# Gas Transfer

## (Diffusion of $O_2$ and $CO_2$)

# Objectives

1-Define partial pressure of a gas, how is influenced by altitude.

2- Understand that the pressure exerted by each gas in a mixture of gases is independent of the pressure exerted by the other gases (Dalton's Law)

3- Understand that gases in a liquid diffuse from higher partial pressure to lower partial pressure (Henry's Law)

4- Describe the factors that determine the concentration of a gas in a liquid.

5- Describe the components of the alveolar-capillary membrane (i.e., what does a molecule of gas pass through).

6- Knew the various factors determining gas transfer: -

Surface area, thickness, partial pressure difference, and diffusion coefficient of gas

7- State the partial pressures of oxygen and carbon dioxide in the atmosphere, alveolar gas, at the end of the pulmonary capillary, in systemic capillaries, and at the beginning of a pulmonary capillary.

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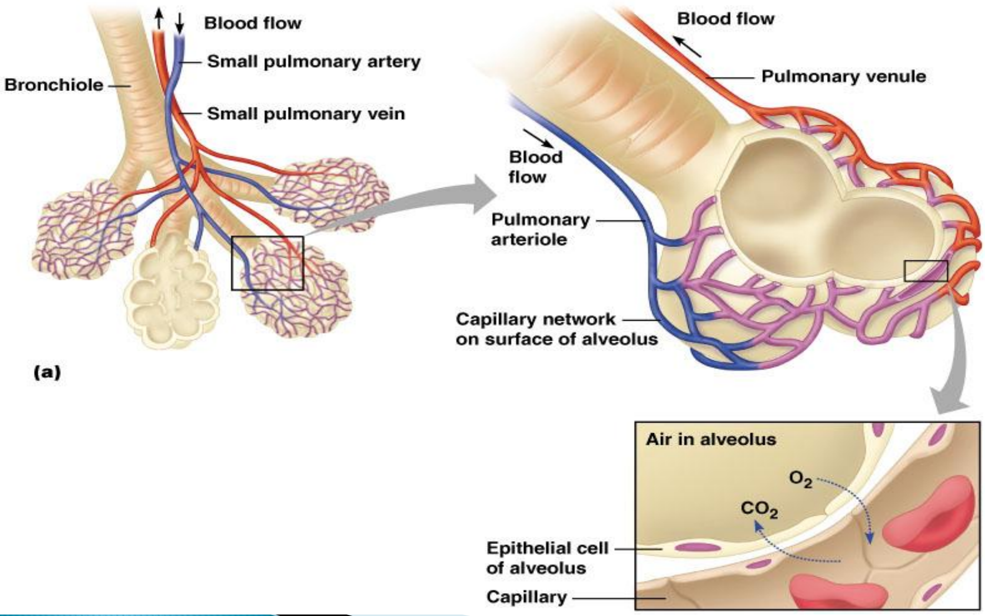
# Gas exchange through the respiratory membrane



- After ventilation of the alveoli with fresh air the next step is the process called Diffusion of oxygen and carbon dioxide.
- The rate of diffusion of each of these gases is directly proportional to the pressure caused by this gas alone which is called the partial pressure of the gas
- Pressure is caused by the constant impact of kinetically moving molecules against a surface.

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## Factors affecting gas diffusion

$$D \;\alpha\; \frac{\Delta P \times A \times S}{d \times \sqrt{MW}}$$

1. P: Partial pressure differences
2. A: Surface area for gas exchange
3. d: Diffusion distance
4. MW: Molecular weight and (S)solubility of gas

$O_2$ has lower molecular weight (31.99) than $CO_2$ (40)
But $CO_2$ is 24 times more soluble than $O_2$
Net result: $CO_2$ diffusion approx. 20 times faster than $O_2$ diffusion

