Luckily the emergency medical technicians arrived just moments after Sammy was rescued from the pond by his mother. A technician immediately began CPR (cardiopulmonary resuscitation), alternately blowing into Sammy's mouth and then pressing on his chest until Sammy began to breathe on his own. All cells of the body require a constant supply of oxygen, and you have to keep breathing in order to bring this oxygen into the body. Any cessation of breathing is a cause for concern, and prolonged cessation usually results in death. The heart needs oxygen to pump the blood that will carry oxygen to all the cells of the body. The cells use oxygen in the process of replenishing their limited supply of ATP, without which they have no energy and cannot keep functioning. In this chapter, the structures and functions of the respiratory system are considered. Also, some of the conditions that decrease the functioning of the system will be discussed.

15.1 Respiratory Tract

During **inspiration** or inhalation (breathing in) and **expiration** or exhalation (breathing out), air is conducted toward or away from the lungs by a series of cavities, tubes, and openings, illustrated in Figure 15.1.

As air moves in along the airways, it is filtered, warmed, and moistened. Filtering is accomplished by coarse hairs, cilia, and mucus in the region of the nostrils and by cilia alone in the rest of the nasal cavity and the airways of the lower respiratory tract. In the nose, the hairs and the cilia act as a screening device. In the trachea and other airways, the cilia beat upward, carrying mucus, dust, and occasional bits of food that "went down the wrong way" into the pharynx, where the accumulation can be swallowed or expectorated. The air is warmed by heat given off by the blood vessels lying close to the surface of the lining of the airways, and it is moistened by the wet surface of these passages.

Conversely, as air moves out during expiration, it cools and loses its moisture. As the air cools, it deposits its moisture on the lining of the windpipe and the nose, and the nose may even drip as a result of this condensation. The air still retains so much moisture, however, that upon expiration on a cold day, it condenses and forms a small cloud.

Air is filtered, warmed, and moistened as it moves from the nose toward the lungs.

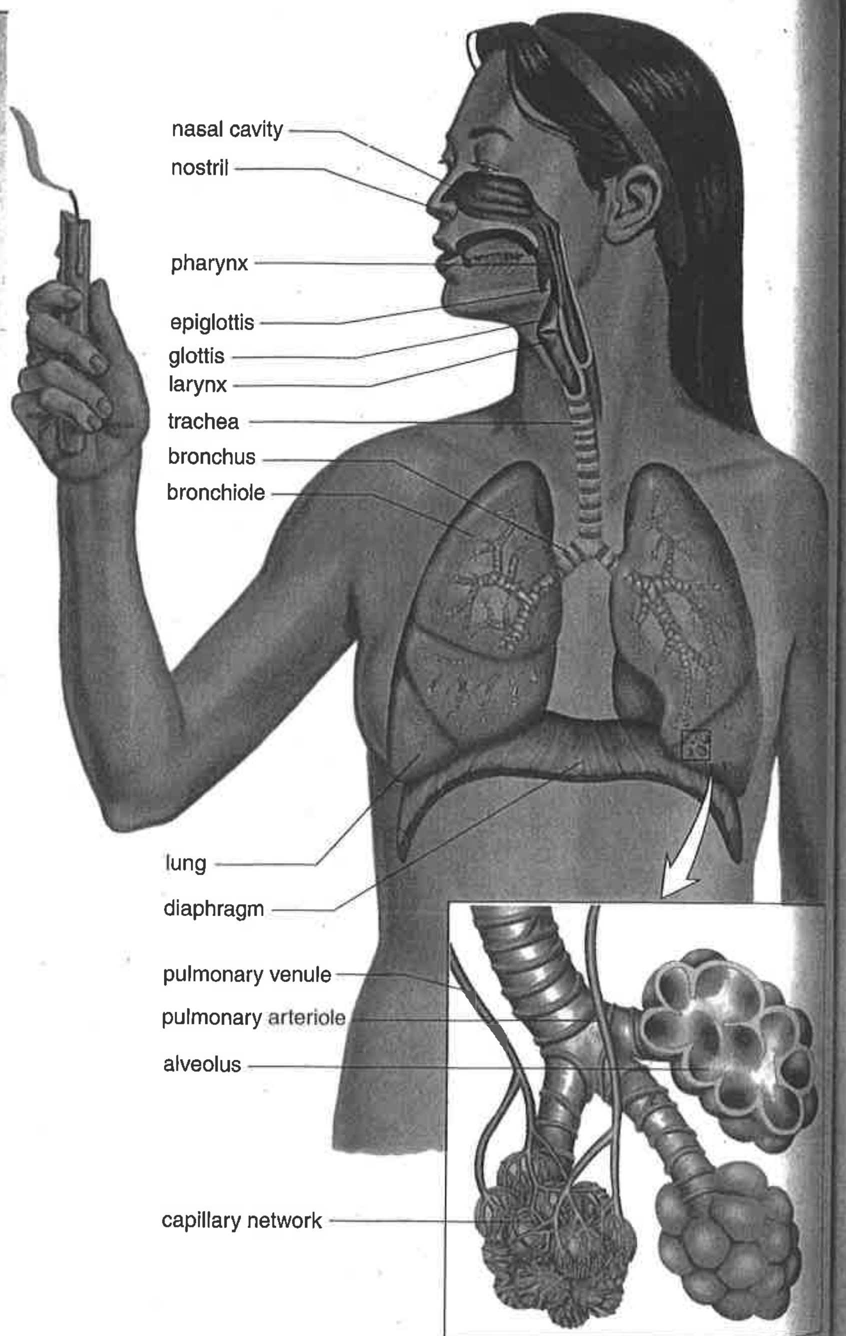


Figure 15.1 The respiratory tract.
The respiratory tract extends from the nose to the lungs, which are composed of air sacs called alveoli. Gas exchange occurs between air in the alveoli and blood within a capillary network that surrounds the alveoli.

Table 15.1 Path of Air

Structure	Description	Function
Nasal cavities	Hollow spaces in nose	Filter, warm, and moisten air
Pharynx	Chamber behind oral cavity and between nasal cavity and larynx	Connection to surrounding regions
Glottis	Opening into larynx	Passage of air into larynx
Larynx	Cartilaginous organ that contains vocal cords (voice box)	Sound production
Trachea	Flexible tube that connects larynx with bronchi (windpipe)	Passage of air to bronchi
Bronchi	Divisions of the trachea that enter lungs	Passage of air to lungs
Bronchioles	Branched tubes that lead from bronchi to the alveoli	Passage of air to each alveolus
Lungs	Soft, cone-shaped organs that occupy a large portion of the thoracic cavity	Gas exchange organs

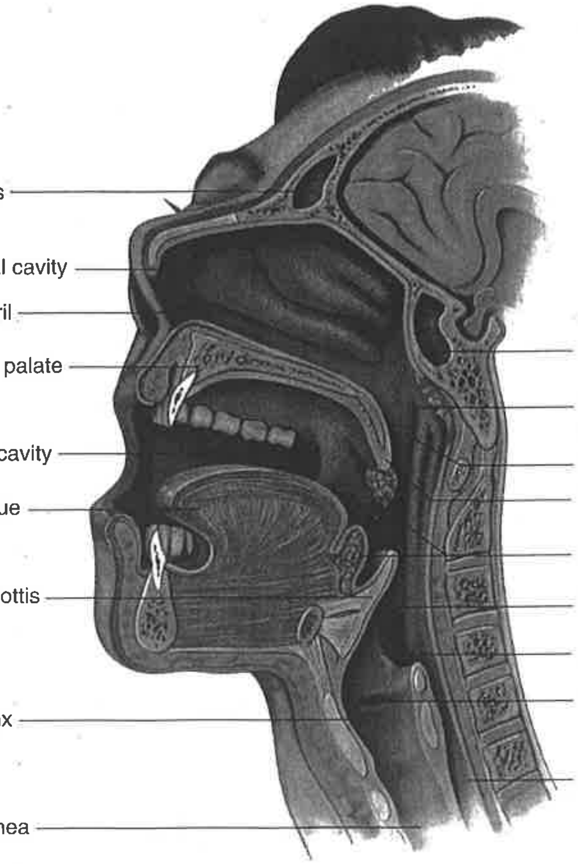


Figure 15.2 The upper respiratory tract.
The upper respiratory tract contains the nasal cavities, pharynx, and larynx.

