Al-ayen Iraqi university

College of Health &Medical Technology

Department of Anesthesia

Lecture 4

transport of gases(O_2,CO_2)

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❖ Exchange of Oxygen and Carbon Dioxide

The exchange of oxygen and carbon dioxide between alveolar air and pulmonary blood occurs via passive diffusion, which is governed by the behavior of gases as described by two gas laws, Dalton's law and Henry's law. Dalton's law is important for understanding how gases move down their pressure gradients by diffusion, and Henry's law helps explain how the solubility of a gas relates to its diffusion.

✔ Dalton's law

according to Dalton's law, each gas in a mixture of gases exerts its own pressure as if no other gases were present. The pressure of a specific gas in a mixture is called its partial pressure (Px); the subscript is the chemical formula of the gas. The total pressure of the mixture is calculated simply by adding all of the partial pressures. Atmospheric air is a mixture of gases—nitrogen (N2), oxygen (O2), argon (Ar), carbon dioxide (CO2), variable amounts of water vapor (H2O), plus other gases present in small quantities. Atmospheric pressure is the sum of the pressures of all of these gases:

$$\text{Atmospheric pressure (760 mmHg)} \\ = P_{N_2} + P_{O_2} + P_{Ar} + P_{H_2O} + P_{CO_2} + P_{\text{other gases}}$$

We can determine the partial pressure exerted by each component in the mixture by multiplying the percentage of the gas in the mixture by the total pressure of the mixture. Atmospheric air is 78.6% nitrogen, 20.9% oxygen, 0.093% argon, 0.04% carbon dioxide, and 0.06% other gases; a variable amount of water vapor is also present. The amount of water varies from practically 0% over a desert to 4% over the ocean, to about 0.4% on a cool, dry day. Thus, the partial pressures of the gases in inhaled air are as

$$\begin{aligned} P_{N_2} &= 0.786 \times 760 \text{ mmHg} = 597.4 \text{ mmHg} \\ P_{O_2} &= 0.209 \times 760 \text{ mmHg} = 158.8 \text{ mmHg} \\ P_{Ar} &= 0.0009 \times 760 \text{ mmHg} = 0.7 \text{ mmHg} \\ P_{H_2O} &= 0.003 \times 760 \text{ mmHg} = 2.3 \text{ mmHg} \\ P_{CO_2} &= 0.0004 \times 760 \text{ mmHg} = 0.3 \text{ mmHg} \\ P_{\text{other gases}} &= 0.0006 \times 760 \text{ mmHg} = \underline{0.5 \text{ mmHg}} \\ \text{Total} &= 760.0 \text{ mmHg} \end{aligned}$$

follows:

These partial pressures determine the movement of O2 and CO2 between the atmosphere and lungs, between the lungs and blood, and between the blood and body cells. Each gas diffuses across a permeable membrane from the area where its partial pressure is greater to the area where its partial pressure is less. The greater the difference in partial pressure, the faster the rate of diffusion.

Compared with inhaled air, alveolar air has less O2 (13.6% versus 20.9%) and more CO2 (5.2% versus 0.04%) for two reasons. First, gas exchange in the alveoli increases the CO2 content and decreases the O2 content of alveolar air. Second, when air is inhaled it becomes humidified as it passes along the moist mucosal linings. As water vapor content of the air increases, the relative percentage that is O2 decreases. In contrast, exhaled air contains more O2 than alveolar air (16% versus 13.6%) and less CO2 (4.5% versus 5.2%) because some of the exhaled air was in the anatomic dead space and did not participate in gas exchange. Exhaled air is a mixture of alveolar air and inhaled air that was in the anatomic dead space.

✔ Henry's law

Henry's law states that the quantity of a gas that will dissolve in a liquid is proportional to the partial pressure of the gas and its solubility. In body fluids, the ability of a gas to stay in solution is greater when its partial pressure is higher and when it has a high solubility in water. The higher the partial pressure of a gas over a liquid and the higher the solubility, the more gas will stay in solution. In comparison to oxygen, much more CO2 is dissolved in blood plasma because the solubility of CO_2 is 24 times greater than that of

O_2. Even though the air we breathe contains mostly N_2, this gas has no known effect on bodily functions, and at sea level pressure very little of it dissolves in blood plasma because its solubility is very low.

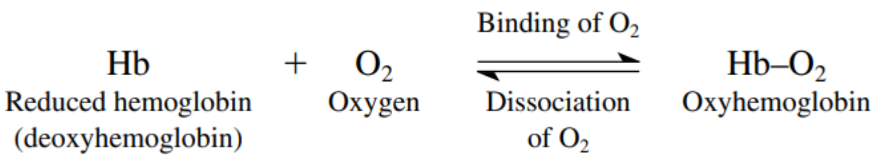
An everyday experience gives a demonstration of Henry's law. You have probably noticed that a soft drink makes a hissing sound when the top of the container is removed, and bubbles rise to the surface for some time afterward. The gas dissolved in carbonated beverages is CO_2. Because the soft drink is bottled or canned under high pressure and capped, the CO_2 remains dissolved as long as the container is unopened. Once you remove the cap, the pressure decreases and the gas begins to bubble out of solution.