**Quantifying the Net Rate of Diffusion in Fluids.**
In addition to the pressure difference, several other factors affect the rate of gas diffusion in a fluid. They are (1) the solubility of the gas in the fluid, (2) the cross-sectional area of the fluid, (3) the distance through which the gas must diffuse, (4) the molecular weight of the gas, and (5) the temperature of the fluid. In the body, the last of these factors, the temperature, remains reasonably constant and usually need not be considered.
The greater the solubility of the gas, the greater the number of molecules available to diffuse for any given partial pressure difference. The greater the cross-sectional area of the diffusion pathway, the greater the total number of molecules that diffuse. Conversely, the greater the distance the molecules must diffuse, the longer it will take the molecules to diffuse the entire distance. Finally, the greater the velocity of kinetic movement of the molecules, which is inversely proportional to the square root of the molecular weight, the greater the rate of diffusion of the gas. All these factors can be expressed in a single formula, as follows:
in which D is the diffusion rate, ΔP is the partial pressure difference between the two ends of the diffusion pathway, A is the cross-sectional area of the pathway, S is the solubility of the gas, d is the distance of diffusion, and MW is the molecular weight of the gas.
It is obvious from this formula that the characteristics of the gas itself determine two factors of the formula: solubility and molecular weight. Together, these two factors determine the *diffusion coefficient of the gas*, which is proportional to that is, the relative rates at which different gases at the same partial pressure levels will diffuse are proportional to their diffusion coefficients. Assuming that the diffusion coefficient for oxygen is 1,

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## Cont....Factors affecting diffusion across the respiratory membrane

- $S/\sqrt{MW}$ is called *the diffusion coefficient* of the gas.

For Oxygen = 1.0 carbon dioxide =20.0 nitrogen =0.53.

The relative rates at which different gases at the same pressure level will diffuse are proportional to their diffusion coefficient.

**Factors That Determine the Partial Pressure of a Gas Dissolved in a Fluid.**

The partial pressure of a gas in a solution is determined not only by its concentration but also by the *solubility coefficient* of the gas. That is, some types of molecules, especially carbon dioxide, are physically or chemically attracted to water molecules, whereas others are repelled. When molecules are attracted, far more of them can be dissolved without building up excess partial pressure within the solution. Conversely, in the case of those that are repelled, high partial pressure will develop with fewer dissolved molecules. These relations are expressed by the following formula, which is *Henry's law:* When partial pressure is expressed in atmospheres (1 atmosphere pressure equals 760 mm Hg) and concentration is expressed in volume of gas dissolved in each volume of water, the solubility coefficients for important respiratory gases at body temperature are the following:

From this table, one can see that carbon dioxide is more than 20 times as soluble as oxygen. Therefore, the partial pressure of carbon dioxide (for a given concentration) is less than one-twentieth that exerted by oxygen.

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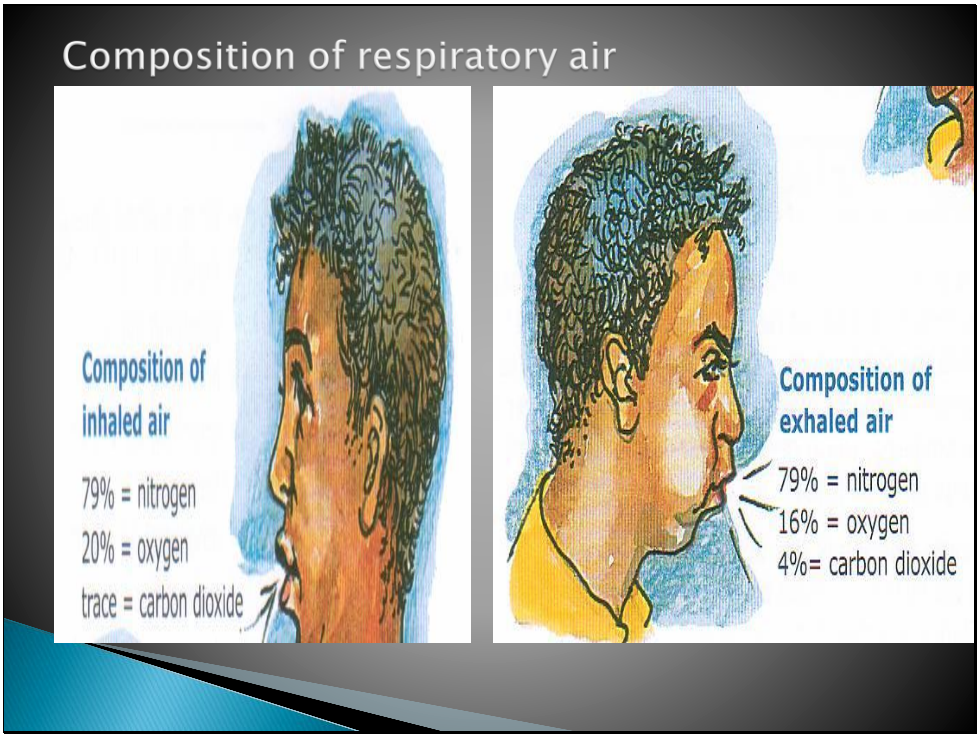


