TRANSPORT OF GASES

Blood serves as the carrier for various substances such as nutrients, vitamins, and gases throughout the body. Gases, including oxygen (O_2) and carbon dioxide (CO_2), exhibit different modes of transportation within the bloodstream. A portion of these gases dissolves in the plasma, facilitating their transportation in a dissolved state. Additionally, another fraction is conveyed in a bound state.

- Oxygen and carbon dioxide, specifically, form associations with hemoglobin, a protein present in red blood cells (RBCs). The subsequent discussion delves into the intricate details of how oxygen and carbon dioxide are transported within the bloodstream.

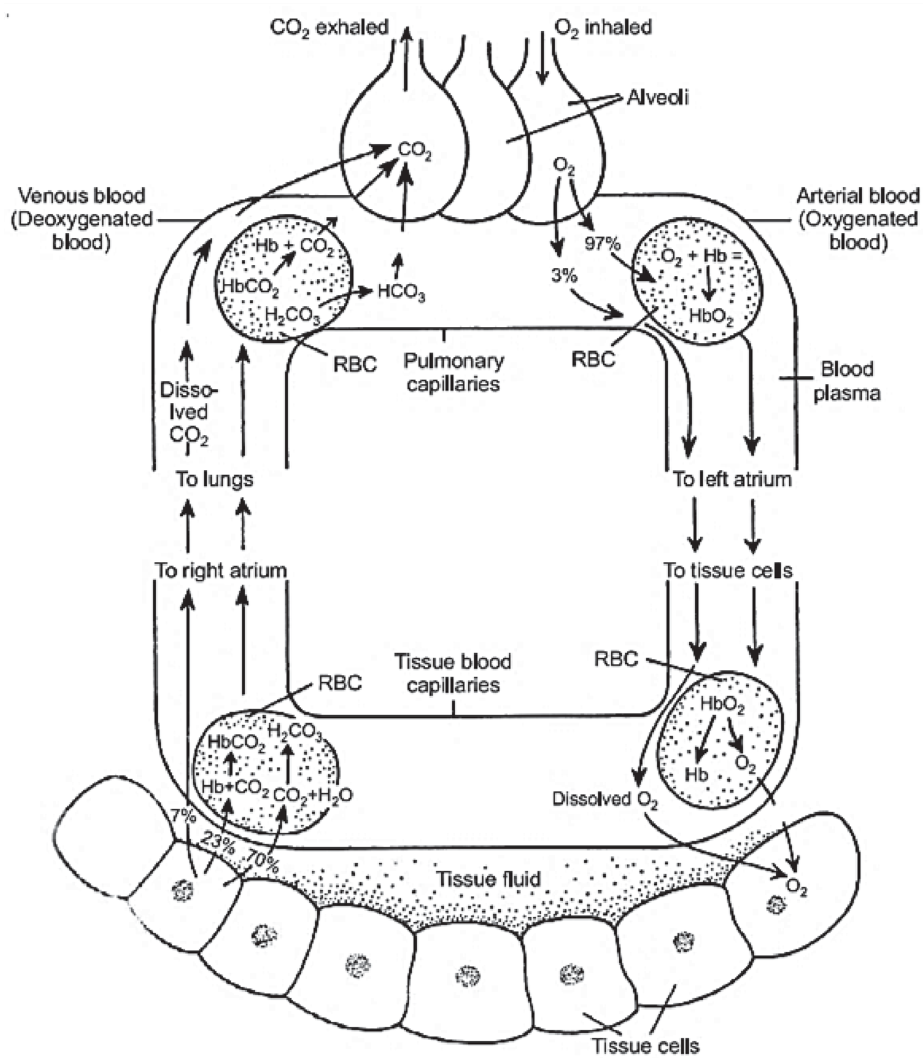


Fig. : Transport of oxygen and carbon dioxide

Transport of oxygen

The transportation of oxygen within the bloodstream involves the conveyance of oxygen from the lungs to the heart and subsequently to various cells throughout the body. Oxygen is transported through the blood in the following manners:

- **Dissolved Form:** Approximately 3% of oxygen is carried in a dissolved state within the plasma of the blood.