The Nose

The nose contains two **nasal cavities** (Table 15.1), which are narrow canals separated from one another by a septum composed of bone and cartilage. Special ciliated cells in the narrow upper recesses of the nasal cavities (Fig. 15.2) act as odor receptors. Nerves lead from these cells to the brain, where the impulses generated by the odor receptors are interpreted as smell.

The tear (lacrimal) glands drain into the nasal cavities by way of tear ducts. For this reason, crying produces a runny nose. The nasal cavities also communicate with the cranial sinuses, air-filled mucosa-lined spaces in the skull. If inflammation due to a cold or an allergic reaction blocks the ducts leading from the sinuses, mucus may accumulate, causing a sinus headache.

The nasal cavities empty into the nasopharynx, the upper portion of the pharynx. The auditory tubes lead from the nasopharynx to the middle ears.

The nasal cavities, which receive air, open into the nasopharynx.

The Pharynx

The **pharynx** is a funnel-shaped passageway that connects the nasal and oral cavities to the larynx. Therefore, the pharynx, which is commonly referred to as the "throat," has three parts: the nasopharynx, where the nasal cavities open above the soft palate; the oropharynx, where the oral cavity opens; and the laryngopharynx, which opens into the larynx. In the pharynx, the air passage and the food passage cross because the larynx, which receives air, is ventral to the esophagus, which receives food. The larynx lies at the top of the trachea. The larynx and trachea are normally open, allowing the passage of air, but the esophagus is normally closed and opens only when swallowing occurs.

Air from either the nose or the mouth enters the pharynx, as does food. The passage of air continues in the larynx and then the trachea.

The Larynx

The **larynx** can be pictured as a triangular box whose apex, the Adam's apple, is located at the front of the neck. The Adam's apple is more prominent in men than women. At the top of the larynx is a variable-sized opening called the **glottis.** When food is swallowed, the larynx moves upward against the **epiglottis,** a flap of tissue that prevents food from passing into the larynx. You can detect this movement by placing your hand gently on your larynx and swallowing.

The larynx is called the voice box because the vocal cords are inside the larynx. The **vocal cords** are mucosal folds supported by elastic ligaments, which are stretched across the glottis (Fig. 15.3). When air passes through the glottis, the vocal cords vibrate, producing sound. At the time of puberty, the growth of the larynx and the vocal cords is much more rapid and accentuated in the male than in the female, causing the male to have a more prominent Adam's apple and a deeper voice. The voice "breaks" in the young male due to his inability to control the longer vocal cords. These changes cause the lower pitch of the voice in males.

The high or low pitch of the voice is regulated when speaking and singing by changing the tension on the vocal cords. The greater the tension, as when the glottis becomes more narrow, the higher the pitch. When the glottis is wider, the pitch is lower (Fig. 15.3*b*). The loudness, or intensity, of the voice depends upon the amplitude of the vibrations, that is, the degree to which vocal cords vibrate.

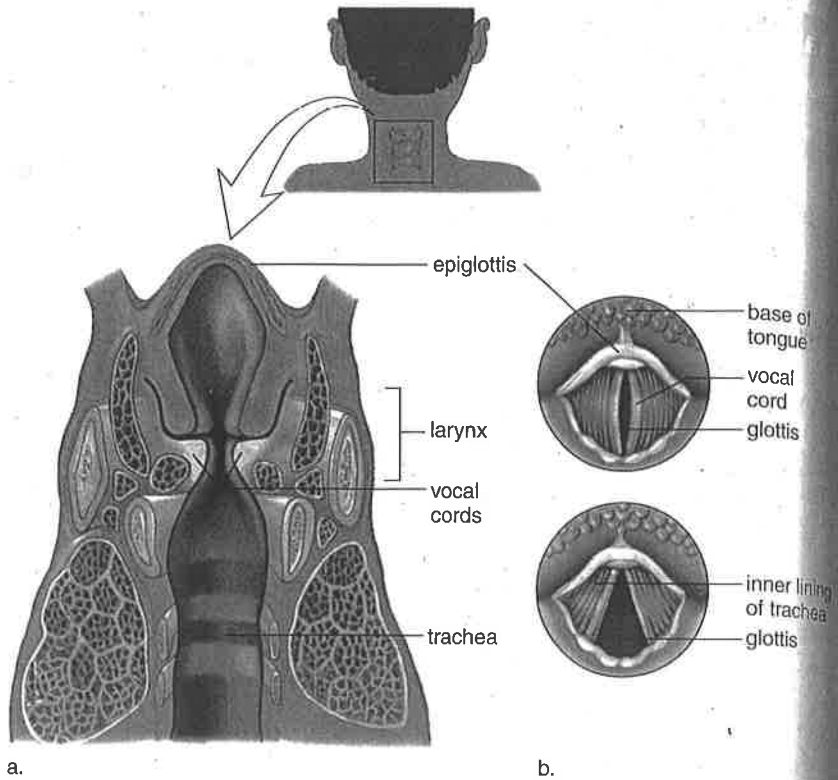
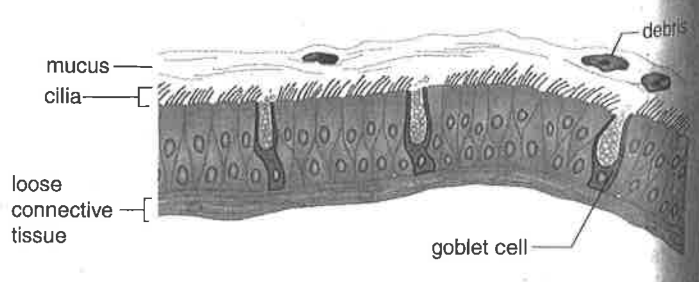


Figure 15.3 Placement of the vocal cords.
a. Frontal section of the larynx shows the location of the vocal cords inside the larynx. The vocal cords viewed from above are stretched across the glottis. When air passes through the glottis, the vocal cords vibrate, producing sound. **b.** The glottis is narrow when we produce a high-pitched sound (*top*) and widens as the pitch deepens (*bottom*).

