Transport and Diffusion of Gases

10.3

Our lives depend on the ability to extract oxygen from the air we breathe and to get rid of carbon dioxide waste. Two main factors determine this ability: the surface area of the respiratory membrane and the differences in concentration of gases across the membrane. As you learned in Section 10.2, the membrane that forms the millions of alveoli in the lungs provides the surface area. In this section you will examine the second factor affecting gas exchange—the concentration of the gases on each side of the respiratory membrane.

The Air We Breathe

Earth is surrounded by a thin envelope of air, the atmosphere. The air is most dense at sea level. At high altitude, a given volume of air contains fewer air molecules than it does at sea level. In other words, as altitude increases, the concentration or density of air molecules decreases. As density decreases, air pressure also decreases (**Figure 1**).

The SI unit for pressure is the pascal (Pa). A pascal is a force of one newton exerted on an area of one square metre. Since the pascal is a very small quantity, pressures are often measured in kilopascals (kPa). At sea level, air pressure is 101.3 kPa. At the top of Mount Everest, about 8850 m above sea level, the air pressure drops to about 31 kPa.

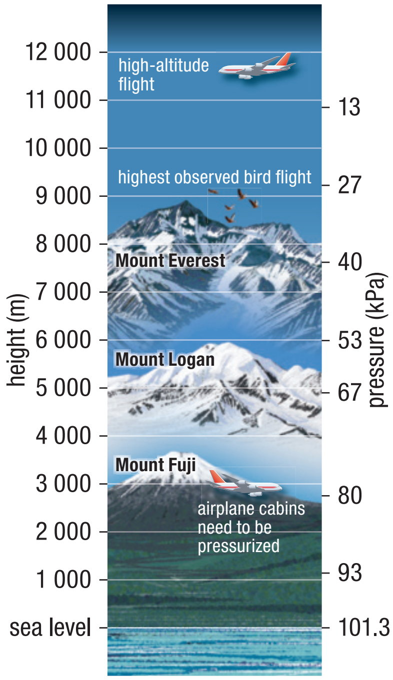

Figure 1 Air density and air pressure decrease with altitude. This means that there are fewer oxygen molecules in a given volume of air at higher altitudes.

Partial Pressures

Although air density and air pressure change at different altitudes, the composition of gases that make up air does not change significantly from sea level to the upper levels of the atmosphere. The proportions of the various gases remain approximately the same.

The air that we breathe is a mixture of gases, but for the purposes of this chapter we are concerned with only two—oxygen and carbon dioxide. Oxygen makes up about 20.9 % of the air in the atmosphere, and carbon dioxide makes up 0.0391 %.

The total air pressure of a mixture of gases is equal to the sum of the **partial pressures** of its component gases. For example, atmospheric pressure at sea level is 101.3 kPa. Since oxygen constitutes 20.9 % of the atmosphere, the partial pressure of oxygen is 20.9 % of the atmospheric pressure at sea level—20.9 % of 101.3 kPa, or 21.17 kPa. Similarly, the partial pressure of carbon dioxide is 0.0397 kPa. The partial pressure of oxygen is written as P_{O_2} and the partial pressure of carbon dioxide is written as P_{CO_2}.

partial pressure the pressure of each of the individual gases that make up the total pressure of a mixture of gases

The concept of partial pressures also applies to gases that are dissolved in liquids. You are likely familiar with what happens when you open a bottle or can of pop. You hear a hissing noise as gas escapes, and you see bubbles rising through the liquid (**Figure 2**). The gases stay in solution as long as the liquid is under pressure. After the pop bottle is opened, the carbon dioxide will continue to escape from the pop until the partial pressure of the carbon dioxide in the pop is the same as the partial pressure of the carbon dioxide in the air above it.

Partial pressures of gases affect gas exchange. Gases will diffuse across a membrane from an area of higher pressure to an area of lower pressure until the pressures are equal. The greater the pressure gradient, the higher is the rate of diffusion.

Figure 2 Gases dissolved in liquids stay in solution while the liquid is under pressure.