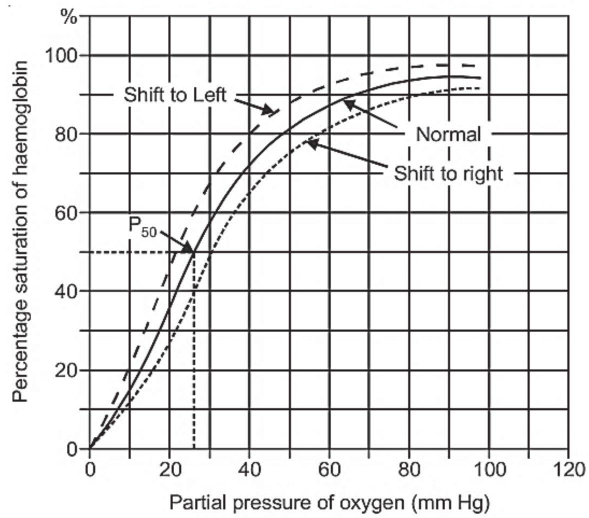
- **Oxyhemoglobin Formation:** The majority, around 97%, of oxygen is transported by red blood cells (RBCs) in the form of oxyhemoglobin (OxyHb). Hemoglobin (Hb), a crucial component of RBCs, consists of two main parts: haem and globin. Haem is the iron-containing portion, while globin is the protein part.

$$\underset{\text{Haemoglobin}}{\text{Hb}} \longrightarrow \underset{\text{(Iron part)}}{\text{Haem}} + \underset{\text{(Protein part)}}{\text{Globin}}$$

- Hemoglobin is a red-colored, iron-containing pigment found in RBCs, capable of binding reversibly with oxygen to form oxyhemoglobin and facilitating its transport. A single hemoglobin molecule can bind with up to four oxygen molecules due to its structure, which comprises four polypeptide chains, each with a haem group containing an iron atom capable of binding oxygen.

$$\underset{\text{Haemoglobin}}{\text{Hb}} + \underset{\text{Oxygen}}{O_2} \underset{\text{Tissues}}{\overset{\text{In lungs}}{\rightleftharpoons}} \underset{\substack{\text{Oxyheamoglobin} \\ \text{(OxyHb)}}}{HbO_2}$$

- Oxygen binds with hemoglobin at the surface of the lungs to form oxyhemoglobin. This oxygenated blood is then transported to various tissues. Upon reaching tissues, where the partial pressure of oxygen decreases, the bonds between oxygen and hemoglobin become unstable, leading to the release of oxygen for cellular metabolism, particularly for the oxidation of glucose.
- The dissociation of oxyhemoglobin near tissues occurs due to factors such as increased acidity and decreased pH, or elevated temperature. In a typical individual, the hemoglobin concentration in blood is approximately 15 grams per 100 milliliters. Each gram of hemoglobin has the capacity to combine with 1.34 milliliters of oxygen. Consequently, arterial blood transports about 20 milliliters of oxygen per 100 milliliters of blood under normal conditions, whereas this level decreases to about 14.4 milliliters per 100 milliliters in the venules. This indicates that approximately 5 milliliters of oxygen are delivered by 100 milliliters of oxygenated blood to the tissues under normal physiological conditions. However, during strenuous activities or exercise, the oxygen level may decrease to around 4.4 milliliters per 100 milliliters, allowing approximately 15 milliliters of oxygen to be delivered by hemoglobin to actively metabolizing tissues during exertion.
- **Oxygen-Dissociation Curve:** The relationship between the partial pressure of oxygen (pO2) and the percentage saturation of hemoglobin with oxygen is graphically represented by the oxygen-dissociation curve, which typically exhibits a sigmoid or 'S' shaped curve. This curve illustrates how the amount of oxygen bound to hemoglobin is influenced by the partial pressure of oxygen in the surrounding environment, representing the percentage saturation of hemoglobin with oxygen.



As depicted in the graph, hemoglobin (Hb) reaches approximately 50% saturation when the partial pressure of oxygen (pO2) is 25 mm Hg. This indicates that the blood contains roughly 50% oxygen at this point. The partial pressure at which hemoglobin saturation is 50% is termed as P50.