The Trachea

The **trachea,** commonly called the windpipe, is a tube connecting the larynx to the primary bronchi. The trachea lies ventral to the esophagus and is held open by C-shaped cartilaginous rings. The open part of the C-shaped rings faces the esophagus and this allows the esophagus to expand when swallowing. If the trachea is blocked because of illness or the accidental swallowing of a foreign object, it is possible to insert a tube by way of an incision made in the trachea. This tube acts as an artificial air intake and exhaust duct. The operation is called a **tracheostomy.**

The mucosa that lines the trachea has a layer of pseudostratified ciliated columnar epithelium. (Pseudostratified means that while the epithelium appears to be layered, actually each cell touches the basement membrane.) The cilia that project from the epithelium keep the lungs clean by sweeping mucus and debris toward the pharynx.



Smoking is known to destroy the cilia, and consequently the soot in cigarette smoke collects in the lungs. Smoking is discussed more fully at the end of this chapter.

The Bronchial Tree

The trachea divides into right and left primary bronchi (sing., **bronchus**), which lead into the right and left lungs (see Fig. 15.1). The bronchi branch into a great number of secondary bronchi that eventually lead to **bronchioles.** The bronchi resemble the trachea in structure, but as the bronchial tubes divide and subdivide, their walls become thinner, and the small rings of cartilage are no longer present. During an asthma attack, the smooth muscle of the bronchioles contracts, causing bronchiolar constriction and characteristic wheezing. Each bronchiole terminates in an elongated space enclosed by a multitude of air pockets, or sacs, called *alveoli* (sing., **alveolus**) (see Fig. 15.1). The alveoli make up the lungs.

The Lungs

The **lungs** are paired cone-shaped organs within the thoracic cavity. The right lung has three lobes, and the left lung has two lobes, allowing room for the heart, which is on the left side of the body. A lobe is further divided into lobules, and each lobule has a bronchiole serving many alveoli. The lungs lie on either side of the heart in the thoracic cavity. The base of each lung is broad and concave so that it fits the convex surface of the diaphragm. The other surfaces of the lungs follow the contours of the ribs and the diaphragm in the thoracic cavity.

The Alveoli

Each alveolar sac is made up of simple squamous epithelium surrounded by blood capillaries. Gas exchange occurs between air in the alveoli and blood in the capillaries (Fig. 15.4). Oxygen diffuses across the alveolar wall and enters the bloodstream, while carbon dioxide diffuses from the blood across the alveolar wall to enter the alveoli.

The alveoli of human lungs are lined with a surfactant, a film of lipoprotein that lowers the surface tension and prevents them from closing. The lungs collapse in some newborn babies, especially premature infants, who lack this film. The condition, called **infant respiratory distress syndrome,** is now treatable by surfactant replacement therapy.

There are approximately 300 million alveoli, with a total cross-sectional area of 50–70 m^2. This is the surface area of a typical classroom and at least 40 times the surface area of the skin. Because of their many air spaces, the lungs are very light; normally, a piece of lung tissue dropped in a glass of water floats.

The trachea divides into the primary bronchi, which divide repeatedly to give rise to the bronchioles. The bronchioles have many branches and terminate at the alveoli, which make up the lungs.

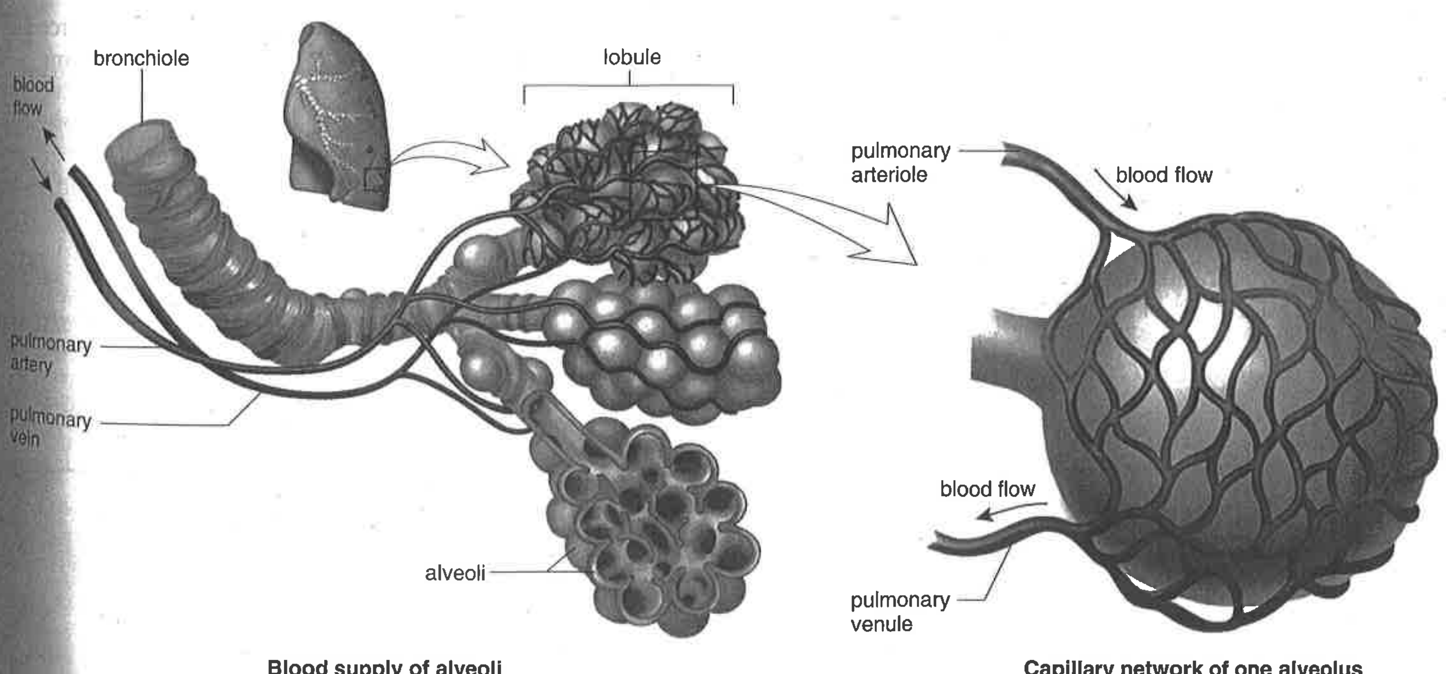
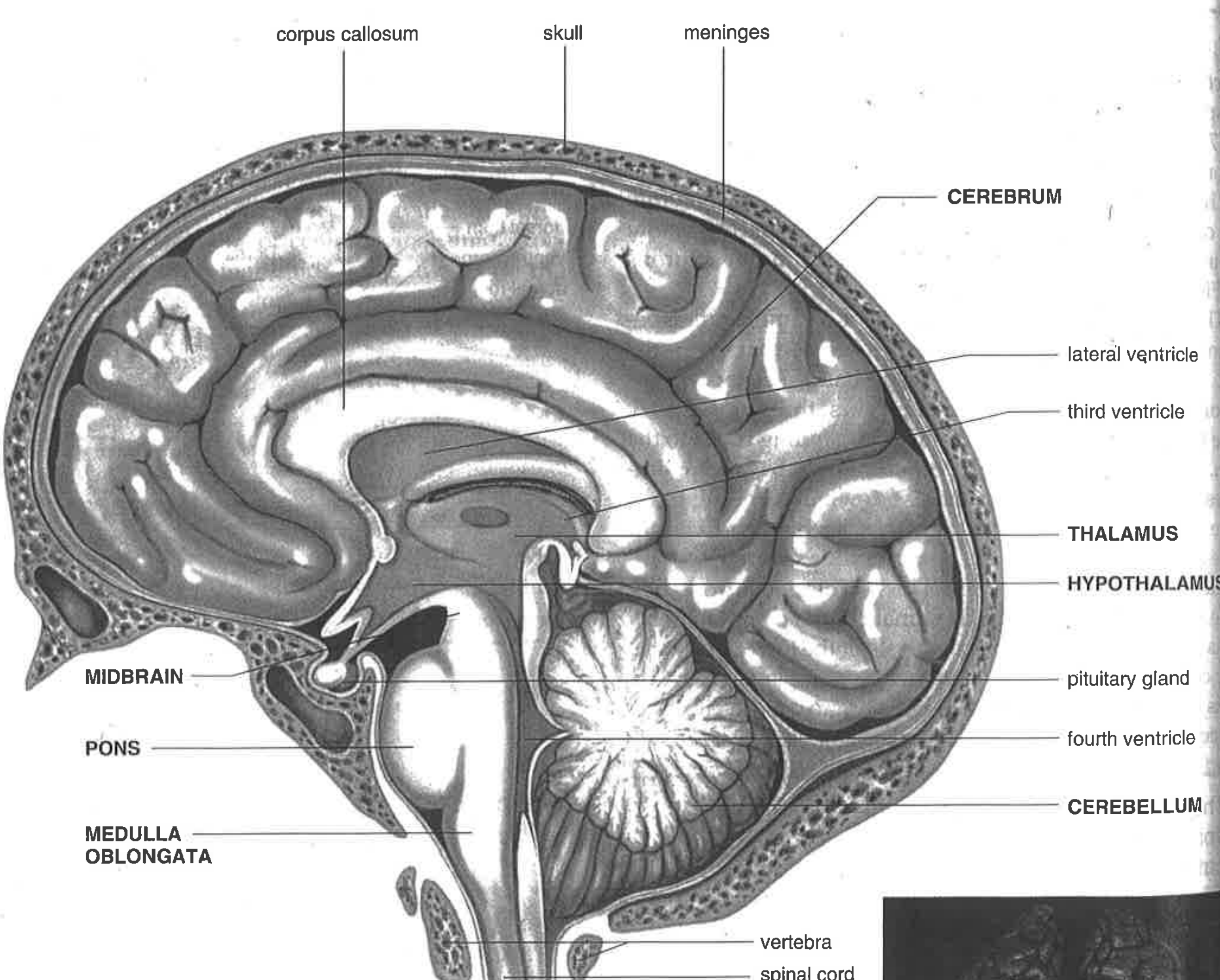