Composition of respiratory air
Composition of inhaled air
79% = nitrogen
20% = oxygen
trace = carbon dioxide
Composition of exhaled air
79% = nitrogen
16% = oxygen
4%= carbon dioxide

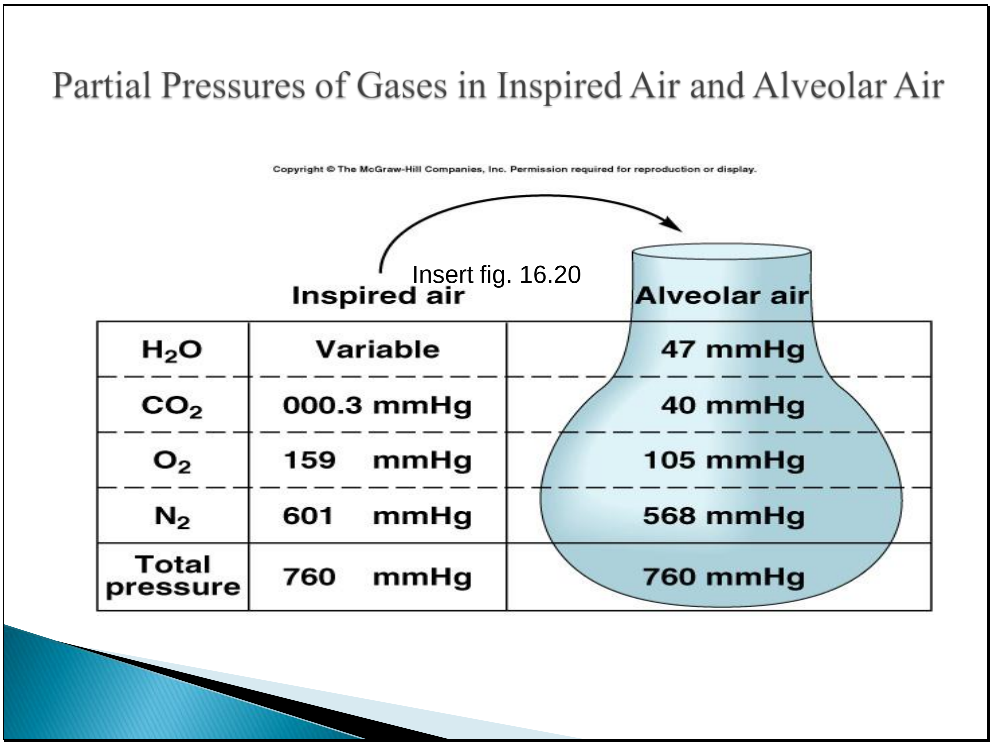
## Partial Pressure of $O_2$ and $CO_2$

- Oxygen concentration in the atmosphere is 21%

  So $PO_2$ in atmosphere = 760 mmHg x 21% = 160 mmHg.
- This mixes with “old” air already present in alveolus to arrive at $PO_2$ of 104 mmHg in alveoli.
- Carbon dioxide concentration in the atmosphere is 0.04%

  So $PCO_2$ in atmosphere =760 mmHg x 0.04% = 0.3 mm Hg
- This mixes with high $CO_2$ levels from residual volume in the alveoli to arrive at $PCO_2$ of 40 mmHg in the alveoli.

•In respiratory physiology, one deals with mixtures of gases, mainly of *oxygen, nitrogen*, and*carbon dioxide*. The rate of diffusion of each of these gases is directly proportional to the pressure caused by that gas alone, which is called the *partial pressure* of that gas. The concept of partial pressure can be explained as follows.