Henry's law explains two conditions resulting from changes in the solubility of nitrogen in body fluids. Even though the air we breathe contains about 79% nitrogen, this gas has no known effect on bodily functions, and very little of it dissolves in blood plasma because of its low solubility at sea level pressure. As the total air pressure increases, the partial pressures of all of its gases increase. When a scuba diver breathes air under high pressure, the nitrogen in the mixture can have serious negative effects. Because the partial pressure of nitrogen is higher in a mixture of compressed air than in air at sea level pressure, a considerable amount of nitrogen dissolves in plasma and interstitial fluid. Excessive amounts of dissolved nitrogen may produce giddiness and other symptoms similar to alcohol intoxication. The condition is called nitrogen narcosis or "rapture of the deep."

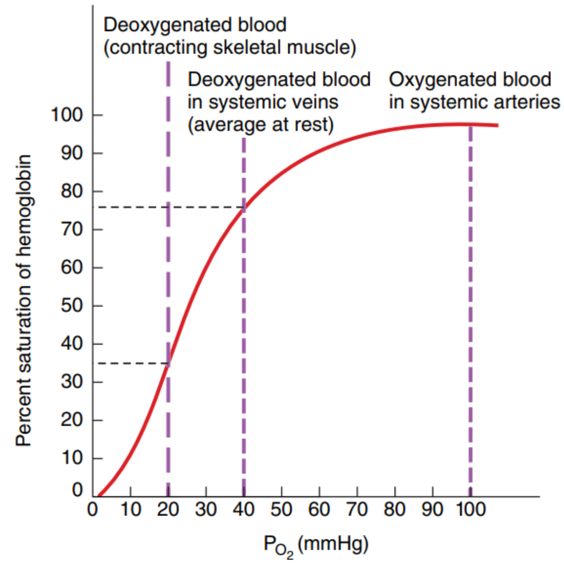
If a diver comes to the surface slowly, the dissolved nitrogen can be eliminated by exhaling it. However, if the ascent is too rapid, nitrogen comes out of solution too quickly and forms gas bubbles in the tissues, resulting in decompression sickness (the bends). The effects of decompression sickness typically result from bubbles in nervous tissue and can be mild or severe, depending on the number of bubbles formed. Symptoms include joint pain, especially in the arms and legs, dizziness, shortness of breath, extreme fatigue, paralysis, and unconsciousness.

- **Oxygen Transport**

Oxygen does not dissolve easily in water, so only about 1.5% of inhaled O_2 is dissolved in blood plasma, which is mostly water. About 98.5% of blood O_2 is bound to hemoglobin in red blood cells. The heme portion of hemoglobin contains four atoms of iron, each capable of binding to a molecule of O_2 (see Figure 19.4b, c). Oxygen and hemoglobin bind in an easily reversible reaction to form oxyhemoglobin:



The 98.5% of the O2 that is bound to hemoglobin is trapped inside RBCs, so only the dissolved O2 (1.5%) can diffuse out of tissue capillaries into tissue cells. Thus, it is important to understand the factors that promote O2 binding to and dissociation (separation) from hemoglobin.

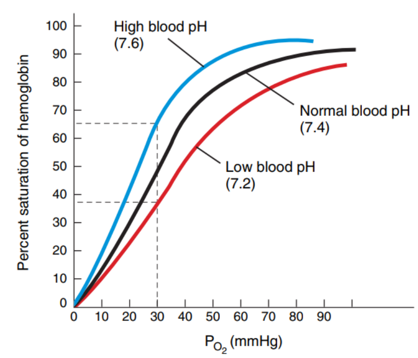


The most important factor that determines how much O2 binds to hemoglobin is the PO2 ; the higher the PO2 , the more O2 combines with Hb. When reduced hemoglobin (Hb) is completely converted to oxyhemoglobin (Hb–O2), the hemoglobin is said to be fully saturated; when hemoglobin consists of a mixture of Hb and Hb–O2, it is partially saturated. The percent saturation of hemoglobin expresses the average saturation of hemoglobin with oxygen. For instance, if each hemoglobin molecule has bound two O2 molecules, then the hemoglobin is 50% saturated because each Hb can bind a maximum of four O2.

when the PO2 is high, hemoglobin binds with large amounts of O2 and is almost 100% saturated. When PO2 is low, hemoglobin is only partially saturated. In active tissues such as contracting muscles, PO2 may drop well below 40 mmHg. Then, a large percentage of the O2 is released from hemoglobin, providing more O2 to metabolically active tissues.