Figure 15.4 Gas exchange in the lungs.
The lungs consist of alveoli, surrounded by an extensive capillary network. Notice that the pulmonary arteriole carries blood low in oxygen (colored blue) and the pulmonary venule carries blood high in oxygen (colored red).

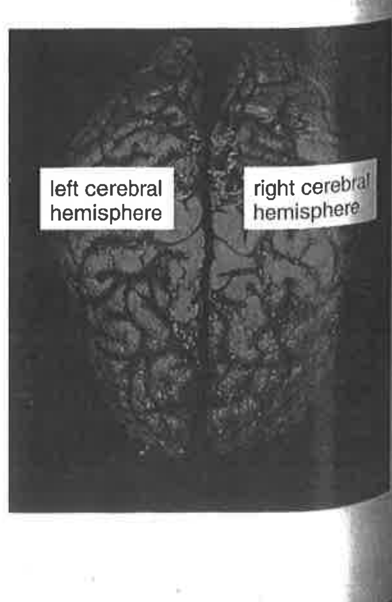
The Brain

The human **brain** has been called the last great frontier of biology. The goal of modern neuroscience is to understand the structure and function of the brain's various parts so well that it will be possible to prevent or correct the more than 1,000 mental disorders that rob human beings of a normal life. This section gives only a glimpse of what is known about the brain and the modern avenues of research.

We will discuss the parts of the brain with reference to the brain stem, the diencephalon, and the cerebrum. The brain has four **ventricles** called, in turn, the fourth ventricle, the third ventricle, and the two lateral ventricles. It may be helpful to you to associate the brain stem with the fourth ventricle, the diencephalon with the third ventricle, and the cerebrum with the two lateral ventricles (Fig. 17.12*a*).



a.



b.

Figure 17.12 The human brain.
a. The cerebrum is the largest part of the brain in humans.
b. The cerebrum has a left and right cerebral hemisphere which are connected by the corpus callosum.

The Brain Stem

The **brain stem,** the initial portion of the brain, contains the medulla oblongata, the pons, and the midbrain. The **medulla oblongata** lies between the spinal cord and the pons. It contains a number of *vital centers* for regulating heartbeat, breathing, and vasoconstriction (blood pressure). It also contains the reflex centers for vomiting, coughing, sneezing, hiccuping, and swallowing. The medulla contains tracts that ascend or descend between the spinal cord and higher brain centers.

The Cerebellum

The **cerebellum** is separated from the brain stem by the fourth ventricle. The cerebellum has two portions that are joined by a narrow median portion. The surface of the cerebellum is gray matter, and the interior is largely white matter. The cerebellum integrates and passes on both sensory and motor information. It maintains normal muscle tone, posture, and balance and also ensures that all of the skeletal muscles work together to produce smooth and coordinated motions. The cerebellum is necessary for learning new motor skills like playing the piano or hitting a baseball.

The word **pons** means bridge in Latin, and true to its name, the pons contains bundles of axons traveling between the cerebellum and the rest of the CNS. In addition, the pons functions with the medulla to regulate breathing rate and has reflex centers concerned with head movements in response to visual and auditory stimuli.

The **midbrain** acts as a relay station for tracts passing between the cerebrum and the spinal cord or cerebellum. It also has reflex centers for visual, auditory, and tactile responses.

The Diencephalon

The hypothalamus and the thalamus are in the **diencephalon,** a region that encircles the third ventricle. The **hypothalamus** forms the floor of the third ventricle. The hypothalamus is the integrating center for the autonomic system. It also helps maintain homeostasis by regulating hunger, sleep, thirst, body temperature, and water balance. The hypothalamus controls the pituitary gland and thereby serves as a link between the nervous and endocrine systems.

The **thalamus** consists of two masses of gray matter located in the sides and roof of the third ventricle. The thalamus integrates sensory information and serves as a central relay station for sensory impulses traveling upward from other parts of the brain to the cerebrum. The thalamus is also involved in arousal and higher mental functions such as memory and emotion.

The pineal gland, which secretes the hormone melatonin, is located in the diencephalon. Presently there is much popular interest in the role of melatonin in our daily rhythms and whether it can help meliorate jet lag or insomnia. Scientists are also interested in the possibility that the hormone may regulate the onset of puberty.

The Cerebrum

The **cerebrum,** also called the telencephalon, is the foremost and largest portion of the brain in humans. Just as the human body has two halves, so does the cerebrum. These halves are called the left and right **cerebral hemispheres** (Fig. 17.12*b*). These two cerebral hemispheres are connected by a bridge of tracts within the corpus callosum.

