 percent of 760, or 597 mmHg; the partial pressure of oxygen (P_{O_2}) is 20.9 percent of 760, or 159 mmHg; the partial pressure of carbon dioxide (P_{CO_2}) is 0.04 percent of 760, or 0.3 mmHg; and the remainder, 3.7 mmHg, is the partial pressure of water vapor. All of the partial pressures of the gases added together equal the total pressure of the air (760 mmHg).

You will need to understand partial pressures as a measurement of the amount of a gas when you study gas exchange in the lung and out at the tissues in the next section of this chapter.

spot check 7 The atmospheric pressure in Miami on Wednesday was 760 mmHg. However, the atmospheric pressure in Denver on the same day was 640 mmHg. What was the partial pressure of CO_2 in Denver that day? What was the partial pressure of O_2?

12.8 learning outcome

Explain gas exchange in terms of the partial pressures of gases at the capillaries and the alveoli and at the capillaries and the tissues.

Gas Exchange

Before studying **gas exchange,** it will be helpful for you to keep these two facts in mind: (1) Carbon dioxide is a waste product produced in the tissues through cellular respiration and (2) blood travels to the lungs to be oxygenated. With that stated, we begin by explaining gas exchange at the **respiratory membrane** between an alveolus and a capillary in the lung. In this discussion, we use general symbols—greater than (>), less than (<), and equal (=)—instead of worrying about specific values for the moment. Follow along with the numbered steps in Figure 12.18 as you read this section on gas exchange.

animation

BODYANIMAT3D POWERED BY connect

warning

Oxygen and carbon dioxide diffuse across a membrane because of a difference in concentration (concentration gradient) of the same gas. You must compare apples to apples and oranges to oranges, never apples to oranges. In other words, always compare the (P_{O_2}) on one side of the respiratory membrane to the (P_{O_2}) on the other side of the membrane, and then compare the (P_{CO_2}) on one side of the respiratory membrane to the (P_{CO_2}) on the other side of the membrane. Never compare the (P_{O_2}) to the (P_{CO_2}). Oxygen diffuses only if there is a concentration gradient for oxygen across the respiratory membrane. Carbon dioxide diffuses only if there is a concentration gradient for carbon dioxide across the respiratory membrane.

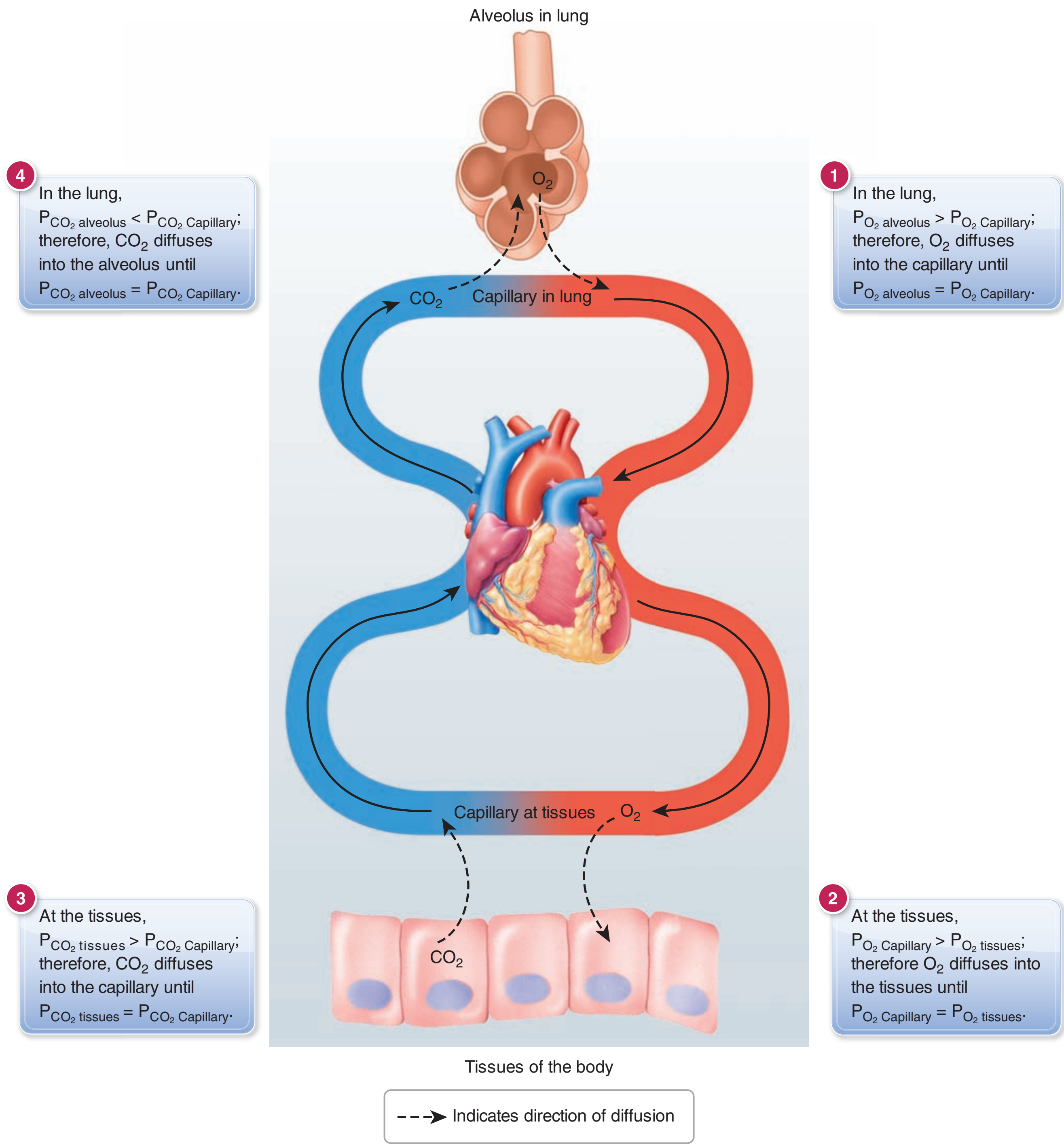

FIGURE 12.18 Gas exchange.

1. Blood coming from the right side of the heart to the lung is low in oxygen. In comparison, the air inspired to the alveolus in the lung is high in oxygen. $P_{O_2\ alveolus} > P_{O_2\ capillary}$, so oxygen diffuses across the respiratory membrane into the blood of the capillary until the partial pressures on both sides of the respiratory membrane are equal: $P_{O_2\ alveolus} = P_{O_2\ capillary}$. Will there still be some oxygen left in the alveolus after the gas exchange has taken place? Yes, because not all of it diffused into the blood; only the amount of oxygen necessary to make the partial pressures equal on both sides diffused. Some oxygen will be expired from the alveolus.

2. The oxygen-rich blood travels from the lung to the left side of the heart before traveling to the capillaries at the tissues of the body. Here the tissues have been using oxygen to perform cellular respiration: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$. As a result, the tissues are relatively low in oxygen compared to the high amount in the blood in the capillary: $P_{O_2 \text{ capillary}} > P_{O_2 \text{ tissues}}$. So oxygen diffuses into the tissues until the partial pressure of oxygen in the blood equals the partial pressure of oxygen in the tissues: $P_{O_2 \text{ capillary}} = P_{O_2 \text{ tissues}}$.

3. Meanwhile, mitochondria in the cells of the tissues have been producing carbon dioxide as a waste product of cellular respiration. As a result, the concentration of carbon dioxide is much higher in the tissues than in the blood of the capillary: $P_{CO_2 \text{ tissues}} > P_{CO_2 \text{ capillary}}$. So carbon dioxide diffuses into the blood of the capillary until the concentrations are equal: $P_{CO_2 \text{ tissues}} = P_{CO_2 \text{ capillary}}$.

4. The blood leaving the capillaries at the tissues of the body travels to the right side of the heart before returning to the lungs. It has lost some of its oxygen and has gained carbon dioxide through diffusion at the tissues of the body. So it makes sense to have started this explanation of gas exchange by saying the blood coming to the lungs was oxygen-poor. It makes just as much sense to say the partial pressure of carbon dioxide is greater in the blood of the capillary at the alveolus than in the air of the alveolus because there is so little carbon dioxide in inspired air (0.04 percent): $P_{CO_2 \text{ capillary}} > P_{CO_2 \text{ alveolus}}$. So carbon dioxide diffuses across the respiratory membrane to the alveolus until the partial pressure of carbon dioxide in the capillary equals the partial pressure of carbon dioxide in the alveolus. $P_{CO_2 \text{ capillary}} = P_{CO_2 \text{ alveolus}}$.

12.9 learning outcome

Compare the composition of inspired and expired air.

Comparison of Inspired and Expired Air Given what you have read about the composition of air and gas exchange, you should be able to compare the composition of inspired and expired air. For this comparison, you will examine gas exchange using specific values. See Figure 12.19. As you can see in this figure, inspired air has more oxygen than expired air, and inspired air has less carbon dioxide than expired air.

12.10 learning outcome

Explain the factors that influence the efficiency of alveolar gas exchange.