OXYGEN TRANSPORT AND DIFFUSION

Partial pressure helps to explain how oxygen diffuses in the lungs. Oxygen moves from the air in the alveoli into the bloodstream, where the partial pressure of oxygen (P_{O_2}) is lower. The P_{O_2} in the alveoli is about 13.3 kPa, which is less than the P_{O_2} of the external surrounding air. This is because some residual or stale air remains in the alveoli, reducing the overall proportion of oxygen. At 13.3 kPa, the P_{O_2} in the alveoli is considerably higher than the P_{O_2} of the blood in the capillaries surrounding the alveoli, which is about 5.33 kPa (**Figure 3(a)**). This significant pressure gradient causes oxygen to diffuse from the air in the alveoli into the liquid component of blood, called **plasma**.

plasma the liquid component of blood in which blood cells are suspended

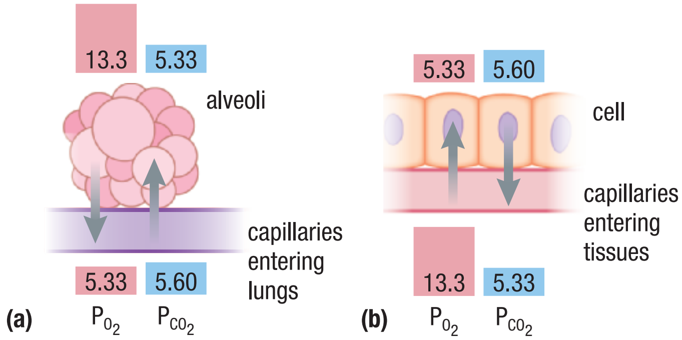

Figure 3 (a) The P_{O_2} in the alveoli is higher than the P_{O_2} in the capillaries surrounding the alveoli, so oxygen diffuses from the air in the alveoli into the blood. Conversely, the P_{CO_2} in the capillaries is higher than the P_{CO_2} in the alveoli, so carbon dioxide diffuses from the blood in the capillaries to the air in the alveoli. (b) Oxygen diffuses from the blood into the tissue cells, and carbon dioxide diffuses from the tissue cells into the capillaries due to the differences in partial pressures.

A constant supply of oxygen is needed by all cells of the body because the cells continuously use oxygen for aerobic cellular respiration. The circulatory system transports oxygen to the body cells in two different ways: attached to hemoglobin molecules within red blood cells (98.5 %) and dissolved in blood plasma (1.5 %). **Hemoglobin** is an iron-containing protein in red blood cells that binds with molecules of oxygen to form oxyhemoglobin. Oxyhemoglobin gives oxygenated blood its bright red colour. Deoxygenated blood is dark red. Blood without hemoglobin carries only about 0.3 mL of oxygen per 100 mL of blood, while blood with hemoglobin carries about 20 mL of oxygen per 100 mL of blood. Hemoglobin increases the blood's capacity to carry oxygen by nearly 70 times!

hemoglobin the protein in red blood cells that bonds with oxygen and enables the transport of oxygen around the body

LEARNING TIP

Blue Blood

Deoxygenated blood in veins is dark red but it appears blue. This is because only the higher-energy blue wavelengths of the visible spectrum can penetrate through the skin and fat covering the vein. The other lower-energy wavelengths are absorbed. The reflection of the blue wavelengths gives veins their characteristic blue colour.

When oxygen-rich blood reaches the body's tissue cells, first the oxygen dissolved in blood plasma diffuses into the tissue fluid, and then into the tissue cells. This diffusion of oxygen reduces the P_{O_2} in the blood plasma. As a result, the oxygen molecules that are attached to hemoglobin in the red blood cells separate from the hemoglobin molecules. These oxygen molecules diffuse into the blood plasma, then into the tissue fluid, and finally into the tissue cells. However, the supply of oxygen in the hemoglobin is not depleted before the blood flows away from the tissues. The P_{O_2} in the veins is 5.33 kPa, so there is still a considerable amount of oxygen in the blood as it moves from the tissues to the heart and on to the lungs. Under normal conditions, blood always contains some oxygen, although much more after it passes through the lungs. This is why you can hold your breath for a short time and not die.