The cerebrum is the highest center to receive sensory input and carry out integration before commanding voluntary motor responses. It is in communication with and coordinates the activities of the other parts of the brain. As we shall see, the cerebrum carries out higher thought processes required for learning and memory and for language and speech.

The Reticular Formation

The **reticular formation** is a complex network of nuclei and fibers that extend the length of the brain stem (Fig. 17.13). In this context, the term **nuclei** means masses of cell bodies in the CNS. The reticular formation receives sensory signals which it sends up to higher centers, and motor signals which it sends to the spinal cord.

One portion of the reticular formation called the reticular activating system (RAS) arouses the cerebrum via the thalamus and causes a person to be alert. It is believed to filter out unnecessary sensory stimuli and this may account for why you can study with the TV on. An inactive reticular formation results in sleep; a severe injury to the RAS can cause a person to be comatose.

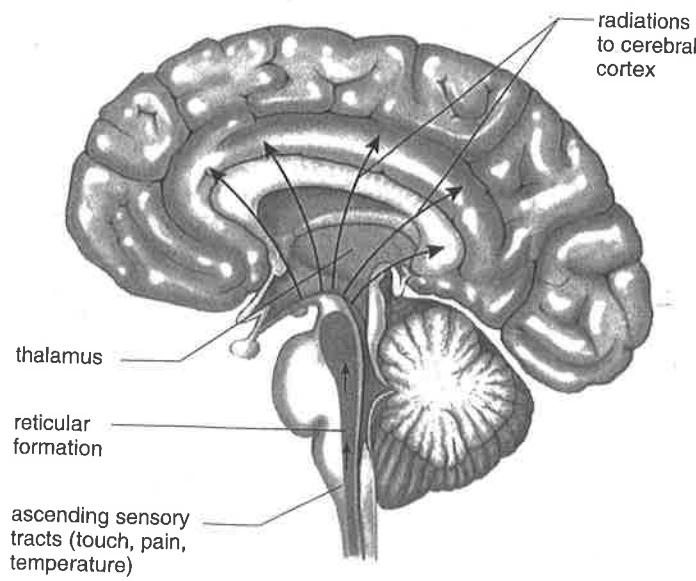


Figure 17.13 The reticular activating system.
The reticular formation receives and sends on motor and sensory information to various parts of the CNS. One portion, the reticular activating system (see arrows), arouses the cerebrum and in this way controls alertness versus sleep.

Inspiration and Expiration

To understand **ventilation,** the manner in which air enters and exits the lungs, it is necessary to remember first that normally there is a continuous column of air from the pharynx to the alveoli of the lungs.

Secondly, the lungs lie within the sealed-off thoracic cavity. The **rib cage** forms the top and sides of the thoracic cavity. It contains the ribs, hinged to the vertebral column at the back and to the sternum (breastbone) at the front, and the intercostal muscles that lie between the ribs. The **diaphragm,** a dome-shaped horizontal sheet of muscle and connective tissue, forms the floor of the thoracic cavity.

The lungs are enclosed by two membranes called **pleural membranes.** An infection of the pleural membranes is called pleurisy. The parietal pleura adheres to the rib cage and the diaphragm, and the visceral pleura is fused to the lungs. The two pleural layers lie very close to one another, separated only by a small amount of fluid. Normally, the intrapleural pressure (pressure between the pleural membranes) is lower than atmospheric pressure by 4 mm Hg.

The importance of the reduced intrapleural pressure is demonstrated when, by design or accident, air enters the intrapleural space. The affected lobules collapse.

> The pleural membranes enclose the lungs and line the thoracic cavity. Intrapleural pressure is lower than atmospheric pressure.

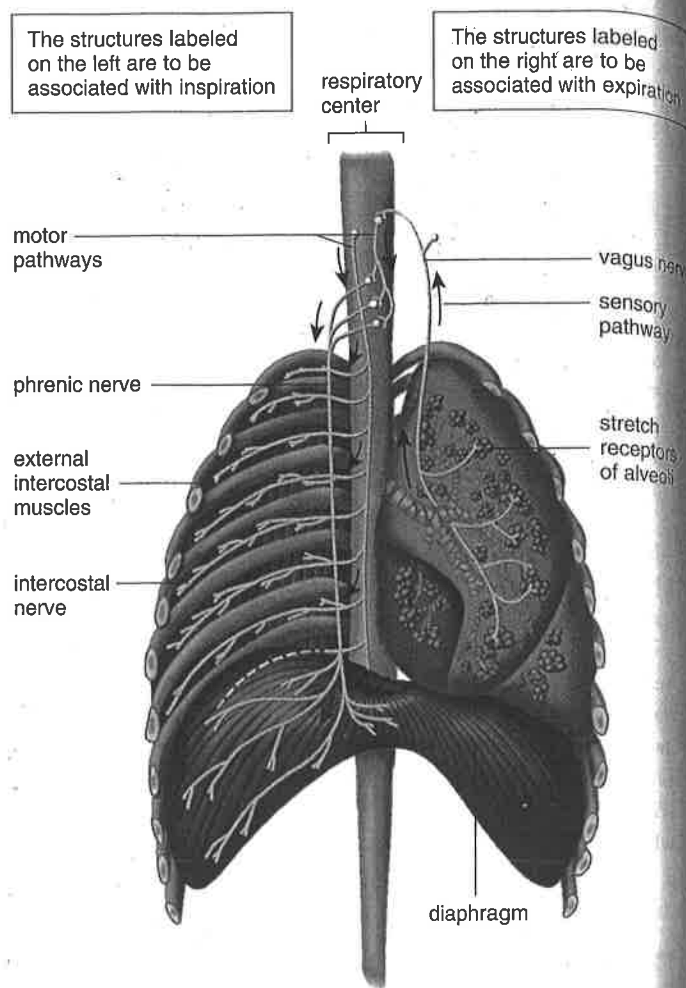


Figure 15.6 Nervous control of breathing.
During inspiration, the respiratory center stimulates the external intercostal (rib) muscles to contract via the intercostal nerves and the diaphragm to contract via the phrenic nerve. Should the tidal volume increase above 1.5 liters, stretch receptors send inhibitory nerve impulses to the respiratory center via the vagus nerve. In any case, expiration occurs due to a lack of stimulation from the respiratory center to the diaphragm and intercostal muscles.

Inspiration

A **respiratory center** is located in the medulla oblongata of the brain. The respiratory center consists of a group of neurons that exhibit an automatic rhythmic discharge that triggers inspiration. Carbon dioxide (CO_2) and hydrogen ions (H^+) are the primary stimuli that directly cause changes in the activity of this center. This center is not affected by low oxygen (O_2) levels. Chemoreceptors in the **carotid bodies,** located in the carotid arteries, and in the **aortic bodies,** located in the aorta, are sensitive to the level of hydrogen ions and also to the levels of carbon dioxide and oxygen in blood. When the concentrations of hydrogen ions and carbon dioxide rise (and oxygen decreases), these bodies communicate with the respiratory center, and the rate and depth of breathing increase.