- **Factors influencing the O_2-dissociation:** This curve play a crucial role in understanding the dynamics of oxygen binding to hemoglobin (Hb) under varying physiological conditions. This curve offers valuable insights into how factors such as partial pressure of oxygen (pO2), partial pressure of carbon dioxide (pCO2), pH, temperature, and other biochemical components affect the affinity of hemoglobin for oxygen.
- **Shift to the Right:** A shift to the right in the O_2-dissociation curve signifies increased dissociation of oxygen from hemoglobin, primarily occurring in the tissues. Several conditions contribute to this shift:
  Low partial pressure of oxygen: When tissue oxygen levels are low, oxygen dissociates more readily from hemoglobin to supply oxygen to tissues.
  High partial pressure of CO_2: Elevated levels of carbon dioxide in tissues promote the release of oxygen from hemoglobin through the Bohr Effect.
  Bohr Effect: Increased CO_2 levels or decreased pH reduce hemoglobin's oxygen affinity, raising the P50 value, facilitating oxygen release.
  High H+ ion concentration and decreased pH: Acidic conditions in tissues favor oxygen release from hemoglobin.
  High temperature: Elevated temperatures in tissues promote oxygen dissociation from hemoglobin.
  These factors collectively enhance oxygen delivery to metabolizing tissues.
- **Shift to the Left:** Conversely, a leftward shift in the curve indicates enhanced oxygen binding to hemoglobin, predominantly occurring in the alveoli. Conditions leading to this shift include:
  High partial pressure of oxygen: In the oxygen-rich environment of the alveoli, hemoglobin readily binds to oxygen molecules.
  Low partial pressure of CO_2: Reduced levels of carbon dioxide favor oxygen binding to hemoglobin.
  Lower H+ ion concentration and higher pH: Alkaline conditions favor oxygen association with hemoglobin.
  Lower temperature: Cooler temperatures, such as those found in the alveoli, promote oxygen binding to hemoglobin.
  These conditions facilitate efficient oxygen uptake in the lungs.

- Furthermore, factors such as elevated pCO_2, increased H+ ions (resulting in decreased pH), higher temperatures, and levels of 2,3-diphosphoglycerate (2,3 DPG) shift the HbO_2 dissociation curve to the right, thereby raising the P_{50} value, while their decrease shifts the curve to the left, enhancing hemoglobin's affinity for oxygen.

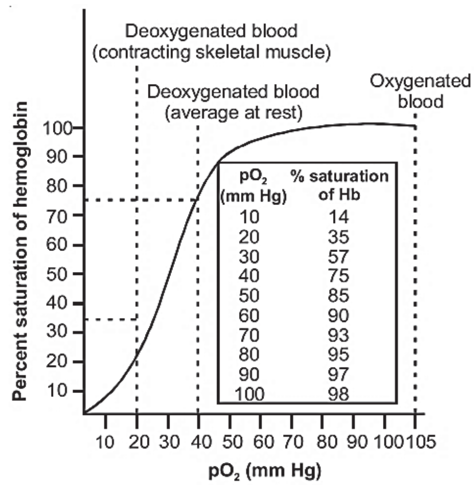


Fig. : Oxygen-hemoglobin dissociation curve at normal body Temperature showing the relationship between hemoglobin saturation and pO_2

- Fetal hemoglobin (Hb-F) exhibits structural differences from adult hemoglobin (Hb-A) and demonstrates a distinct affinity for oxygen (O_2). Hb-F displays a heightened affinity for O_2 due to its weaker binding with 2, 3-bisphosphoglycerate (BPG). Consequently, under conditions of low partial pressure of oxygen (pO_2), Hb-F can bind up to 30% more O_2 compared to maternal Hb-A. As a result of this increased affinity, the oxygen-hemoglobin dissociation curve for fetal hemoglobin appears shifted to the left side.

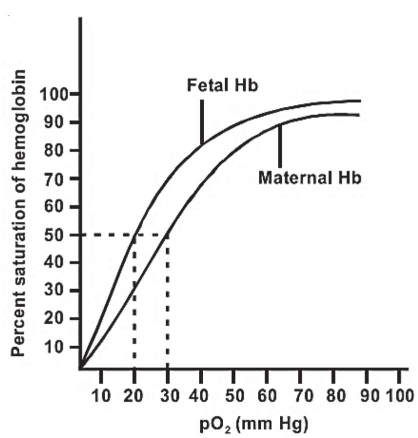


Fig. : Oxygen-hemoglobin dissociation curves comparing fetal and maternal hemoglobin

Transport of Carbon dioxide

When oxygen (O_2) reaches the body cells, the process of food (glucose) oxidation occurs, leading to the production of carbon dioxide (CO_2), water (H_2O), and energy. CO_2, in its gaseous form, diffuses out of the cells into the capillaries, where it undergoes transportation through three distinct mechanisms.