Factors That Influence Gas Exchange Several factors influence the effectiveness of alveolar gas exchange. They are explained in the following list:

- **Concentration of the Gases.** The concentration of the gases matters because the greater the concentration gradient, the more diffusion takes place. For example, gas exchange of oxygen will increase if a patient is administered oxygen instead of breathing room air. In contrast, gas exchange of oxygen will be less at higher altitudes because the air is thinner and does not contain as much oxygen.

- **Membrane Area.** Membrane area matters because the greater the area of the respiratory membrane, the greater the opportunity for gas exchange. For example, Figure 12.20 shows alveolar tissue for a healthy individual, a pneumonia patient, and a person with emphysema. You will notice the lack of respiratory membrane for the emphysema patient. This is because emphysema breaks down the alveolar walls. The reduced membrane area means less gas will be exchanged.

- **Membrane Thickness.** The thickness of the respiratory membrane matters because the thicker the membrane, the harder it is for gases to diffuse across it. Look again at Figure 12.20. Pneumonia may cause excess fluid in the alveoli and swelling of the alveolar walls, which make gas exchange much more difficult.

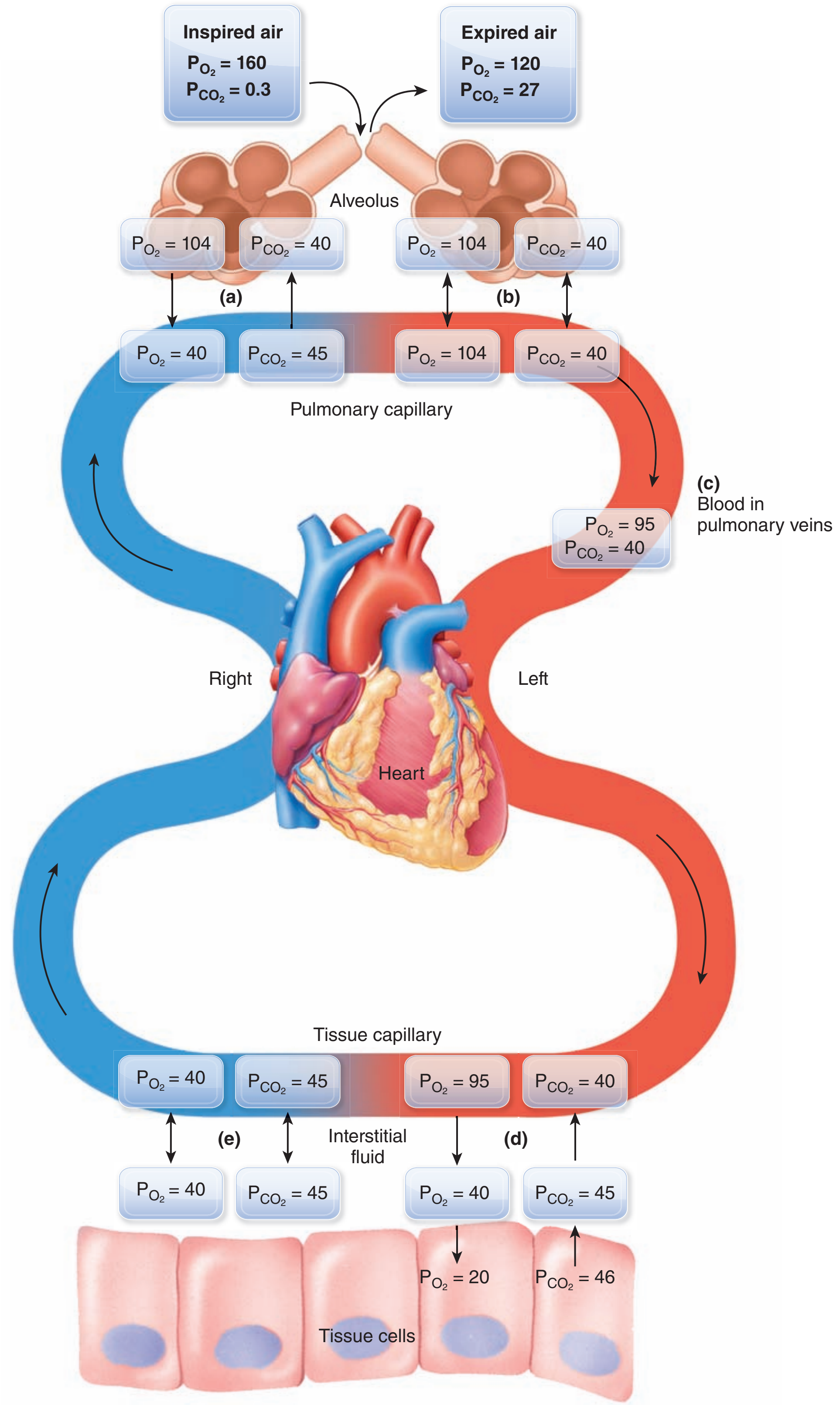

FIGURE 12.19 Changes in P_{O_2} and P_{CO_2} along the respiratory route. Values are expressed in mmHg. (a) Oxygen diffuses into the arterial ends of pulmonary capillaries, and CO_2 diffuses into the alveoli because of differences in partial pressures. (b) As a result of diffusion (at the venous ends of the pulmonary capillaries), the concentrations of O_2 are equal on both sides of the respiratory membrane, as are the concentrations of CO_2 on both sides of the respiratory membrane. (c) The partial pressure of O_2 is reduced in the pulmonary veins due to the mixing of blood drained from the bronchi and bronchial tree. (d) Oxygen diffuses out of the arterial end of capillaries to the tissues, and CO_2 diffuses out of the tissues to the capillaries due to the differences in partial pressures. (e) As a result of diffusion (at the venous ends of tissue capillaries), the concentrations of O_2 are equal in the capillaries and the tissues, as are the concentrations of CO_2 in the capillaries and the tissues.

- **Solubility of the gas.** Gases must be able to dissolve in water if they are to diffuse across a membrane into the blood. For example, nitrogen is 78.6 percent of the air you breathe, but it does not diffuse across the respiratory membrane because it is not soluble at normal atmospheric pressure. Oxygen and carbon dioxide are soluble at normal atmospheric pressure.

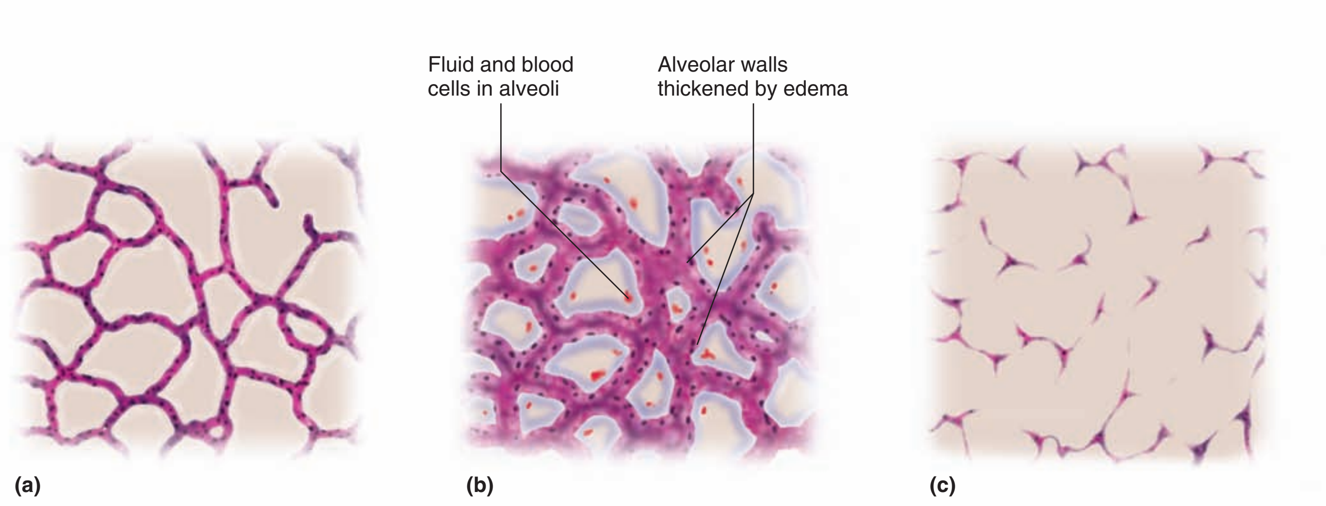

FIGURE 12.20 Influences on gas exchange: (a) normal alveoli, (b) alveoli of pneumonia patient, (c) alveoli of emphysema patient.

clinical point

Scuba divers breathe air from their tanks. It is not pure oxygen; it is air that has been compressed so that the tank can hold more. If divers go to significant depths, nitrogen becomes soluble because of the increased pressure—every 10 meters of water is equal to another full atmosphere of pressure. Although nitrogen can then diffuse across the respiratory membrane, this is alright because nitrogen does not react with anything in the blood. It becomes very relevant, however, during the ascent from the dive. If the diver comes up too quickly, nitrogen comes out of solution as a gas wherever it is in the body. This is similar to club soda being uncapped and poured. See Figure 12.21. Removing the cap relieves the pressure within the can or bottle. The carbon dioxide in the club soda quickly comes out of solution as bubbles with the reduced pressure. The nitrogen bubbles can cause severe damage to the diver's nerves and other tissues. Divers must ascend very slowly to allow nitrogen to slowly come out of solution, diffuse across the respiratory membrane in the alveoli, and be exhaled. **Decompression sickness,** or the **bends,** is the disorder that results if a diver ascends from depths too quickly. The treatment is to put the diver immediately in a hyperbaric (increased-pressure) chamber and put the body under sufficient pressure to have the nitrogen dissolve again and then to slowly decrease the pressure so that the nitrogen can be exhaled.