The respiratory center sends out impulses by way of nerves to the diaphragm and the muscles of the rib cage (Fig. 15.6). In its relaxed state, the diaphragm is dome-shaped, but upon stimulation, it contracts and lowers. Also, the external intercostal muscles contract, causing the rib cage to move upward and outward. Now the thoracic cavity increases in size, and the lungs expand. As the lungs expand, air pressure within the enlarged alveoli lowers and air enters through the nose or the mouth.

Inspiration is the active phase of breathing (Fig. 15.7a). During this time, the diaphragm and the rib muscles contract, intrapleural pressure decreases, the lungs expand, and air comes rushing in. Note that air comes in because the lungs already have opened up; air does not force the lungs open. This is why it is sometimes said that *humans breathe by negative pressure.* The creation of a partial vacuum in the alveoli causes air to enter the lungs.

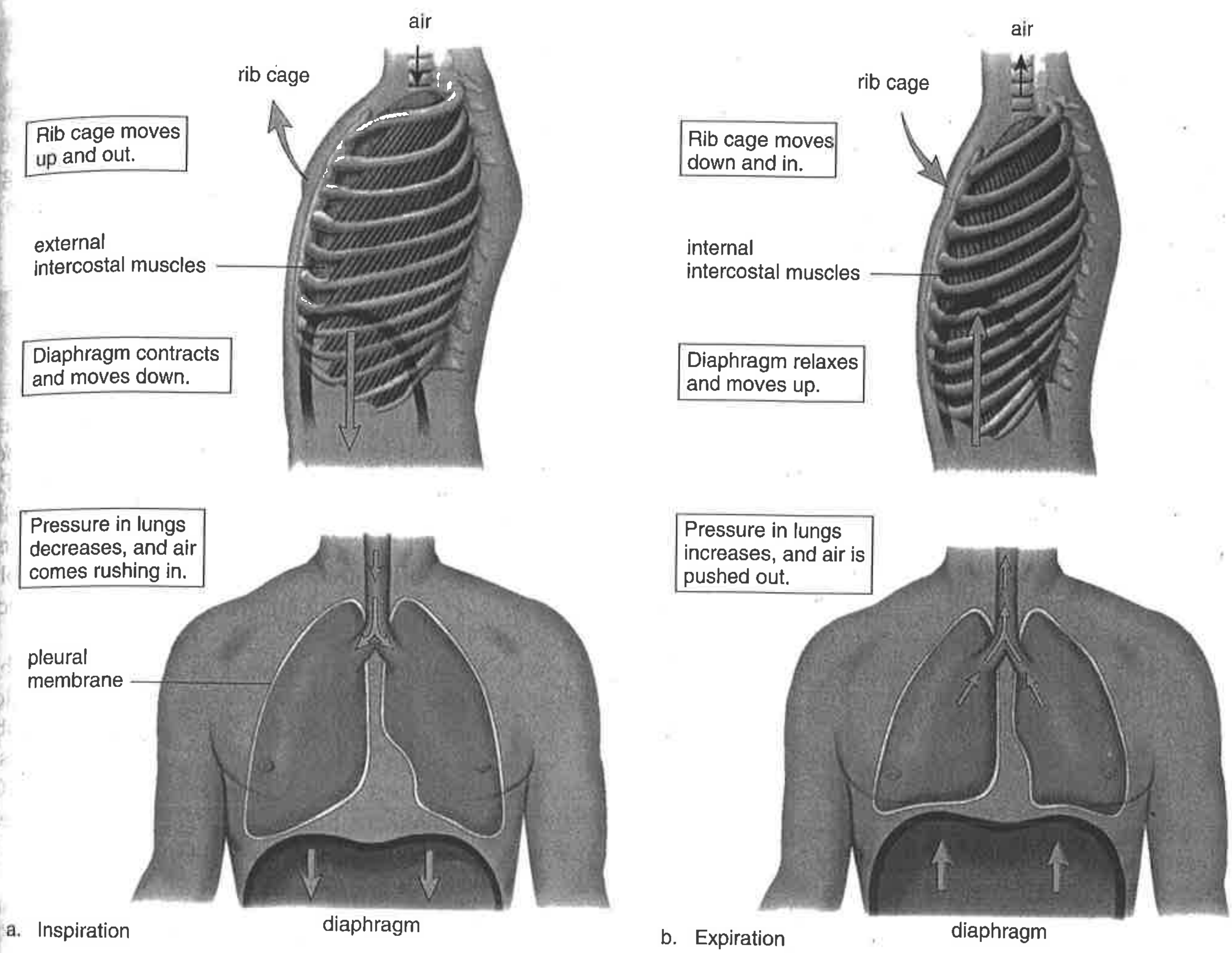


Figure 15.7 Inspiration versus expiration.
a. During inspiration, the thoracic cavity and lungs expand so that air is drawn in. **b.** During expiration, the thoracic cavity and lungs resume their original positions and pressures. Now, air is forced out.

Expiration

When the respiratory center stops sending nervous signals to the diaphragm and the rib cage, the diaphragm relaxes and it resumes its dome shape. The abdominal organs press up against the diaphragm, and the rib cage moves down and inward (Fig. 15.7*b*). Now, the elastic lungs recoil, and air is pushed out. The respiratory center acts rhythmically to bring about breathing at a normal rate and volume. If by chance we inhale more deeply, the lungs are expanded and the alveoli stretch. This stimulates stretch receptors in the alveolar walls, and they initiate inhibitory nerve impulses that travel from the inflated lungs to the respiratory center. This causes the respiratory center to stop sending out nerve impulses.

While inspiration is the active phase of breathing, expiration is usually passive—the diaphragm and external intercostal muscles are relaxed when expiration occurs. When breathing is deeper and/or more rapid, expiration can also be active. Contraction of internal intercostal muscles can force the rib cage to move downward and inward. Also, when the abdominal wall muscles are contracted, they push on the viscera, which push against the diaphragm, and the increased pressure in the thoracic cavity helps to expel air.

During inspiration, due to nervous stimulation, the diaphragm lowers and the rib cage lifts up and out. During expiration, due to a lack of nervous stimulation, the diaphragm rises and the rib cage lowers.