CARBON DIOXIDE TRANSPORT AND DIFFUSION

Carbon dioxide is produced in the body cells as a by-product of aerobic cellular respiration and must be removed. As aerobic cellular respiration continues, carbon dioxide accumulates in cells and diffuses from the cells into the tissue fluid. Under normal conditions, the P_{CO_2} of tissue fluid is 5.60 kPa. This is higher than the P_{CO_2} in the capillaries, where it is about 5.33 kPa (**Figure 3(b)**, above). This pressure gradient is sufficient for carbon dioxide to diffuse from the tissue fluid into the bloodstream.

Carbon dioxide is transported though the blood in three different ways. About 7 % of the carbon dioxide in the bloodstream remains dissolved in the plasma. Another 20 % attaches to hemoglobin to form carbaminohemoglobin. The rest of the carbon dioxide, about 73 %, reacts with the water in plasma to form carbonic acid. Carbonic acid quickly separates into bicarbonate ions, HCO_3^-, and hydrogen ions, H^+ (**Figure 4(a)** and **(b)**). This creates a problem—the increase of hydrogen ions increases the acidity of the plasma, which can be life-threatening.

This problem is solved by hemoglobin. As hemoglobin releases oxygen molecules to the tissue cells, it attaches hydrogen ions, H^+. The attachment of H^+ ions to hemoglobin prevents the dangerous accumulation of these ions in blood and tissue fluid. The bicarbonate ions, HCO_3^-, remain dissolved in the blood plasma and are carried by the bloodstream to the lungs.

In the lungs, the H^+ ions separate from the hemoglobin molecules and diffuse into the blood plasma. The H^+ ions react with the bicarbonate ions in the blood plasma to re-form carbon dioxide and water (**Figure 4(c)**). This is essentially the reverse of the reaction that occurred in the tissues where hemoglobin picked up the H^+ ions. The carbon dioxide molecules produced in this reaction mix with the carbon dioxide molecules that were carried in dissolved form in the plasma. As a result, the P_{CO_2} of the blood in the capillaries surrounding the alveoli is approximately 5.60 kPa. The P_{CO_2} of the air in the alveoli is approximately 5.33 kPa (Figure 3(a), page 448). This difference in the partial pressures of carbon dioxide causes the carbon dioxide to diffuse from the blood plasma into the air within the alveoli. The act of breathing then takes the carbon dioxide–rich air from the alveoli to the external environment.

(a) $CO_2 + H_2O \rightarrow H_2CO_3$

(b) $H_2CO_3 \rightarrow H^+ + HCO_3^-$

(c) $H^+ + HCO_3^- \rightarrow CO_2 + H_2O$

Figure 4 (a) CO_2 produced during aerobic cellular respiration dissolves in the tissue fluid around the cells. This forms carbonic acid (H_2CO_3). (b) Carbonic acid separates into H^+ ions and HCO_3^- ions. (c) These H^+ ions and HCO_3^- ions combine in the red blood cells to form CO_2 and H_2O. The CO_2 is released into the air in the alveoli.

The Effect of Altitude on Respiration

The respiratory system faces challenges at high altitudes. The atmospheric pressure at 2000 m is about 80 kPa. At 7000 m, the atmospheric pressure is only 40 kPa. Above 7000 m, the atmospheric pressure is so low that humans cannot survive. The reason is that even though oxygen still constitutes 20.9 % of the air, the density and partial pressure of oxygen are too low—there are not enough oxygen molecules in a given volume of air. A breath of air at high altitude contains fewer oxygen molecules than the same breath of air at sea level.

The partial pressure of oxygen in the air at 2000 m is 20.9 % of 80 kPa, or about 17 kPa. This is significantly lower than the P_{O_2} of air at sea level. The pressure gradient between the P_{O_2} of the air and the P_{O_2} of the blood is reduced, so the rate of diffusion across the respiratory membrane decreases, and the supply of oxygen to the body is reduced. Depending on the altitude, the decreased oxygen supply can cause altitude sickness. The symptoms of altitude sickness include shortness of breath, headache, dizziness, tiredness, and nausea.