FIGURE 12.21 Glass of club soda.

- **Ventilation-perfusion coupling.** This basically means that the airflow to the lung must match the blood flow to the lung. Ideally, the maximum amount of air should go to where there is the maximum amount of blood in the lung. This is accomplished through local control in two ways:

    1. **Lung perfusion** (blood flow to alveoli). As blood flows toward alveolar capillaries, it is directed to lobules in the lung where the partial pressure of oxygen is high. How? Alveolar capillaries constrict where the partial pressure of oxygen is low, so blood is diverted to where the partial pressure of oxygen is high.

    2. **Alveolar ventilation** (airflow to alveoli). Smooth muscles in the walls of bronchioles are sensitive to the partial pressure of carbon dioxide. If the partial pressure of carbon dioxide increases, the bronchioles dilate. If the partial pressure of carbon dioxide decreases, the bronchioles constrict. Airflow is therefore directed to lobules where partial pressure of carbon dioxide is high.

Ventilation-perfusion coupling is very important because it allows the respiratory system to compensate for damaged lung tissue. If an area of the lung is damaged, less air and less blood are directed to that area. See Figure 12.22.

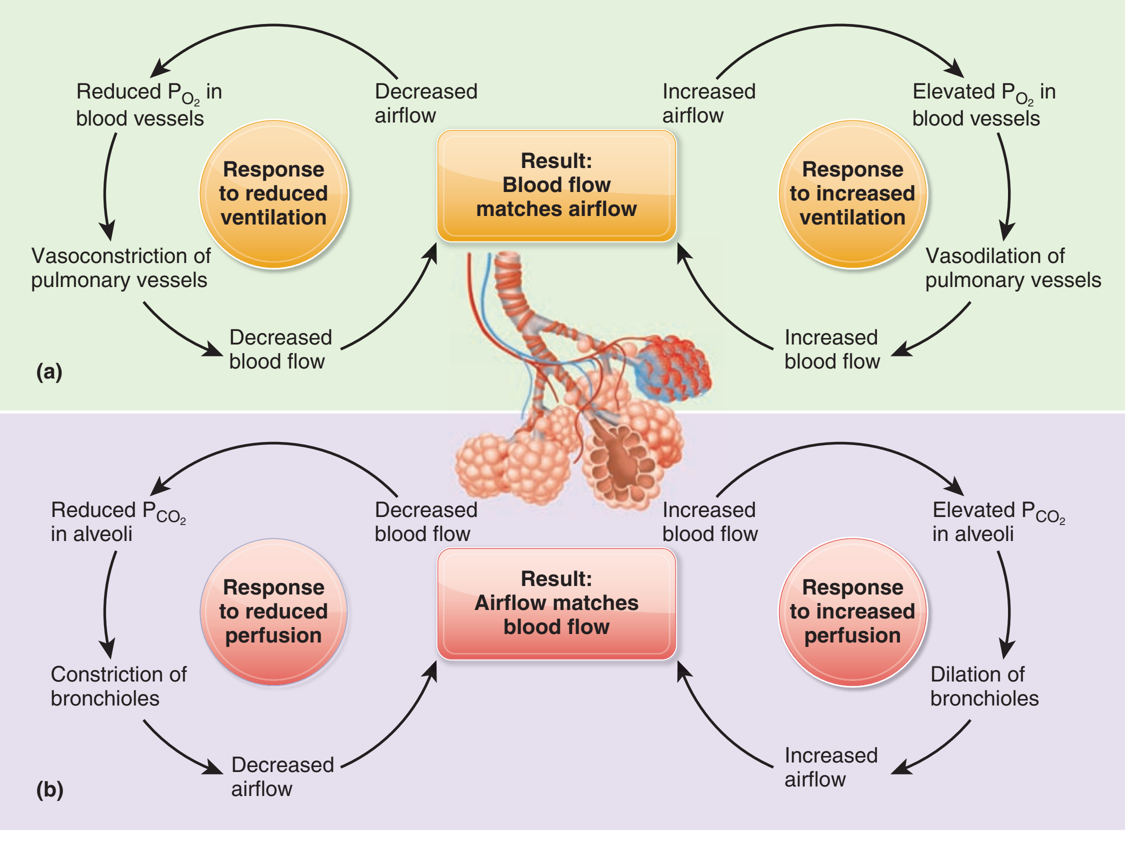

FIGURE 12.22 **Ventilation-perfusion coupling:** (a) perfusion adjusted to changes in ventilation, (b) ventilation adjusted to changes in perfusion.

spot check 8 The atmospheric pressure is 760 mmHg in New York City and 630 mmHg in Breckenridge, Colorado. In which city should more gas exchange take place? Explain.

12.11 learning outcome

Describe the mechanisms for transporting O_2 and CO_2 in the blood.

Gas Transport

You have now studied how carbon dioxide and oxygen are exchanged across membranes into and out of the blood, but how are these gases carried in the blood from one place to another? To understand gas transport, first look at Figures 12.23 (systemic gas exchange and transport) and 12.24 (alveolar gas exchange and transport). Notice the red and blue arrows in these figures. The blue arrows represent CO_2, while the red arrows represent O_2. The thickness of the arrows represents the relative amounts of the gases being exchanged. Although there are three blue arrows and two red arrows in each figure, concentrate on the largest blue arrow (representing 70 percent of the CO_2) and the largest red arrow (representing 98.5 percent of the O_2). These two arrows explain the majority of gas transport in the blood happening at the body's tissues (Figure 12.23) and at the alveoli (Figure 12.24).

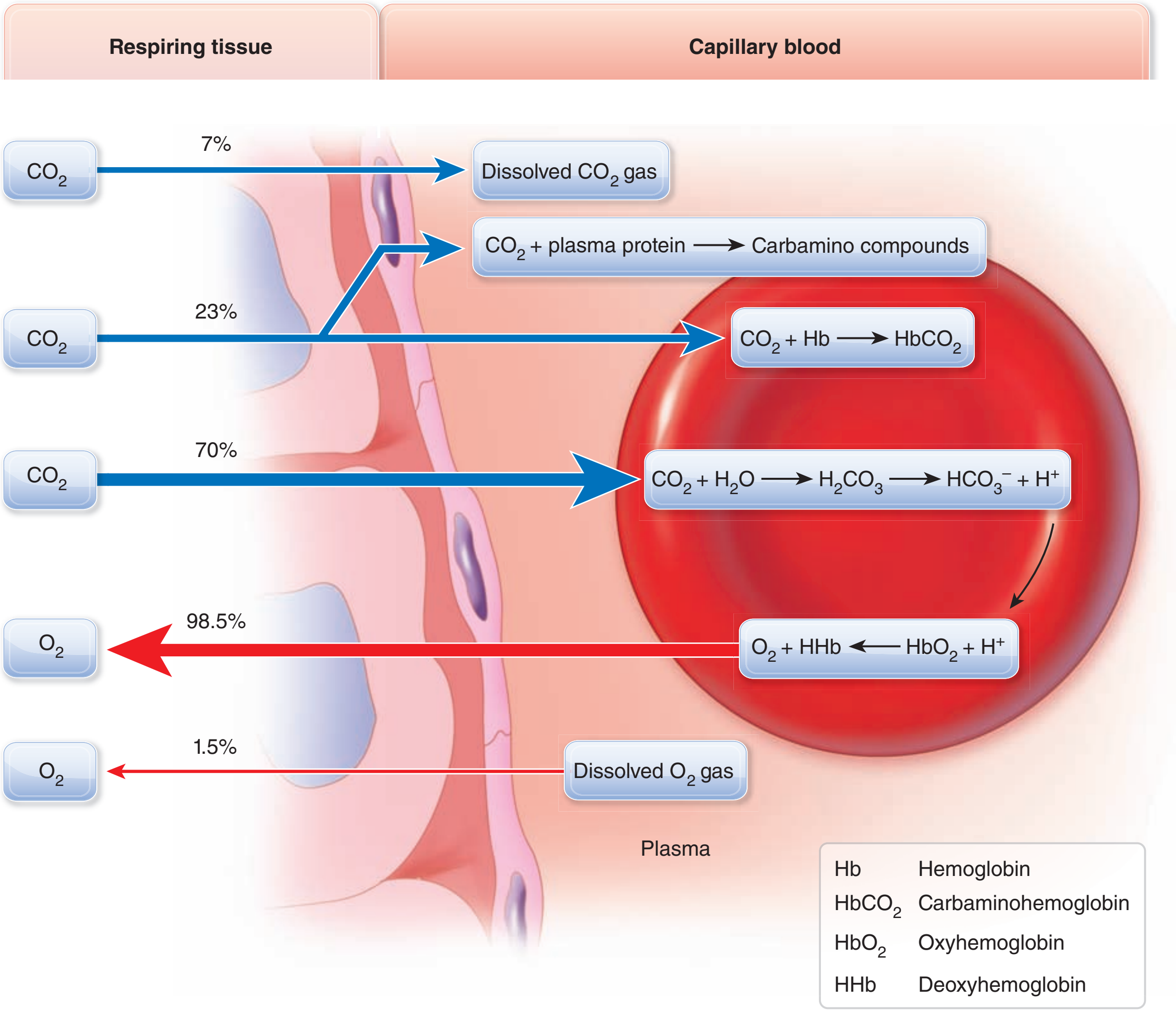

FIGURE 12.23 Systemic gas exchange and transport. The blue arrows represent CO_2 transport, while the red arrows represent O_2 transport. The thickness of the arrows represents the relative amounts of the gases being transported.