Consider air, which has an approximate composition of 79 percent nitrogen and 21 percent oxygen. The total pressure of this mixture at sea level averages 760 mm Hg. It is clear from the preceding description of the molecular basis of pressure that each gas contributes to the total pressure in direct proportion to its concentration. Therefore, 79 percent of the 760 mm Hg is caused by nitrogen (600 mm Hg) and 21 percent by oxygen (160 mm Hg). Thus, the “partial pressure” of nitrogen in the mixture is 600 mm Hg, and the “partial pressure” of oxygen is 160 mm Hg; the total pressure is 760 mm Hg, the sum of the individual partial pressures. The partial pressures of individual gases in a mixture are designated by the symbols $PO_2$, $PCO_2$, $PN_2$, PHe, and so forth.

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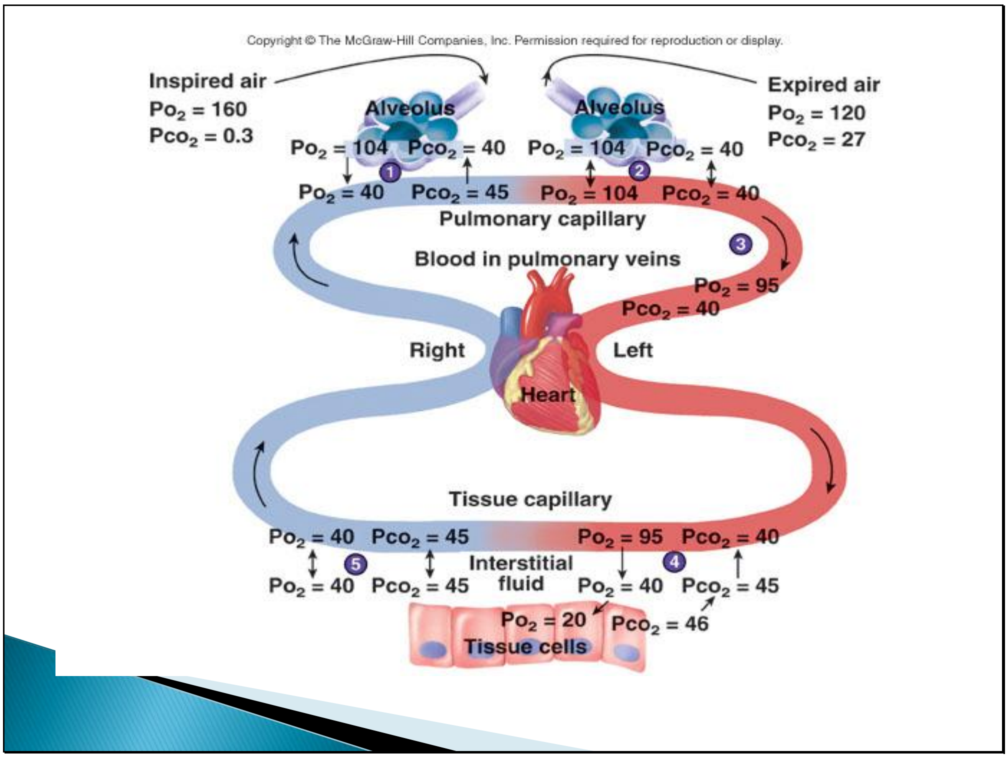