Over time, when the supply of oxygen is reduced, the kidneys increase the secretion of a substance called erythropoietin (EPO). EPO is a hormone that stimulates the production of red blood cells. Increasing the number of red blood cells increases the amount of oxygen that can be absorbed from the air and delivered to the body cells. Some endurance athletes, such as long-distance runners and triathletes, train at high altitudes to increase the number of red blood cells (**Figure 5**). Training at a high altitude for just a few weeks can increase the red blood cell count from about 5 000 000/mL to about 7 000 000/mL. Since the lifespan of red blood cells is between 90 and 120 days, the additional red blood cells will remain active for several weeks afterward, giving athletes an extra reservoir of oxygen. Recent studies have suggested that although living at high altitudes provides benefits for endurance athletes, training at high altitudes may not. One of the newer techniques involves sleeping or resting at a high altitude and moving to a lower altitude to train.

Figure 5 Training at high altitudes may provide a legal competitive advantage because of the additional red blood cells that the body produces naturally.

Although EPO is a naturally occurring substance that is produced in the human body, the synthetic version (which is virtually identical to the natural substance and is used to treat anemia) is a banned substance in competitions such as the Olympic Games. A new urine test is available that can distinguish between natural and synthetic EPO.

The Control of Breathing

Breathing is largely an involuntary action. It is controlled by the coordinated efforts of the nervous system and the circulatory system. The normal rhythmic movements of inhalation and exhalation are controlled by signals from the respiratory centre in the brain stem (**Figure 6**). The brain sends out signals that cause the diaphragm and external intercostal muscles to contract, causing inhalation. Stretch receptors in the lungs send signals back to the brain, indicating that the lungs have expanded. The brain then stops signalling the diaphragm and intercostal muscles, causing them to relax and bringing about exhalation. We can consciously override these signals for a short period, such as when we intentionally hold our breath, talk, or sing. This override is controlled by other centres in the brain.

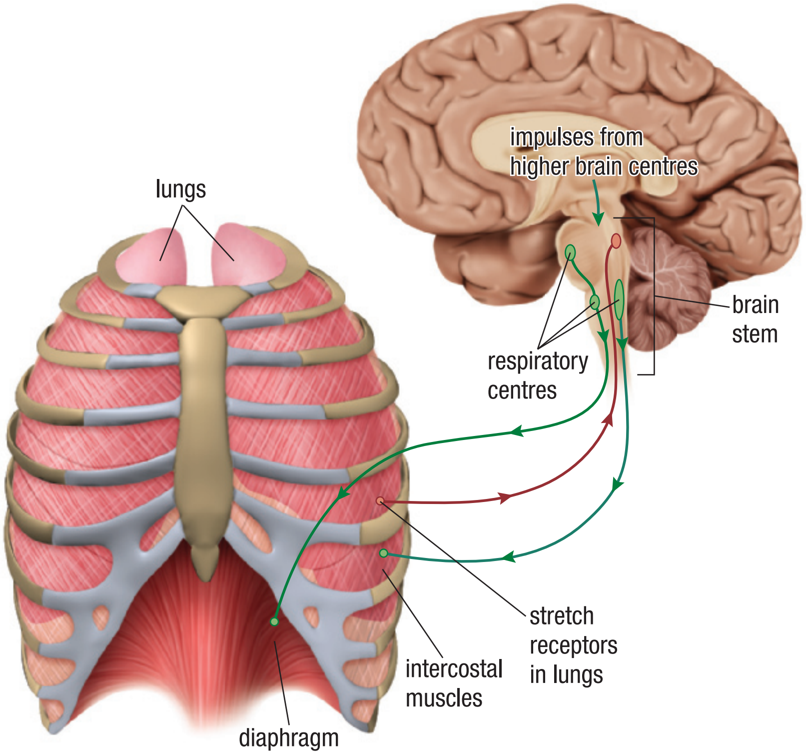

Figure 6 Another example of the interdependence of organ systems can be seen in the contraction and relaxation of the muscles that enable breathing. These muscles are controlled by the respiratory centre in the brain stem.