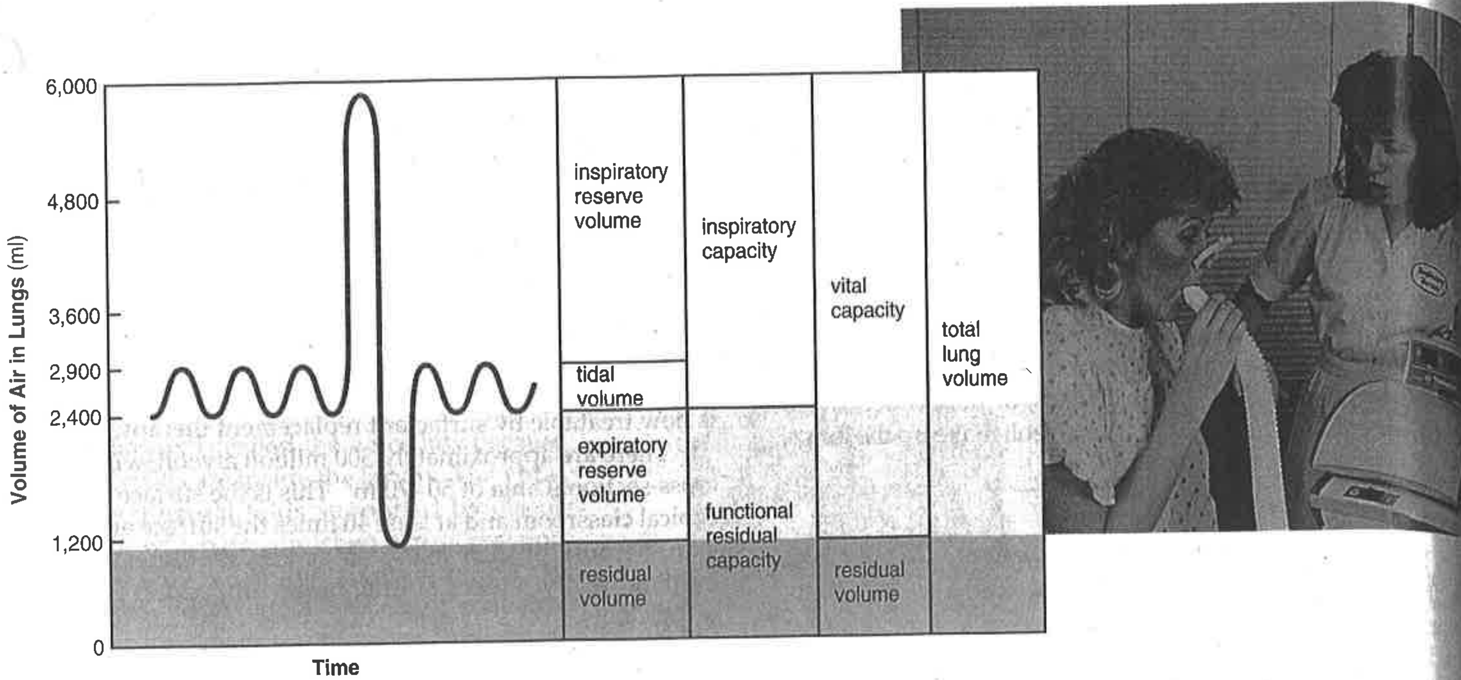


Figure 15.5 Vital capacity.
A spirometer measures the maximum amount of air that can be inhaled and exhaled when breathing by way of a tube connected to the instrument. During inspiration, a pen moves up, and during expiration, a pen moves down. The resulting pattern, such as the one shown here, is called a spirograph.

15.2 Mechanism of Breathing

The term respiration refers to the complete process of supplying oxygen to body cells for aerobic cellular respiration and the reverse process of ridding the body of carbon dioxide given off by cells. Respiration includes the following components:

1. Breathing: inspiration (entrance of air into the lungs) and expiration (exit of air from the lungs).
2. External respiration: exchange of the gases oxygen (O_2) and carbon dioxide (CO_2) between air and blood in the lungs.
3. Internal respiration: exchange of the gases O_2 and CO_2 between blood and tissue fluid.
4. Cellular respiration: production of ATP in cells.

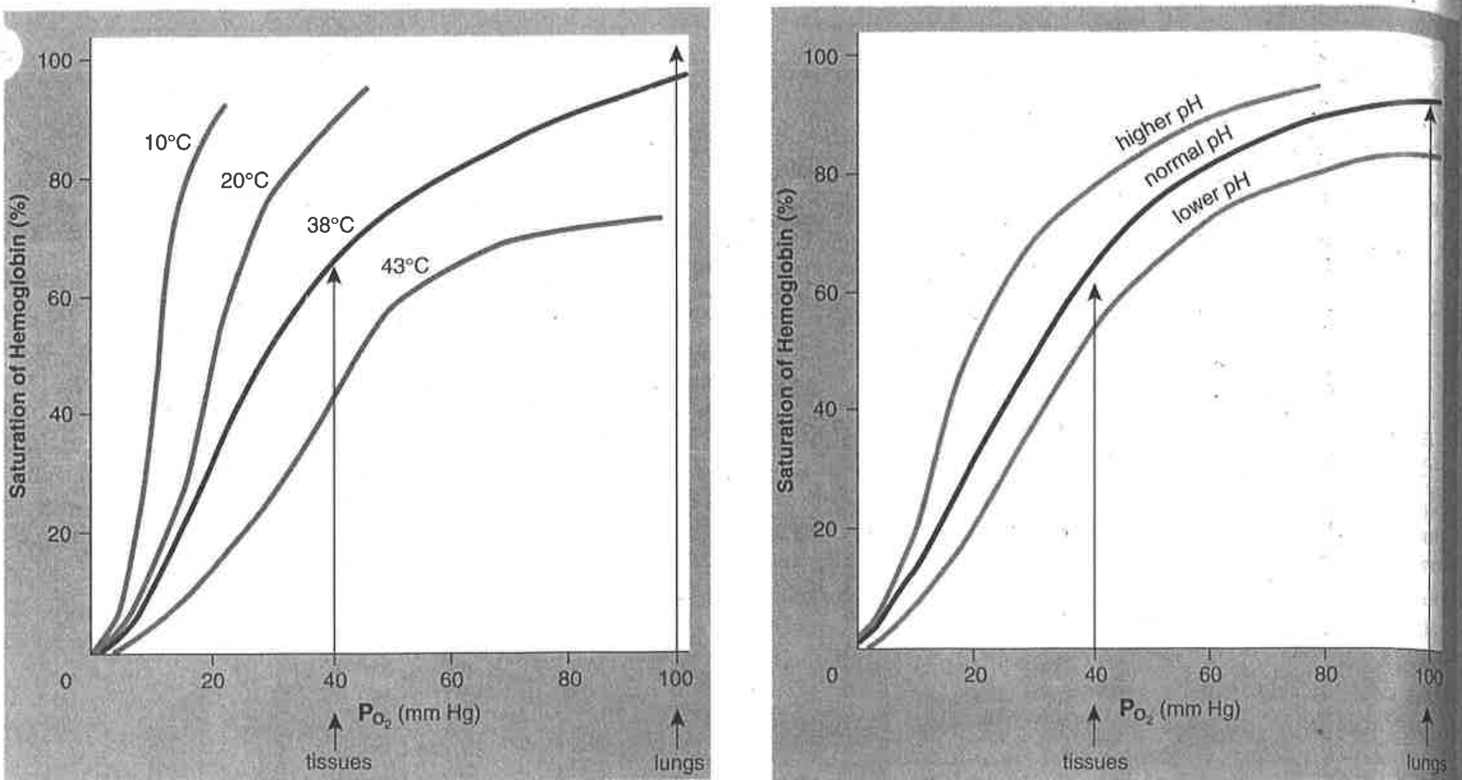
Respiratory Volumes

When we breathe, the amount of air moved in and out with each breath is called the **tidal volume.** Normally, the tidal volume is about 500 ml, but we can increase the amount inhaled and exhaled by deep breathing. The maximum volume of air that can be moved in and out during a single breath is called the **vital capacity** (Fig. 15.5). First, we can increase inspiration by as much as 3,100 ml of air by forced inspiration. This is called the **inspiratory reserve volume.**

Even so, some of the inspired air never reaches the lungs; instead it fills the nose, trachea, bronchi, and bronchioles (see Fig. 15.1). These passages are not used for gas exchange, and therefore, they are said to contain dead space air. To ensure that inspired air reaches the lungs, it is better to breathe slowly and deeply. Similarly, we can increase expiration by contracting the abdominal and thoracic muscles. This is called the **expiratory reserve volume,** and it measures approximately 1,400 ml of air. Vital capacity is the sum of tidal, inspiratory reserve, and expiratory reserve volumes.