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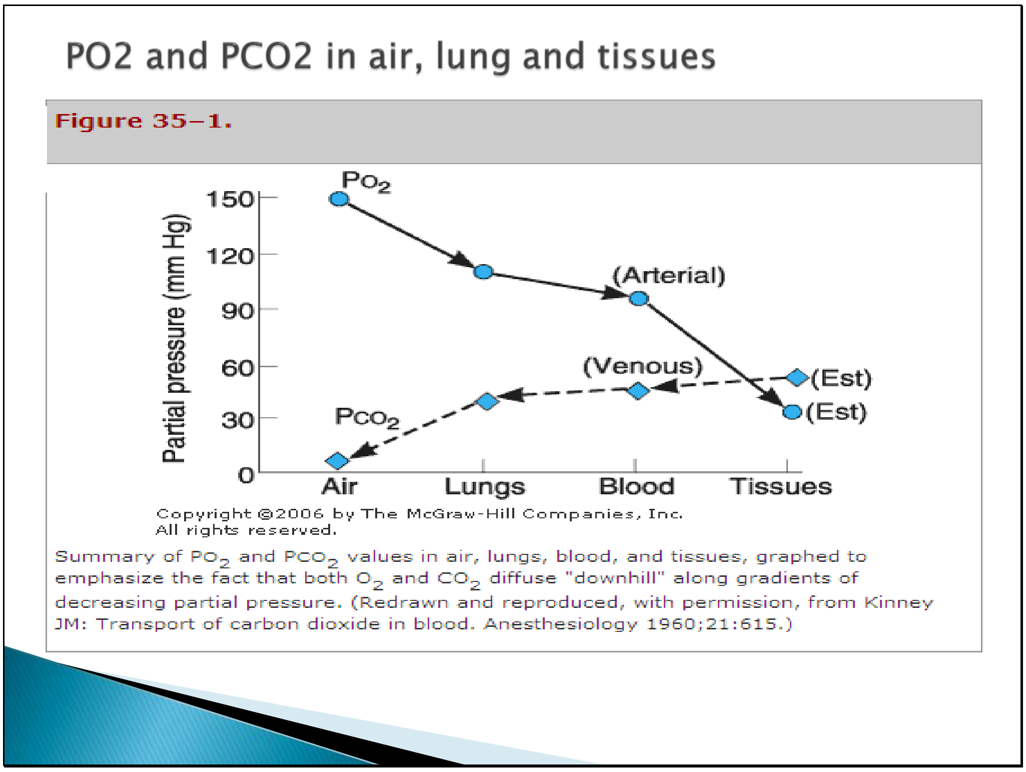
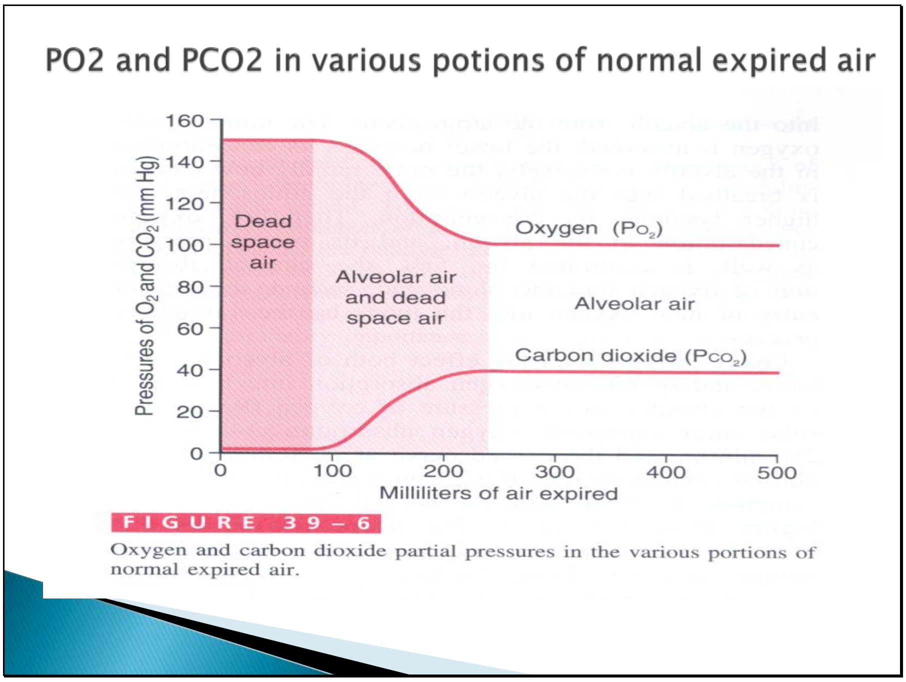
Inspired air
$Po_2$ = 160
$Pco_2$ = 0.3
Alveolus
Alveolus
Expired air
$Po_2$ = 120
$Pco_2$ = 27
$Po_2$ = 104
$Pco_2$ = 40
$Po_2$ = 104
$Pco_2$ = 40
$Po_2$ = 40
$Pco_2$ = 45
$Po_2$ = 104
$Pco_2$ = 40
Pulmonary capillary
Blood in pulmonary veins
$Po_2$ = 95
$Pco_2$ = 40
Right
Left
Heart
Tissue capillary
$Po_2$ = 40
$Pco_2$ = 45
$Po_2$ = 95
$Pco_2$ = 40
Interstitial fluid
$Po_2$ = 40
$Pco_2$ = 45
$Po_2$ = 40
$Pco_2$ = 45
$Po_2$ = 20
$Pco_2$ = 46
Tissue cells




