Respiration

The main function of the respiratory system is gas exchange. Gas exchange is achieved through a process called *respiration*, or breathing. The cardiovascular system and the respiratory system work together to accomplish respiration.

External Respiration

During external respiration, fresh oxygen from outside the body fills the lungs and alveoli, and carbon dioxide is transported from the body tissues to the lungs. For oxygen to reach the body's tissues and carbon dioxide to leave the body, gas exchange must occur in the alveolar capillary membrane.

The alveoli and the capillaries that surround them make up the alveolar (al-VEE-oh-lar) capillary membrane (**Figure 9.5** in the textbook). The alveolar capillary membrane is built for gas exchange, as explained by Fick's Law.

Fick's Law states that the diffusion of oxygen and carbon dioxide between the capillaries and the alveolar sacs is proportional to the surface area (S.A.) of the lungs, the diffusion constant (D) of each gas, and the difference in partial pressure between each capillary and alveolar sac (P_1-P_2). According to this law, the diffusion of gases is also inversely related to the thickness of the tissues (T) involved. In simpler terms, thin-walled tissues allow for easier gas exchange.

Diffusion = $\frac{S.A.}{T} \times D\ (P_1 - P_2)$

Therefore, oxygen easily diffuses across the membrane of the alveolar sacs and into the capillaries. Carbon dioxide passes from the capillaries into the alveolar sacs, where it can be expelled from the body via the lungs (**Figure 9.5**).

How fast does gas exchange occur in the lungs? Faster than you might think. At rest, our blood becomes 98% oxygenated in no more than 0.75 seconds. Let's explore the different components that allow gas exchange to occur so quickly.

Surface Area.

The surface area of the lungs is immense. If we were to lay the alveolar sacs of the lungs side by side on the ground, they would almost cover an entire tennis court. These millions of alveolar sacs provide a nearly unlimited number of sites for gas exchange between the blood and alveolar sacs. This vast amount of available sites means gas exchange can occur rapidly.

Diffusion Constant of Gases.

The diffusion constant of a gas is proportional to its solubility but inversely related to the square root of its molecular weight. Oxygen has a lower molecular weight than carbon dioxide, so it should diffuse more quickly across the alveolar capillary membrane. However, the solubility of CO_2 is approximately 24 times greater than oxygen, so CO_2 actually diffuses 20 times faster than O_2.

Partial Pressure.

The pressure that one gas in a mixture would exert if it occupied the same volume on its own is referred to as *partial pressure*. Gases always flow from areas of high concentration to areas of low concentration. The difference between the partial pressure ($P_1 - P_2$) of gas in the tissues and gas in the blood is called a *pressure gradient* (PG). The pressure gradient between the venous capillary blood and the alveolar sacs is 65 mmHg for oxygen and 6mmHg for carbon dioxide during external respiration. Similarly, there are pressure gradients that promote gas exchange between the arterial and venous blood and the body's tissues during internal respiration.

Tissue Thickness.

The thickness of tissue affects how easily gases can diffuse from one area to another. The oxygen and carbon dioxide molecules involved in gas exchange only have to travel from the red blood cells, through the capillary wall and its membrane, and then through the alveolar wall and its membrane during external respiration. These membranes are razor thin—even thinner than a sheet of tissue paper. This makes it easy for oxygen and carbon dioxide to move freely between the alveoli and the bloodstream.

Respiratory Gas Transport

Respiratory gas transport involves transporting oxygen and carbon dioxide in the blood between the lungs and peripheral body tissues. At the lungs, oxygen is collected to take to peripheral tissues, and carbon dioxide is delivered from the peripheral tissues. At the peripheral tissues, carbon dioxide is collected to take to the lungs, and oxygen is delivered from the lungs.

Each gas is transported by binding to specific molecules. Oxygen is primarily transported by hemoglobin, due to hemoglobin's *affinity*, or binding strength, for oxygen. Carbon dioxide is primarily transported by the bicarbonate ion, but hemoglobin also transports some carbon dioxide. Both gases are also transported when they diffuse into the blood.

Oxygen Transport.

There are two ways in which oxygen is transported in the bloodstream. More than 98% of oxygen is transported by hemoglobin, a protein found in the body's 20–30 million red blood cells. The shape of the red blood cell, which is often referred to as a *biconcave disc* shape, gives the cell a high surface area in proportion to its volume. As mentioned above, a high surface area allows for more diffusion of dissolved oxygen and carbon dioxide into and out of the cell. At the lungs, oxygen is picked up by hemoglobin for transport to the peripheral tissues.

When oxygen is "picked up," it binds to hemoglobin (Hb), and the *oxyhemoglobin* (HbO_2) molecule is formed. As the oxyhemoglobin molecule is transported throughout the body in the plasma, oxygen is dispensed to cells in the peripheral tissues that need oxygen to survive.

Exercise, which causes an increase in the body's pH and temperature, decreases the affinity of hemoglobin. This results in a greater unloading of oxygen. Therefore, these factors help to meet the increased oxygen demands that occur during exercise.

Oxygen is also transported to peripheral tissues by dissolving in plasma, but this accounts for less than 2% of oxygen transport.

Carbon Dioxide Transport.

Carbon dioxide is transported in one of three ways. At the peripheral tissues, carbon dioxide is bound to bicarbonate ion, bound to hemoglobin, or dissolved into plasma. Through these methods, carbon dioxide is carried to the lungs for expulsion.

Approximately 60–70% of carbon dioxide is transported as the bicarbonate ion (HCO_3^-). Bicarbonate is one of the primary buffers found in the plasma, and it helps to maintain a normal pH range. At the peripheral tissues, carbon dioxide may combine with water to form carbonic acid (H_2CO_3), which is unstable and dissociates into hydrogen ions (H^+) and bicarbonate ion. When the bicarbonate ion reaches the lungs, it forms carbonic acid, which rapidly breaks apart into water and carbon dioxide. Carbon dioxide is expelled during expiration.

About 20–30% of carbon dioxide is bound to hemoglobin to form the *carbaminohemoglobin* ($HbCO_2$) molecule. Hemoglobin has two binding sites—an iron-containing heme site and a globin site. Oxygen binds at the iron-containing heme site. Carbon dioxide binds to amino acids on the globin site. Therefore, oxygen and carbon dioxide do not have to compete for a binding site. Both are easily transported by hemoglobin. Carbon dioxide binds to hemoglobin at the peripheral tissue, is transported to the lungs, and then hemoglobin dispenses it.

Finally, 7–10% of carbon dioxide is dissolved in plasma, which carries it to the lungs.

Internal Respiration

Internal respiration is the process of gas exchange that occurs between blood in the tissue capillaries and the body's tissues. In internal respiration, carbon dioxide in the body tissues diffuses into the blood. Simultaneously, oxygen in the blood is released from the hemoglobin to which it was bound. The oxygen then diffuses into the tissues, which need oxygen to function. The venous blood is sent back to the lungs, where the process of external respiration will occur, the deoxygenated blood will become oxygenated, and CO_2 will diffuse into the alveoli.

Critical Thinking

1. According to Fick's Law, which characteristics of the alveolar capillary membrane make it ideal for gas exchange?
2. Explain how *affinity* contributes to respiratory gas transport.
3. How does the structure of a hemoglobin molecule allow it to easily transport oxygen and carbon dioxide simultaneously?
4. Explain the role of diffusion in external respiration, respiratory gas transport, and internal respiration.