Although PO2 is the most important factor that determines the percent O2 saturation of hemoglobin, several other factors influence the tightness or affinity with which hemoglobin binds O2. The changing affinity of hemoglobin for O2 is another example of how homeostatic mechanisms adjust body activities to cellular needs. The following four factors affect the affinity of hemoglobin for O2:

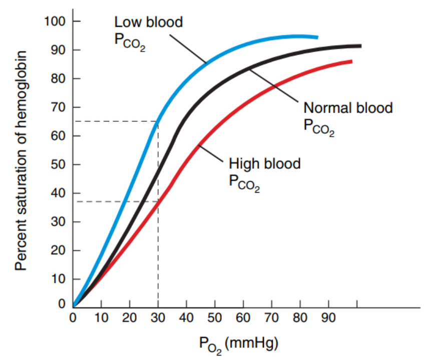
1. ***Acidity (pH).*** As acidity increases (pH decreases), the affinity of hemoglobin for O2 decreases, and O2 dissociates more readily



(a) Effect of pH on affinity of hemoglobin for oxygen from hemoglobin. The main acids produced by metabolically active tissues are lactic acid and carbonic acid.

2. ***Partial pressure of carbon dioxide.*** CO2 also can bind to hemoglobin, and the effect is similar to that of H+. As PCO2 rises, hemoglobin releases O2 more readily. PCO2 and pH are related factors because low blood pH (acidity) results from high PCO2. As CO2 enters the blood, much of it is temporarily converted to carbonic acid (H2CO3), a reaction catalyzed by an enzyme in red blood cells called carbonic anhydrase (CA):

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Water}}{H_2O} \overset{CA}{\rightleftharpoons} \underset{\text{Carbonic acid}}{H_2CO_3} \rightleftharpoons \underset{\text{Hydrogen ion}}{H^+} + \underset{\text{Bicarbonate ion}}{HCO_3^-}$$

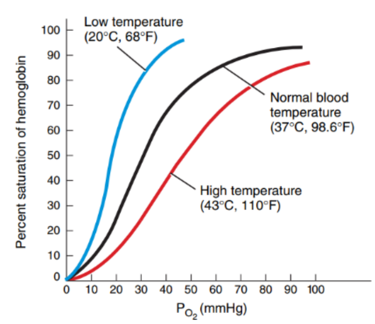


(b) Effect of P_{CO_2} on affinity of hemoglobin for oxygen

The carbonic acid thus formed in red blood cells dissociates into hydrogen ions and bicarbonate ions. As the H+ concentration increases, pH decreases. Thus, an increased PCO2 produces a more acidic environment, which helps release O2 from hemoglobin. During exercise, lactic acid—a by-product of anaerobic metabolism within muscles—also decreases blood pH.

3. ***Temperature.*** Within limits, as temperature increases, so does the amount of O2 released from hemoglobin. heat released by contracting muscle fibers tends to raise body temperature. Metabolically active cells require more O2 and liberate more acids and heat. The acids and heat in turn promote release of O2 from oxyhemoglobin. Fever produces a similar result. In contrast, during hypothermia (lowered body temperature) cellular metabolism slows, the need for O2 is reduced, and more O2 remains bound to hemoglobin.

As temperature increases, the affinity of hemoglobin for O_2 decreases.



❖ **Carbon Dioxide Transport**

Under normal resting conditions, each 100 mL of deoxygenated blood contains the equivalent of 53 mL of gaseous CO2, which is transported in the blood in three main forms:

1. Dissolved CO2. The smallest percentage—about 7%—is dissolved in blood plasma. On reaching the lungs, it diffuses into alveolar air and is exhaled.

2. Carbamino compounds. A somewhat higher percentage, about 23%, combines with the amino groups of amino acids and proteins in blood to form carbamino compounds. Because the most prevalent protein in blood is hemoglobin (inside red blood cells), most of the CO2 transported in this manner is bound to hemoglobin. Hemoglobin that has bound CO2 is termed carbamino-hemoglobin (Hb–CO2):

$$\underset{\text{Hemoglobin}}{Hb} + \underset{\text{Carbon dioxide}}{CO_2} \rightleftharpoons \underset{\text{Carbaminohemoglobin}}{Hb\text{–}CO_2}$$

3. Bicarbonate ions. The greatest percentage of CO2—about 70%—is transported in blood plasma as bicarbonate ions (HCO3-). As CO2 diffuses into systemic capillaries and enters red blood cells, it reacts with water in the presence of the enzyme carbonic anhydrase (CA) to form carbonic acid, which dissociates into H+ and HCO3-:

$$\underset{\substack{\text{Carbon}\\\text{dioxide}}}{CO_2} + \underset{\text{Water}}{H_2O} \overset{CA}{\rightleftharpoons} \underset{\substack{\text{Carbonic}\\\text{acid}}}{H_2CO_3} \rightleftharpoons \underset{\substack{\text{Hydrogen}\\\text{ion}}}{H^+} + \underset{\substack{\text{Bicarbonate}\\\text{ion}}}{HCO_3^-}$$

Thus, as blood picks up CO2, HCO3- accumulates inside RBCs. Some HCO3- moves out into the blood plasma, down its concentration gradient. In exchange, chloride ions (Cl-) move from plasma into the RBCs. This exchange of negative ions, which maintains the electrical balance between blood plasma and RBC cytosol, is known as the chloride shift. The net effect of these reactions is that CO2 is removed from tissue cells and transported in blood plasma as HCO3-. As blood passes through pulmonary capillaries in the lungs, all of these reactions reverse and CO2 is exhaled.