- **In dissolved form through plasma:** Approximately 7% of CO_2 is transported in its dissolved form. It dissolves in the blood plasma and is conveyed in a dissolved state to the lungs. Notably, CO_2 exhibits higher solubility than O_2. Consequently, while only about 3% of O_2 is transported in a dissolved state, nearly 7% of CO_2 is transported in this manner.
- **As bicarbonate ions:** Around 70% of CO_2 undergoes conversion into bicarbonate ions (HCO_3) and is transported in the plasma. CO_2 diffuses into the red blood cells (RBCs), where it combines with water to form carbonic acid (H_2CO_3). Due to its instability, carbonic acid rapidly dissociates into hydrogen and HCO_3 ions. This reaction is facilitated by the presence of an enzyme called carbonic anhydrase, which is highly concentrated in RBCs and present in smaller quantities in plasma.

$$\underset{}{CO_2} + H_2O \underset{Zn^{2+}}{\overset{\text{Carbonic anhydrase}}{\rightleftharpoons}} \underset{\text{Carbonic acid}}{H_2CO_3} \overset{\text{Carbonic anhydrase}}{\rightleftharpoons} \underset{\text{Hydrogen Ion}}{H^+} + \underset{\text{Bicarbonate Ion}}{HCO_3^-}$$

As is well understood, the partial pressure of carbon dioxide (pCO_2) is elevated in tissues due to the metabolic process, which involves the breakdown of glucose into water (H_2O), carbon dioxide (CO_2), and energy. This higher concentration of CO_2 in tissues compared to blood capillaries prompts the diffusion of CO_2 from the tissues into the bloodstream, encompassing both red blood cells (RBCs) and plasma, where bicarbonate ions (HCO_3^-) and hydrogen ions (H^+) are generated. The bicarbonate ions produced within the RBCs rapidly diffuse into the plasma, where they are subsequently transported to the lungs. Sodium predominates as the primary cation in the extracellular fluid.

At the alveolar level, situated within the lungs, the process undergoes a reversal, wherein carbon dioxide (CO_2) and water (H_2O) are regenerated from bicarbonate ions (HCO_3^-) and hydrogen ions (H^+). This reaction progresses as follows:

$$HCO_3^- + H^+ \underset{\text{Anhydrase}}{\overset{\text{Carbonic}}{\rightleftharpoons}} H_2CO_3 \underset{\text{Anhydrase}}{\overset{\text{Carbonic}}{\rightleftharpoons}} H_2O + CO_2$$

Bicarbonate ions re-enter the red blood cells (RBCs) and combine with hydrogen ions (H^+) to produce carbonic acid (H_2CO_3), which subsequently undergoes rapid decomposition into water (H_2O) and carbon dioxide (CO_2). Eventually, CO_2 traverses from the bloodstream to the lungs, where the partial pressure of carbon dioxide (pCO_2) is notably lower.

By RBCs as carbaminohaemoglobin ($HbCO_2$): Approximately 20-25% of carbon dioxide (CO_2) is conveyed through the blood as carbaminohaemoglobin ($HbCO_2$). When CO_2 enters red blood cells (RBCs), it undergoes a reversible binding process, forming $HbCO_2$. Unlike oxygen, which binds with the haem portion of hemoglobin (Hb), CO_2 binds with the amino group of the globin protein, a constituent of Hb. This reaction is akin to the oxygen binding mechanism, but CO_2 interacts with the protein segment rather than the haem component of Hb.

$$\underset{\text{Haemoglobin (RBCs)}}{Hb} + \underset{\text{Carbon dioxide}}{CO_2} \rightleftharpoons \underset{\text{Carbamino-Haemoglobin}}{HbCO_2}$$

Factors influencing the binding of carbon dioxide (CO_2) with hemoglobin (Hb) are as follows:

- **In tissues:** The presence of high partial pressure of CO_2 (pCO_2) and low partial pressure of oxygen (pO_2) in the tissues facilitates the binding of more CO_2 with Hb. This can be represented by the equation:
  $Hb + CO_2 \rightarrow HbCO_2$

- **In alveoli:** Conversely, the low pCO_2 and high pO_2 in the alveoli lead to the dissociation of CO_2 from carbaminohaemoglobin. This dissociation is depicted as:
  $HbCO_2 \rightarrow Hb + CO_2$

  This mechanism ensures that CO_2 bound to Hb in the tissues is transported to the alveoli, where it is expelled during exhalation.
  Under typical physiological conditions, approximately 4 milliliters of CO_2 is transported to the alveoli per 100 milliliters of deoxygenated blood.