Systemic Gas Exchange and Transport You should already be aware that the tissues of the body produce CO_2 as a waste product of cellular respiration and that, because the $P_{CO_2\text{ tissues}} > P_{CO_2\text{ capillary}}$, CO_2 diffuses from the tissues into the capillaries. Now you need to understand that the diffused carbon dioxide mixes with water in the blood to form **carbonic acid** (H_2CO_3). Carbonic acid, because it is in water, separates into its two ions: a **bicarbonate ion** HCO_3^- and a hydrogen ion (H^+)—

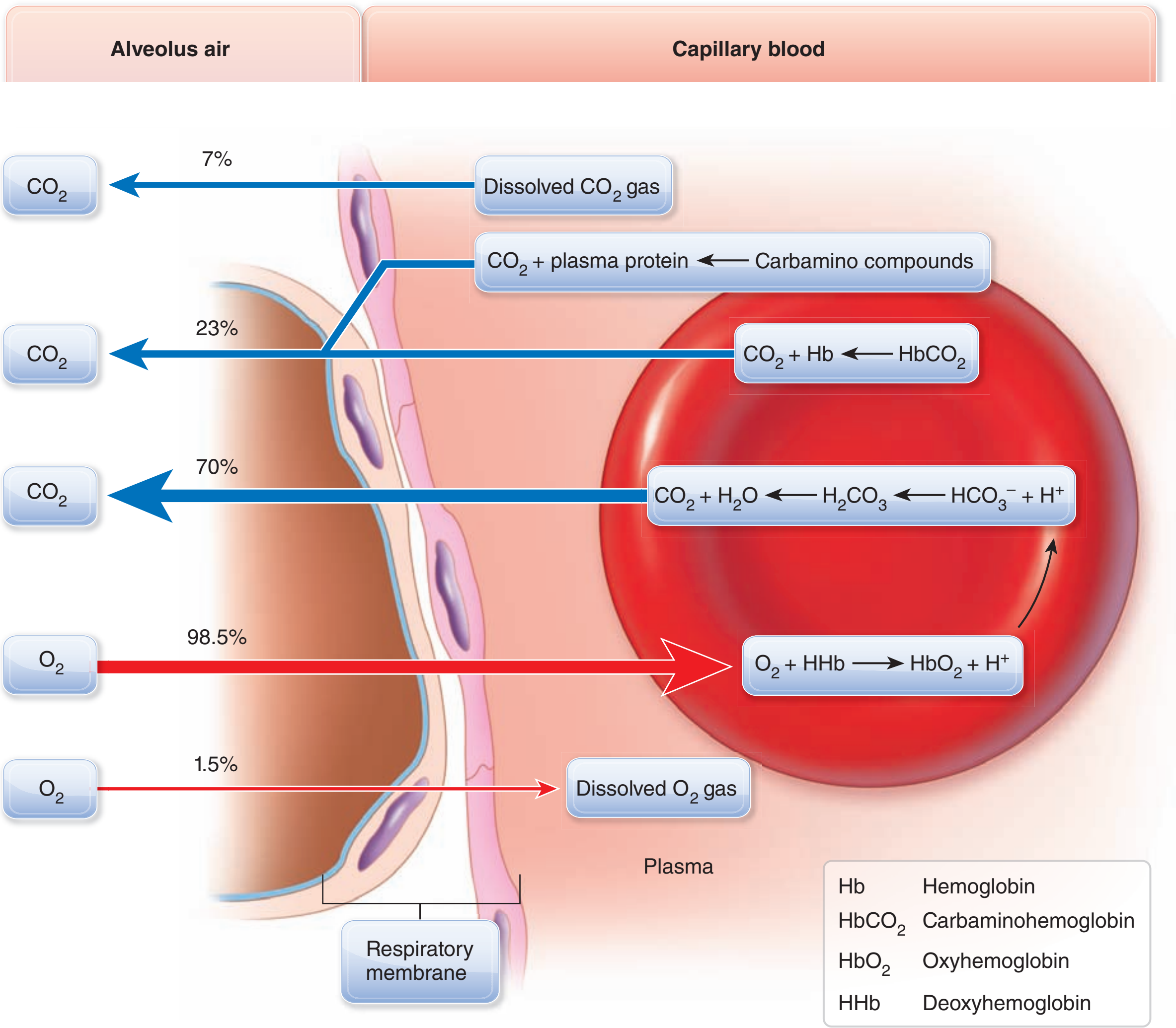

FIGURE 12.24 Alveolar gas exchange and transport. The blue arrows represent CO_2 transport, while the red arrows represent O_2 transport. The thickness of the arrows represents the relative amounts of the gases being transported.

remember from Chapter 2 that water allows for ions in solution. This reaction is shown in Figure 12.23 where the largest blue arrow enters the blood:

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+$$

Free hydrogen ions in the blood would lower the pH of the blood, but notice in Figure 12.23 that the free hydrogen ion (H^+) reacts with **oxyhemoglobin** (HbO_2) to become **deoxyhemoglobin** (HHb) and oxygen (O_2):

$$H^+ + HbO_2 \rightarrow HHb + O_2$$

Hemoglobin releases oxygen in the presence of a hydrogen ion and then binds to it (H^+). By binding to the free hydrogen ions, hemoglobin acts as a buffer, resisting a change of pH in the blood. $P_{O_2\ \text{capillary}} > P_{O_2\ \text{tissues}}$, so oxygen diffuses to the tissues until $P_{O_2\ \text{tissues}} = P_{O_2\ \text{capillary}}$.

The blood containing deoxyhemoglobin and bicarbonate ions continues to the right side of the heart and on to the alveoli of the lung. Below, you will learn what happens in alveolar gas exchange and transport, as shown in Figure 12.24.

Alveolar Gas Exchange and Transport Again, you should focus on the largest red and blue arrows representing oxygen and carbon dioxide in Figure 12.24. In the alveolus, the $P_{O_2\ \text{alveolus}} > P_{O_2\ \text{capillary}}$, so oxygen diffuses into the capillaries. When it does, deoxyhemoglobin reacts with oxygen to release hydrogen ions and form oxyhemoglobin:

$$HHb + O_2 \rightarrow HbO_2 + H^+$$

The now free hydrogen ions ($H+$) in the capillary at the alveolus bind to the bicarbonate ions (HCO_3^-) to form carbonic acid (H_2CO_3) in the blood. This results in carbon dioxide and water. Notice that this is the reverse of the reaction happening for carbon dioxide at the tissues. $P_{CO_2\ capillary} > P_{CO_2\ alveolus}$, so carbon dioxide diffuses across the respiratory membrane to the alveolus until $P_{CO_2\ capillary} = P_{CO_2\ alveolus}$.

$$H^+ + HCO_3^- \rightarrow H_2CO_3 \rightarrow CO_2 + H_2O$$

animation bodyANIMAT3D
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Basically, most of the oxygen is transported in the blood by hemoglobin as oxyhemoglobin, and most of the carbon dioxide is transported in the blood as bicarbonate ions. Hemoglobin functions to carry oxygen from the lungs to the tissues and hydrogen ions from the tissues to the lungs.

clinical point

You have already read about hemoglobin carrying carbon monoxide (CO) in Chapter 9. Hemoglobin binds to carbon monoxide 210 times more tightly than to oxygen, and it does not carry oxygen as long as it is bound to carbon monoxide. CO is produced during combustion, so it can be emitted from improperly vented furnaces, cars (exhaust), and even cigarettes as they are smoked. Typically, less than 1.5 percent of hemoglobin is bound to carbon monoxide in nonsmokers, while 10 percent of a heavy smoker's hemoglobin may be bound to carbon monoxide. Mechanics need to ventilate their garages while they work because even just a 0.1 percent concentration of CO in the air can bind to 50 percent of the worker's hemoglobin, and a 0.2 percent atmospheric concentration can be lethal.

12.12 learning outcome

Explain how respiration is regulated to homeostatically control blood gases and pH.

Regulation of Respiration

Now that you have become familiar with how oxygen and carbon dioxide are transported in the blood, you are ready to examine how the respiratory system is regulated to homeostatically control blood gases and pH.

The main control centers for respiration are located in the medulla oblongata. See Figure 12.25. From there, messages to stimulate inspiration travel through inspiratory (I) neurons that go to the spinal cord and then out to the diaphragm and intercostal muscles (by way of the phrenic and intercostal nerves). Expiratory (E) neurons in the medulla oblongata send signals only for forced expiration.