Maintaining Oxygen and Carbon Dioxide Levels

The rate of breathing is determined by the demand for oxygen or the need to eliminate carbon dioxide. But how does the body know when there is insufficient oxygen or too much carbon dioxide? The levels of oxygen and carbon dioxide in the blood are continuously monitored by chemical receptors in the brain itself, in the arteries leading to the brain, and in the arteries leaving the heart.

The first and most significant effect on breathing is the level of carbon dioxide. An increase in aerobic cellular respiration increases the amount of carbon dioxide in the blood, which in turn produces carbonic acid and lowers the pH of the blood. Receptors in the brain detect the decrease in pH and recognize this as a sign that carbon dioxide levels are too high. There are also chemical receptors in the arteries in the neck and the arteries leaving the heart that are sensitive to the pH of the blood. A decrease in the pH will trigger a signal to the respiratory centre in the brain. In response, the brain sends out signals that increase both the breathing rate and the volume of inhalation by causing the diaphragm and intercostal muscles to contract more rapidly and more forcefully. The heart rate also increases at the same time, so that oxygen is quickly delivered to the body while additional carbon dioxide is removed.

The monitoring of oxygen levels is a secondary breathing control mechanism and is not as significant as monitoring carbon dioxide levels. Receptors in the arteries monitor the level of oxygen in the blood leaving the heart and going to the brain. However, these receptors will not signal the respiratory centre of the brain to trigger an increase in breathing rate until the oxygen level falls significantly below normal. In most circumstances, the higher carbon dioxide levels will have triggered a response before this happens.

10.3 Summary

- The air that we breathe is a mixture of gases. Oxygen makes up 20.9 % of the atmosphere. Carbon dioxide constitutes only 0.0391 % of the atmosphere.
- The pressure of a mixture of gases is equal to the sum of the partial pressures of the component gases.
- Oxygen and carbon dioxide are exchanged between the interior and exterior of the body by diffusion. These gases will diffuse from an area with a higher partial pressure to an area of lower partial pressure.
- Hemoglobin is an iron-containing protein in red blood cells that binds with molecules of oxygen.
- Carbon dioxide diffuses from cells into the plasma, where it forms carbonic acid. The hydrogen ions make the blood more acidic. Hemoglobin adjusts the pH of the blood by picking up the hydrogen ions and carrying them back to the lungs, where they recombine with bicarbonate ions in the plasma to produce carbon dioxide and water.
- Involuntary breathing is controlled by the respiratory centre in the brain stem. Breathing rate and depth increase if the concentration of carbon dioxide in the blood increases.

UNIT TASK **BOOKMARK**

Consider what you have learned about how oxygen and carbon dioxide are transported in the human respiratory system. How can this information help you complete Parts A and C of the Unit Task?

10.3 Questions

1. (a) At higher altitudes the air is described as “thinner.” Explain what this means.
   (b) Is the composition of air different at different altitudes? Explain.
   (c) How does the partial pressure of oxygen change with altitude? K/U T/I A
2. Why is the partial pressure of carbon dioxide in the blood higher than the partial pressure of carbon dioxide in the atmosphere? K/U T/I A
3. Gas exchange occurs in two locations—the alveoli in the lungs and the body cells. Using the concepts of partial pressures and pressure gradients, explain the gas exchange that occurs at each of these locations. K/U T/I A
4. Describe the roles of hemoglobin in gas exchange. K/U
5. (a) How does the body respond if a person moves to a higher altitude?
   (b) How do athletes use this information? K/U A
6. (a) How is breathing rate regulated?
   (b) How does the respiratory system respond when carbon dioxide levels are too high? How does the circulatory system respond? K/U
7. Use the Internet and other sources to find out why carbon monoxide is a dangerous substance. Write a brief report outlining the causes, physiological effects, treatments, and risks of carbon monoxide poisoning. T/I C A

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