Note in Figure 15.5 that even after very deep breathing some air (about 1,000 ml) remains in the lungs; this is called the **residual volume.** This air is no longer useful for gas exchange purposes. In some lung diseases, such as emphysema (p. 297), the residual volume builds up because the individual has difficulty emptying the lungs. This means that the vital capacity is reduced and the lungs tend to be filled with useless air.

The air used for gas exchange excludes both the air in the dead space of the respiratory tract and the residual volume in the lungs.



a. Saturation of Hb relative to temperature

b. Saturation of Hb relative to pH

igure 15.9 Effect of environmental conditions on hemoglobin saturation.
.ne partial pressure of oxygen (P_{O_2}) in pulmonary capillaries is about 98–100 mm Hg, but only about 40 mm Hg in tissue capillaries. Hemoglobin is about 98% saturated in the lungs because of P_{O_2}, and also because **(a)** the temperature is cooler and **(b)** the pH is higher in lungs. On the other hand, hemoglobin is only about 60% saturated in the tissues because of the P_{O_2} and also because **(a)** the temperature is warmer and **(b)** the pH is lower in the tissues.

Binding Capacity of Hemoglobin

The binding capacity of hemoglobin is also affected by partial pressures. The P_{O_2} of air entering the alveoli is about 100 mm Hg, and at this pressure the hemoglobin in the blood becomes saturated with O_2. This means that iron in hemoglobin molecules has combined with O_2. On the other hand, the P_{O_2} in the tissues is about 40 mm Hg, causing hemoglobin molecules to release O_2, and O_2 to diffuse into the tissues.

In addition to the partial pressure of O_2, temperature and pH also affect the amount of oxygen hemoglobin can carry. The lungs have a lower temperature and a higher pH than the tissues:

	pH	Temperature
Lungs	7.40	37°C
Tissues	7.38	38°C

Both Figure 15.9*a* and *b* show that, as expected, hemoglobin more saturated with O_2 in the lungs than in the tissues. .his effect, which can be attributed to the difference in P_{O_2} between the lungs and tissues, is potentiated by the difference in temperature and pH between the lungs and tissues. Notice in Figure 15.9*a* that the saturation curve for hemoglobin is steeper at 10°C compared to 20°C, and so forth. Also, Figure 15.9*b* shows that the saturation curve for hemoglobin is steeper at higher pH than at lower pH.

This means that the environmental conditions in the lungs are favorable for the uptake of O_2 by hemoglobin, and the environmental conditions in the tissues are favorable for the release of O_2 by hemoglobin. Hemoglobin is about 98–100% saturated in the capillaries of the lungs and about 60–70% saturated in the tissues. During exercise, hemoglobin is even less saturated in the tissues because muscle contraction leads to higher body temperature (up to 103°F in marathoners!) and lowers the pH (due to the production of lactic acid).

The difference in P_{O_2}, temperature, and pH between the lungs and tissues causes hemoglobin to take up oxygen in the lungs and release oxygen in the tissues.

Visual Focus

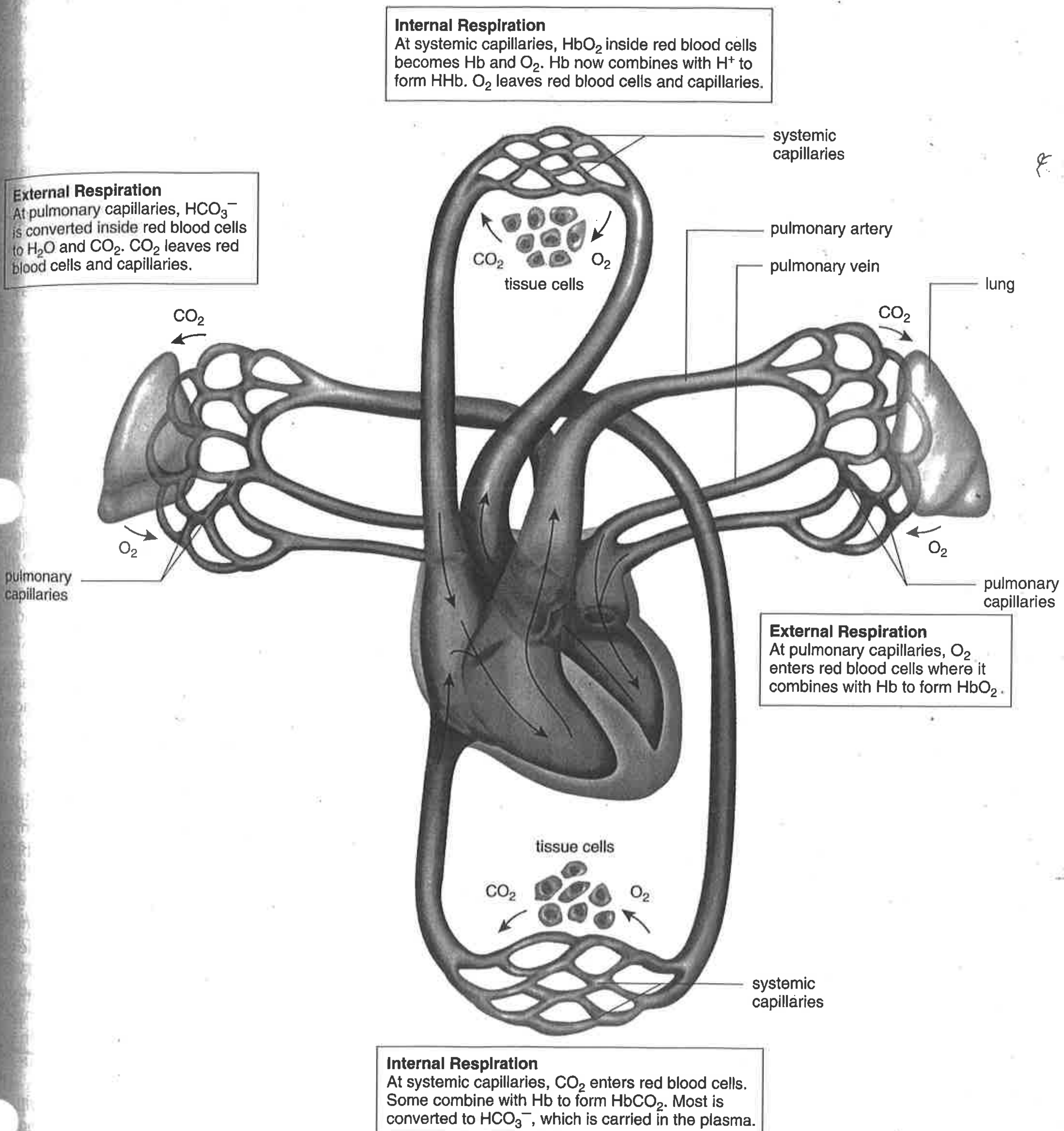


Figure 15.8 External and internal respiration.
During external respiration in the lungs, CO_2 leaves blood and O_2 enters blood. During internal respiration in the tissues, O_2 leaves blood and CO_2 enters blood.