As you have previously learned, increasing the frequency of nerve impulses causes longer muscle contractions and, therefore, deeper inspirations. If the length of time (duration) is increased for each stimulus, the inspiration is prolonged and the breathing is slower. When nerve impulses from the inspiratory neurons end, muscles relax and expiration takes place.

Information concerning the need for regulation comes to the respiratory centers in the medulla oblongata from several sources. These sources are explained in the following list:

- Stretch receptors in the thoracic wall send signals to the medulla oblongata as to the degree of the chest's expansion. When maximum expansion has been reached, the medulla oblongata stops sending inspiratory messages. This prevents overinflation of the lungs, and it is most important in infants. This action is called the **Hering-Breuer** reflex.

- Proprioceptors in the muscles and joints send signals to respiratory centers during exercise so that ventilation is increased. The respiratory centers in the medulla oblongata can increase the depth and rate of respiration.
- The **pontine respiratory group** in the pons receives input from the hypothalamus, limbic system, and cerebral cortex. It then sends signals to the medulla oblongata to adjust the transitions from inspiration to expiration. In that way, the breaths become shorter and shallower or longer and deeper. This center helps adjust respirations to special circumstances, such as sleep, exercise, or emotional responses like crying.
- The cerebral cortex can exert voluntary control over the respiratory system, but this is limited control. For example, a stubborn child may threaten to hold his breath to get his way. However, if he is allowed to do so, he will eventually pass out and will start breathing again.
- **Peripheral chemoreceptors** in the aortic arch and carotid arteries (discussed in Chapter 10) and **central chemoreceptors** in the medulla oblongata send information to the respiratory centers in the medulla oblongata concerning pH, CO_2, and O_2. The peripheral chemoreceptors (shown in Figure 12.26) monitor the blood, while the central chemoreceptors monitor the cerebral spinal fluid (CSF). Why monitor both fluids? Hydrogen ions in the blood cannot pass the blood-brain barrier, but carbon dioxide does cross the barrier. When it does, it reacts with the water in the CSF to form H^+, just as it does at the tissues when mixing with the water in the blood. An increased concentration of hydrogen ions in either fluid means reduced pH. The most important driver of respiration is pH, the next is CO_2, and the driver of minor importance is O_2. Respiration is adjusted by the medulla oblongata to maintain pH in the homeostasis range for blood of 7.35 to 7.45. **Acidosis** occurs if the pH of the blood is less than 7.35. The medulla oblongata then stimulates **hyperventilation** (increased respiratory rate) to blow off CO_2 through expiration to raise the pH. **Alkalosis** results if the pH of the blood is greater than 7.45. The medulla oblongata then stimulates **hypoventilation** (decreased respiratory rate) to keep CO_2 in the blood to lower the pH. **Hypercapnia,** increased carbon dioxide in the blood, causes the pH to fall in both fluids. Oxygen is of minor importance as a driver of respiration because the blood's hemoglobin is usually 97 percent saturated with oxygen during normal breathing. Oxygen drives respiration only during extreme conditions, such as mountain climbing at high altitudes, and when it does, this is called **hypoxic drive.**

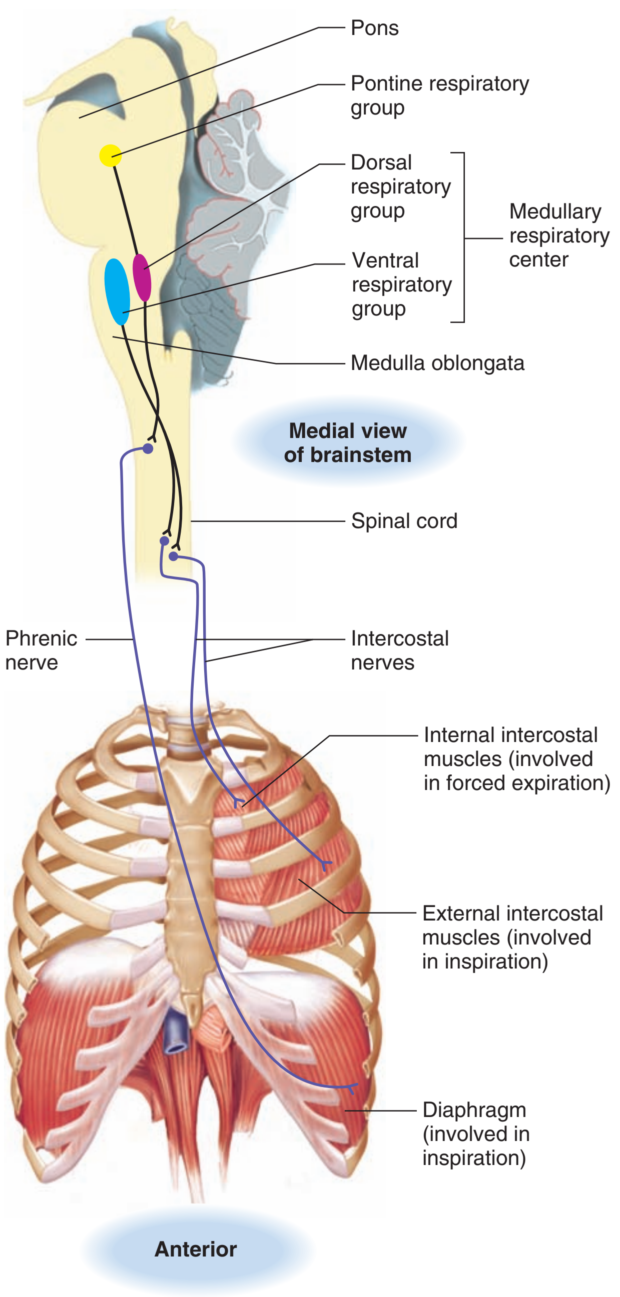
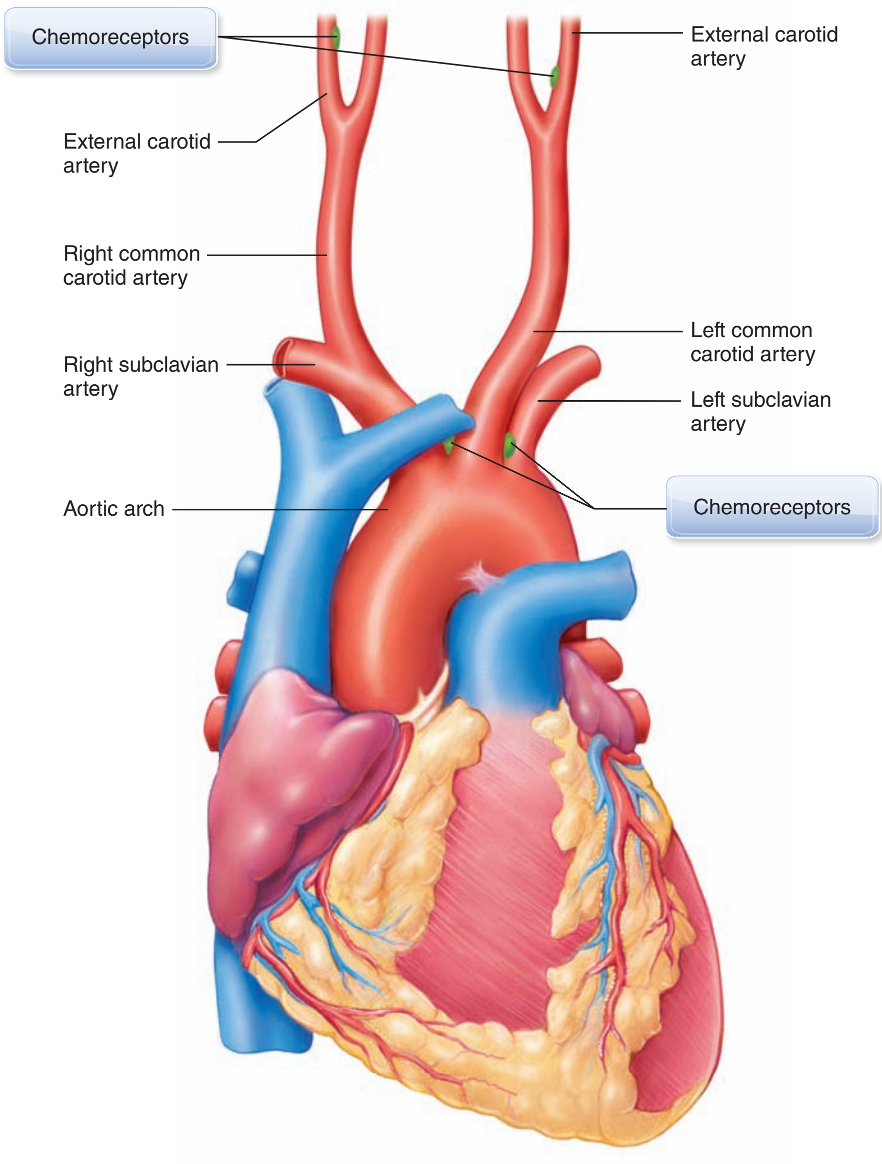


FIGURE 12.25 Control centers for respiration.

You have now explored all of the respiratory anatomy and the physiology of this system. It is time to put that information together to see how the functions of this system are carried out for Carol, who is on a break from her job in the business office at the hospital. See Figure 12.27.

FIGURE 12.26 Peripheral chemoreceptors of respiration. These chemoreceptors monitor blood gases (CO_2 and O_2) and blood pH. They send signals to the respiratory centers in the medulla oblongata along the vagus and glossopharyngeal nerves.



12.13 learning outcome

Explain the functions of the respiratory system.

Functions of the Respiratory System

Carol appears to be a relatively young, healthy woman who is a smoker. Although her respiratory system functions normally at present, her lifestyle choice to continue to smoke may have harmful, long-term effects on her respiratory system. In the list below, we explain the effects on each of the functions of this system:

- **Gas exchange.** Carol's respiratory system functions to exchange carbon dioxide and oxygen across the respiratory membranes of her lungs and out at the tissues of her body. However, each time she inspires through a lit cigarette, she also exchanges carbon monoxide across her respiratory membrane, which then binds to the hemoglobin in her blood. Hemoglobin bound to CO no longer functions to carry oxygen, so her levels of O_2 in the blood will fall (hypoxia). Her kidneys notice the decreased O_2 levels and secrete erythropoietin (EPO, discussed in Chapter 9) to stimulate erythropoiesis to increase the RBC count and the available hemoglobin to carry O_2.

- **Acid-base balance.** Carol's respiratory system regulates her acid-base balance by increasing respirations whenever the pH of her blood begins to fall below homeostasis. Hyperventilation gets rid of more CO_2, so the pH of the blood increases. If Carol's blood pH rises above homeostasis, her respiratory rate will slow (hypoventilation), so any CO_2 in her system remains in the blood longer, thus lowering her pH to normal levels.

- **Speech.** The muscles of Carol's larynx contract to move the arytenoid and corniculate cartilages that operate her vocal cords and cause them to vibrate to produce sound. Even the sinuses connected to her nasal cavity will aid in her speech by giving resonance to her voice. However, her smoking tends to irritate and dry the lining of her larynx. This may lead to laryngitis and a scratchy voice.

- **Sense of smell.** Olfactory neurons in the epithelium of the roof of Carol's nasal cavity detect odors for her sense of smell (covered in detail in Chapter 7). Carol's smoking may cause these receptors to become less sensitive, limiting her ability to sense odors and appreciate flavors.

- **Creation of pressure gradients necessary to circulate blood and lymph.** The muscles used during respiration increase the volume of the thoracic cavity, causing the pressure inside the cavity to fall. As you have learned in this chapter, this pressure decrease will cause air to flow into Carol's lungs. However, you have also studied this mechanism in the circulatory and lymphatic systems as the thoracic pump. This pressure decrease in the thorax also helps Carol's blood return (through the inferior vena cava) to her heart and helps her lymph return (through the thoracic duct) to her left subclavian vein. The thoracic pump created by this system will be less effective if Carol's blood becomes thicker due to smoking-related polycythemia (discussed in Chapter 9).

FIGURE 12.27 Carol.

Carol's respiratory system is functioning now, but what can she expect to be the effects of growing older even if she decides to stop smoking?

Effects of Aging on the Respiratory System

12.14 learning outcome

Summarize the effects of aging on the respiratory system.

Aging has many effects on the respiratory system, which basically lead to a decline in maximum function. These effects are as follows:

- With age, more mucus accumulates in the respiratory tract because the ciliated escalator becomes less efficient. The inability to clear debris efficiently leaves the elderly open to more respiratory infections. So vaccines to prevent infections, such as flu and pneumonia, are highly recommended for the elderly.

- Thoracic wall compliance decreases due to the diminished ability to expand the chest that comes with age. This can be due to weakened respiratory muscles, stiffening of the cartilages in the rib cage, decreased height of the vertebrae from age-related osteoporosis, and kyphosis. The net effect of the reduced compliance is reduced vital capacity because the ability to fill the lungs (inspiratory reserve volume) and the ability to empty the lungs (expiratory reserve volume) are both decreased.

- Some of the alveoli walls may break down, and this reduces the area of the respiratory membrane. The remaining membrane thickens with age, reducing alveolar gas exchange. Tidal volume gradually increases with age to compensate for the reduced area and thickening of the respiratory membrane.
- Obstructive sleep **apnea** (breathing repeatedly stops and starts during sleep) may develop in the elderly as the pharyngeal muscles intermittently relax and block the airway during sleep. This form of apnea may or may not be accompanied by snoring, and it is more prevalent in people who are overweight.

The effects of aging may not be readily apparent in a healthy individual, but they may diminish even the healthy individual's ability to perform vigorous exercise. You will complete your study of this system by examining what can go wrong—respiratory disorders.

12.15 learning outcome

Describe respiratory system disorders.

Respiratory System Disorders

The respiratory disorders discussed below fall into three categories: infections, chronic obstructive pulmonary diseases (COPDs), and lung cancer.

Respiratory Infections

Cold The most common respiratory infection is the common cold, which is commonly caused by a rhinovirus. Its symptoms include congestion, sneezing, and increased mucus production. This infection can easily spread to the sinuses, throat, and middle ear. Typically, a cold runs its course in about a week.

applied genetics

Cystic fibrosis is the most common fatal genetic disease in the United States. As you read in Chapter 2, cystic fibrosis is caused by a single gene in the human DNA that codes for a faulty chloride channel on cell membranes. People with a faulty cystic fibrosis transmembrane regulator gene (CFTR) produce a sticky mucus that cannot be easily moved by the respiratory epithelium's ciliated escalator. As a result, the sticky mucus accumulates in the lungs and airways, and this then leads to infection. Gene therapy for cystic fibrosis began in 1990 when scientists were successful in introducing correct copies of the gene to cells in laboratory cultures. In 1993, common rhinoviruses were tried as a delivery mechanism (vector) to deliver the correct gene. These viruses were tried as vectors because rhinoviruses specifically invade respiratory cells and deliver a piece of nucleic acid to the invaded cell. If the rhinovirus could be modified to carry and insert the correct copy of the CFTR gene, it would deliver it to the appropriate type of cell in a cystic fibrosis patient. Since then, other vectors have been tried in an effort to find the most efficient way of introducing the correct gene to the affected cells. Life span of the respiratory cells also needs to be considered to determine the correct vector and treatment schedule. The research into gene therapy for this disease continues.[1]

Influenza Flu is a respiratory—not digestive—illness caused by a virus. In addition to its cold symptoms, flu is characterized by fever, chills, and muscle aches. The mortality rate for influenza is approximately 1 percent, with most of the deaths occurring in the very young and the elderly. Influenza viruses mutate and change often, so vaccines are created each year to protect against the expected viral flu strains for that year.

Tuberculosis This infection is caused by a bacterium that enters the lungs by way of air, blood, or lymph. The lungs react to the infection by walling off bacterial lesions with scar tissue that diminishes lung compliance. Health care workers are tested for exposure to the bacteria with a Mantoux test.

Pertussis This highly contagious bacterial infection causes the paralysis of cilia in the respiratory epithelium. The accumulation of mucus and debris results in a *whooping cough,* which gives this disorder its common name. Pertussis vaccine is one part of the DPT shot routinely given in the United States to children. (D stands for *diphtheria,* P stands for *pertussis,* and T stands for *tetanus*).

Pneumonia This infection can be caused by bacteria, a virus, a fungus, or even a protozoan. Symptoms include fever, difficulty breathing, and chest pain. In this type of infection, fluid accumulates in the alveoli (pulmonary edema), and inflammation causes the respiratory membrane to thicken, thereby reducing gas exchange.

COPDs

Chronic obstructive pulmonary disorders cause the long-term decrease in ventilation of the lungs. Many COPDs are the result of cigarette smoking.

Chronic Bronchitis This disorder often results from long-term irritation of the epithelium of the bronchial tree. With the subsequent inflammation, cilia are lost and mucus is overproduced. Without the cilia escalator, mucus and debris accumulate, leading to further chronic inflammation and infections. The long-term effect is a decrease in the diameter of the bronchioles, which reduces ventilation of the alveoli. Chronic bronchitis often leads to emphysema.

Emphysema In this disorder, constant inflammation from irritants narrows bronchioles, reducing the airflow to the lungs. The respiratory system tries to clear built-up mucus and debris—often from chronic bronchitis—by coughing. The coughing causes increased pressure in the alveoli that results in rupturing of the alveolar walls. This loss of respiratory membrane reduces gas exchange and reduces the recoil of the lung (compliance). Symptoms of emphysema include shortness of breath and an enlargement of the thoracic cavity (barrel chest).

Asthma This disorder involves increased constriction of the lower respiratory tract due to a variety of stimuli. The symptoms include wheezing, coughing, and shortness of breath. Although no definitive cause has been found, asthma and allergies often go together. Whatever the cause, asthma is characterized by chronic airway inflammation, airway obstruction, and airway hyperreactivity, in which the smooth muscle overreacts to a stimulus by constricting the bronchioles. Treatment involves avoiding the stimulus—if it can be determined—and drug therapy.

Lung Cancer

More people die every year from lung cancer than from any other form of cancer. The most common cause of lung cancer is cigarette smoking. See Figure 12.28. According to the Centers for Disease Control (CDC), at least 50 carcinogens can be found in cigarette smoke.[2] There are three forms of lung cancer:

- **Squamous cell carcinoma** originates in the bronchial epithelium. In this form of lung cancer, the ciliated epithelium undergoes metaplasia first, changing to stratified epithelial tissue. Cancerous cells further divide, invading tissues of the bronchial walls and forming tumors that can block airways.

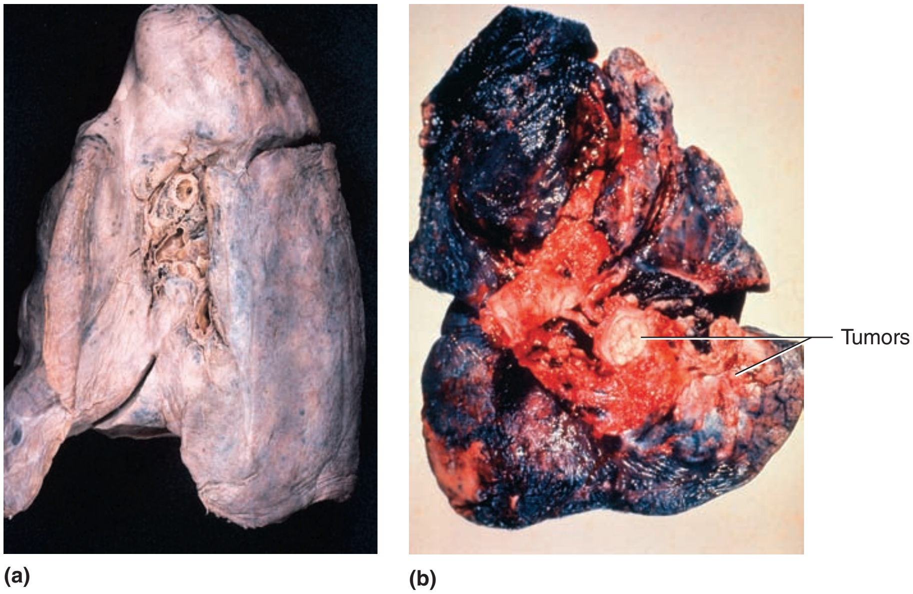


FIGURE 12.28 Effects of Smoking: (a) healthy lung, medial surface, (b) smoker's lung with carcinoma.

- **Adenocarcinoma** originates in the mucous glands of the bronchial tree in the lung. Like squamous cell carcinoma, it also invades other tissues of the bronchial tree and lung.
- **Oat cell carcinoma** is the least common form of lung cancer, but it is the most deadly because it easily metastasizes to other tissues. It usually begins in a main bronchus and then invades the mediastinum and travels to other organs.

putting the pieces **together**

The Respiratory System

Integumentary system

Has guard hairs in the nose to trap debris.

Allows for the exchange of O_2 and CO_2 in system tissues.

Skeletal system

Ribs protect lungs, bone gives structure to the nasal passages to warm and moisturize inspired air, and sinuses give resonance to the voice.

Allows for the exchange of O2 and CO_2 in system tissues.

Muscular system

Skeletal muscles are responsible for inspiration and forced expiration.

Allows for the exchange of O_2 and CO_2 in system tissues.

Nervous system

Medulla oblongata regulates the respiratory rate.

Allows for the exchange of O_2 and CO_2 in system tissues.

Endocrine system

Hormones such as epinephrine increase airflow and respiratory rate.

Allows for the exchange of O_2 and CO_2 in system tissues.

Cardiovascular system

Blood transports O_2 and CO_2.

Allows for the exchange of O_2 and CO_2.

Lymphatic system

Sends white blood cells to fight pathogens in the respiratory system.

Allows for the exchange of O_2 and CO_2 in system tissues; thoracic pump helps return lymph to the cardiovascular system.

Digestive system

Provides nutrients for respiratory system tissues.

Allows for the exchange of O_2 and CO_2 in system tissues.

Excretory/urinary system

Kidney secretes EPO when the blood oxygen level is low.

Allows for the exchange of O_2 and CO_2 in system tissues.

Reproductive system

Allows for the exchange of O_2 and CO_2 in a fetus.

Allows for the exchange of O_2 and CO_2 in system tissues.

FIGURE 12.29 **Putting the Pieces Together—The Respiratory System:** connections between the respiratory system and the body's other systems.

summary

Overview

- Cellular respiration is performed by mitochondria in cells to process energy.
- Respiration as a system refers to the movement of gases into and out of the lungs and the exchange of gases between the alveoli and capillaries in the lung and capillaries and tissues in the body.

Anatomy of the Respiratory System

- The air in an inspiration enters the nasal cavity through the nose and continues on to the nasopharynx, oropharynx, and laryngopharynx. It then travels through the glottis to the larynx, to the trachea, to the main bronchi, to the bronchial tree, and finally to the alveoli.

Nose

- The nasal bones and nasal cartilages shape the nose.

Nasal Cavity

- The mucous membranes of the nasal cavity warm and moisturize the air and remove debris
- Nasal conchae provide extra surface area.

Pharynx

- The pharynx is composed of the nasopharynx, oropharynx, and laryngopharynx.
- The epithelial tissue varies in each part of the pharynx based on the materials that travel through each area.

Larynx

- The larynx is a cartilaginous box that contains the vocal cords.
- Muscles in the larynx move cartilages that allow the vocal cords to vibrate to produce sound.

Trachea

- The trachea has 18 to 20 C-shaped cartilages that hold it open for the easy passage of air.
- The trachea splits to form the main bronchi.

Lungs and the Bronchial Tree

- Each main bronchus enters a lung and then further divides to form the bronchial tree.
- Bronchioles have smooth muscle in their walls and lead to small air sacs in the lung called *alveoli*.
- Alveoli have walls of simple squamous cells and great alveolar cells that produce surfactant.
- Surfactant reduces the surface tension of water so that alveoli do not collapse.
- The respiratory membrane is composed of the thin layer of water with surfactant in the alveoli, the single squamous cell alveolar wall, and the single cell capillary wall.

Physiology of the Respiratory System

Mechanics of Taking a Breath

- Inspiration results from intercostal muscles and the diaphragm's contracting to increase the volume of the thoracic cavity, thereby decreasing its pressure.
- Air flows due to pressure gradients.
- Pleural membranes cause the lung to expand with the thoracic cavity.
- Normal expiration is caused by the relaxation of the intercostal muscles and diaphragm.
- Forced expiration is caused by muscle contraction.

Measurements of Pulmonary Function

- A spirometer can be used to measure lung volumes and capacities.
- Compliance measures how well the lung can expand and return to shape.

Composition of Air

- Air is a mixture of gases including nitrogen, oxygen, carbon dioxide, and water vapor.
- Partial pressure is the amount of pressure an individual gas contributes to the total pressure of the mixture.

Gas Exchange

- Gas exchange happens between the alveoli and the capillaries in the lung and between the capillaries and the tissues of the body.
- Gases diffuse across membranes because of a concentration gradient until the concentrations on both sides of the membrane are equal.
- Inspired air has more oxygen and less carbon dioxide than expired air.
- Gas exchange is influenced by concentration of the gases, membrane area, membrane thickness, solubility of the gas, and ventilation-perfusion coupling.

Gas Transport

- Most of the oxygen is transported in the blood by hemoglobin as oxyhemoglobin, and most of the carbon dioxide is transported in the blood as bicarbonate ions.
- Hemoglobin functions to carry oxygen from the lungs to the tissues and to carry hydrogen ions from the tissues to the lungs.

Regulation of Respiration

- Respiration is controlled by respiratory centers in the medulla oblongata.
- The medulla oblongata receives information concerning the need to control respiration from stretch receptors, the pons, the cerebral cortex, and chemoreceptors.
- The drivers of respiration are pH, CO_2, and O_2 (in that order).

Functions of the Respiratory System

- The functions of the respiratory system include gas exchange, acid-base balance, speech, sense of smell, and creation of pressure gradients necessary to circulate blood and lymph.

Effects of Aging on the Respiratory System

- The ciliated escalator becomes less efficient, so more mucus and debris accumulate in the respiratory tract, and this can lead to infection.
- Thoracic wall compliance decreases, causing reduced vital capacity.
- Some alveolar walls break down with age and thicken, thereby reducing gas exchange.
- Obstructive sleep apnea may occur if the pharyngeal muscles block the airway.

Respiratory System Disorders

Respiratory Infections

- Respiratory infections include colds, flu, tuberculosis, pertussis, and pneumonia.

COPDs

- COPDs are often the result of smoking and include chronic bronchitis, emphysema, and asthma.

Lung Cancer

- Lung cancer causes more deaths than any other form of cancer.

keywords for review

The following terms are defined in the glossary.

alveoli
bronchial tree
chronic obstructive pulmonary disorders (COPDs)
compliance
expiration
functional residual capacity (FRC)
gas exchange
gas transport
inspiration
inspiratory reserve volume (IRV)
partial pressure
pharynx
pneumothorax
respiratory membrane
spirometry
surfactant
tidal volume (TV)
ventilation
ventilation-perfusion coupling
vital capacity (VC)

chapter review questions

Word Building: *Use the word roots listed in the beginning of the chapter and the prefixes and suffixes inside the back cover to build words with the following meanings:*

1. Incision into the chest wall: ______
2. Pertaining to the lung: ______
3. Removal of a lobe of a lung: ______
4. Inflammation of the larynx: ______
5. Instrument for examining the air passageway entering the lung: ______

Multiple Select: *Select the correct choices for each statement. The choices may be all correct, all incorrect, or a combination of correct and incorrect.*

1. Which of the following statements is (are) true concerning gas exchange between the capillaries and the tissues?
   a. Gas exchange occurs between the capillaries and the tissues until partial pressures are equal.
   b. Carbon dioxide moves to the capillaries.
   c. The partial pressure of carbon dioxide is greater in the capillaries than in the tissues.
   d. The partial pressure of oxygen is greater in the tissues than in the capillaries.
   e. Oxygen moves from the capillaries to the tissues.
2. What happens at the alveoli?
   a. Oxygen diffuses to the capillaries and combines with hemoglobin to form oxyhemoglobin.
   b. Hemoglobin binds to hydrogen ions.
   c. Gases move across the respiratory membrane by active transport, requiring energy.
   d. Oxygen diffuses across the respiratory membrane until $P_{O_2} = P_{CO_2}$.
   e. Carbon dioxide diffuses across the respiratory membrane until $P_{CO_2\ \text{capillary}} = P_{CO_2\ \text{alveoli}}$.
3. How does inspired air compare to expired air?
   a. Inspired air is higher in oxygen and lower in carbon dioxide than expired air.
   b. The partial pressure of oxygen in inspired air is 0.03 percent of the total pressure of the air.
   c. Nitrogen is the gas in highest concentration in inspired air.
   d. There is no oxygen in expired air because it all diffuses across the respiratory membrane into the blood.
   e. Expired air contains more carbon dioxide than inspired air.
4. Which of the following factors affect(s) alveolar gas exchange?
   a. Alveolar gas exchange of nitrogen is decreased when a diver dives deep because nitrogen is less soluble under pressure.
   b. Alveolar gas exchange is decreased in pneumonia because the respiratory membrane has become thinner.
   c. Alveolar gas exchange is decreased in emphysema because the respiratory membrane has become more extensive.
   d. Alveolar gas exchange is reduced in asthma because ventilation does not keep up with blood perfusion.
   e. Alveolar gas exchange is increased if the concentration of the gas is increased.
5. What happens when you breathe?
   a. The visceral pleura lining the chest pulls on the parietal pleura attached to the lung due to surfactant.
   b. The diaphragm and intercostal muscles expand the chest.
   c. The Hering-Breuer reflex limits how much is exhaled.
   d. The pons sends inhibitory messages.
   e. The medulla oblongata sends a message by way of inspiratory neurons to cause skeletal muscle contractions.
6. What pathway does air travel through the respiratory system?
   a. Inspired air moves from the bronchial tree to bronchioles to alveolar ducts.
   b. Inspired air goes through the trachea to the larynx.
   c. Inspired air travels from the nasopharynx to the laryngopharynx to the oropharynx.
   d. Air moves from areas of higher pressure to areas of lower pressure.
   e. Inspired air moves through the glottis into the larynx.

7. Which of the following statements is (are) true about hemoglobin?
   a. Hemoglobin functions to carry oxygen from the lungs to the tissues and hydrogen ions from the tissues to the lungs.
   b. Hemoglobin binds to bicarbonate ions.
   c. Hemoglobin is used to carry oxygen to the tissues.
   d. Hemoglobin acts as a buffer to reduce the change in pH of blood when it combines with hydrogen ions to form HHb.
   e. Hemoglobin combines with hydrogen ions to form bicarbonate ions in the capillaries near the tissues.

8. $CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$. What is true about this equation?
   a. The carbon dioxide is produced in the tissues through cellular respiration.
   b. This reaction happens in the direction indicated at the tissues and capillaries.
   c. The products of this reaction indicate an acid.
   d. The water in this reaction is found in the blood.
   e. This reaction is reversed at the capillaries and alveoli.

9. What would happen if a runner does a sprint at the end of a race and undergoes anaerobic respiration, resulting in a buildup of lactic acid, which enters the blood?
   a. Her respiratory rate would increase.
   b. Her respiratory rate would decrease.
   c. Anaerobic respiration is at the cellular level and would have no effect on the rate of breathing.
   d. Chemoreceptors in the medulla oblongata would detect increased hydrogen ions, and the medulla oblongata would therefore decrease respirations.
   e. Chemoreceptors in the aortic arch and the carotid arteries would send a message to the medulla oblongata to increase respirations.

10. Which of the following statements is (are) true concerning respiratory disorders?
   a. Diphtheria, pertussis, and tuberculosis can be prevented with a DPT shot.
   b. Asthma, chronic bronchitis, and emphysema are examples of COPDs.
   c. Emphysema involves bacterial lesions in the lung walled off by scar tissue.
   d. Flu and tuberculosis are viral infections.
   e. A cold is caused by a rhinovirus.

Matching: *Match volume or capacity to the definition. Some answers may be used more than once. Some questions may have more than one correct response.*

_____ 1. The maximum amount of air that can be moved
_____ 2. The amount of air that is left in the lung after a maximum expiration
_____ 3. The amount of air that can still be inhaled after a normal inspiration at rest
_____ 4. The maximum amount of air that can be inspired after a normal expiration at rest
_____ 5. The maximum amount of air that can be expired after a normal expiration at rest

a. Total lung volume
b. Residual volume
c. Inspiratory reserve volume
d. Expiratory reserve volume
e. Functional residual capacity
f. Vital capacity
g. Inspiratory capacity

Matching: *Match the respiratory disorder with the description. Some answers may be used more than once. Some questions may have more than one correct response.*

_____ 6. A viral infection
_____ 7. A bacterial infection
_____ 8. Degeneration of alveolar walls
_____ 9. COPD
_____ 10. Disorder that results in whooping cough

a. Tuberculosis
b. Emphysema
c. Cold
d. Influenza
e. Asthma
f. Pertussis

Critical Thinking

1. The effects of smoking on Carol's respiratory system function were discussed in this chapter. What other environmental factors and lifestyle choices would adversely affect the respiratory system? Explain.
2. What can be done to minimize the effects of aging on the respiratory system? Explain.
3. Bob participated in an A&P lab during the respiratory system unit. He recorded his respiratory rate and his tidal volume at rest and then again after running around the parking lot at his school. His results were as shown to the right:

	At rest	Immediately after the run
Respiratory rate:	12 breaths/min	20 breaths/min
Tidal volume:	400 mL	650 mL

How much more air per minute was Bob's respiratory system able to move after the run than before it? What caused his values to change? Explain your response in terms of the physiology of the respiratory system.

12 chapter mapping

This section of the chapter is designed to help you find where each outcome is covered in this text.

	Outcomes	Readings, figures, and tables	Assessments
12.1	Use medical terminology related to the respiratory system.	Word roots: p. 445	Word Building: 1–5
12.2	Trace the flow of air from the nose to the pulmonary alveoli and relate the function of each part of the respiratory tract to its gross and microscopic anatomy.	Take a breath: pp. 446–457 Figures 12.2, 12.13	Spot Check: 1–6 Multiple Select: 6
12.3	Explain the role of surfactant.	Surfactant: pp. 457–458	
12.4	Describe the respiratory membrane.	Respiratory membrane: p. 458 Figure 12.12c	
12.5	Explain the mechanics of breathing in terms of anatomy and pressure gradients.	Mechanics of breathing: pp. 458–461 Figures: 12.14, 12.15	Multiple Select: 5
12.6	Define the measurements of pulmonary function.	Measurements of pulmonary function: pp. 462–463 Figures: 12.16, 12.17 Table 12.1	Matching: 1–5
12.7	Define partial pressure and its relationship to a gas mixture such as air.	Composition of air: p. 464	Spot Check: 7
12.8	Explain gas exchange in terms of the partial pressures of gases at the capillaries and the alveoli and at the capillaries and the tissues.	Gas exchange: pp. 464–466 Figure 12.18, 12.19	Multiple Select: 1–3
12.9	Compare the composition of inspired and expired air.	Comparison of inspired and expired air: p. 466 Figure 12.19	Multiple Select: 3
12.10	Explain the factors that influence the efficiency of alveolar gas exchange.	Factors that influence gas exchange: pp. 466–469 Figures 12.20–12.22	Spot Check: 8 Multiple Select: 4

	Outcomes	Readings, figures, and tables	Assessments
12.11	Describe the mechanisms for transporting O_2 and CO_2 in the blood.	Gas transport: pp. 470–472 Figures: 12.23, 12.24	Multiple Select: 2, 7, 8
12.12	Explain how respiration is regulated to homeostatically control blood gases and pH.	Regulation of respiration: pp. 472–474 Figures 12.25–12.27	Multiple Select: 5, 9
12.13	Explain the functions of the respiratory system.	Functions of the respiratory system: pp. 474–475 Figure 12.27	Critical Thinking: 1
12.14	Summarize the effects of aging on the respiratory system.	Effects of Aging on the respiratory system: pp. 475–476	Critical Thinking: 2
12.15	Describe respiratory system disorders.	Respiratory system disorders: pp. 476–478 Figure 12.28	Multiple Select: 10 Matching: 6–10

footnotes

1. National Human Genome Research Institute. (2010, July 2). *Learning about cystic fibrosis*. Retrieved September 22, 2010, from http://www.genome.gov/10001213.
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