**Diffusion of Gases Through Tissues**

The gases that are of respiratory importance are all highly soluble in lipids and, consequently, are highly soluble in cell membranes. Because of this, the major limitation to the movement of gases in tissues is the rate at which the gases can diffuse through the tissue water instead of through the cell membranes. Therefore, diffusion of gases through the tissues, including through the respiratory membrane, is almost equal to the diffusion of gases in water,




**Expired Air Is a Combination of Dead Space Air and Alveolar Air**
**Figure 39-6** Oxygen and carbon dioxide partial pressures in the various portions of normal expired air.The overall composition of expired air is determined by (1) the amount of the expired air that is dead space air and (2) the amount that is alveolar air. Figure 39-6 shows the progressive changes in oxygen and carbon dioxide partial pressures in the expired air during the course of expiration. The first portion of this air, the dead space air from the respiratory passageways, is typical humidified air, as shown in Table 39-1. Then, progressively more and more alveolar air becomes mixed with the dead space air until all the dead space air has finally been washed out and nothing but alveolar air is expired at the end of expiration. Therefore, the method of collecting alveolar air for study is simply to collect a sample of the last portion of the expired air after forceful expiration has removed all the dead space air. Normal expired air, containing both dead space air and alveolar air, has gas concentrations and partial pressures approximately as shown in Table 39-1 (i.e., concentrations between those of alveolar air and humidified atmospheric air).

## $O_2$ and $CO_2$ concentration in the alveoli

- At resting condition 250 ml of oxygen enter the pulmonary capillaries/min at ventilatory rate of 4.2 L/min.
- During exercise 1000 ml of oxygen is absorbed by the pulmonary capillaries per minute, the rate of alveolar ventilation must increase 4 times to maintain the alveolar $PO_2$ at the normal value of 104 mmHg.
- Normal rate of $CO_2$ excretion is 200 ml/min, at normal rate of alveolar ventilation of 4.2 L/min.

**Oxygen Concentration and Partial Pressure in the Alveoli**

Oxygen is continually being absorbed from the alveoli into the blood of the lungs, and new oxygen is continually being breathed into the alveoli from the atmosphere. The more rapidly oxygen is absorbed, the lower its concentration in the alveoli becomes; conversely, the more rapidly new oxygen is breathed into the alveoli from the atmosphere, the higher its concentration becomes. Therefore, oxygen concentration in the alveoli, as well as its partial pressure, is controlled by (1) the rate of absorption of oxygen into the blood and (2) the rate of entry of new oxygen into the lungs by the ventilatory process.

**Figure 39-4** Effect of alveolar ventilation on the alveolar $PO_2$ at two rates of oxygen absorption from the…Figure 39-4 shows the effect of both alveolar ventilation and rate of oxygen absorption into the blood on the alveolar partial pressure of oxygen ($PO_2$). One curve represents oxygen absorption at a rate of 250 ml/min, and the other curve represents a rate of 1000 ml/min. At a normal ventilatory rate of 4.2 L/min and an oxygen consumption of 250 ml/min, the normal operating point in Figure 39-4 is point A. The figure also shows that when 1000 milliliters of oxygen is being absorbed each minute, as occurs during moderate exercise, the rate of alveolar ventilation must increase fourfold to maintain the alveolar $PO_2$ at the normal value of 104 mm Hg.

Another effect shown in Figure 39-4 is that an extremely marked increase in alveolar ventilation can never increase the alveolar $PO_2$ above 149 mm Hg as long as the person is breathing normal atmospheric air at sea level pressure, because this is the maximum $PO_2$ in humidified air at this pressure. If the person breathes gases that contain partial pressures of oxygen higher than 149 mm Hg, the alveolar $PO_2$ can approach these higher pressures at high rates of ventilation.

**$CO_2$ Concentration and Partial Pressure in the Alveoli**

**Figure 39-5** Effect of alveolar ventilation on the alveolar $PCO_2$ at two rates of carbon dioxide excretion from…Carbon dioxide is continually being formed in the body and then carried in the blood to the alveoli; it is continually being removed from the alveoli by ventilation. Figure 39-5 shows the effects on the alveolar partial pressure of carbon dioxide ($PCO_2$) of both alveolar ventilation and two rates of carbon dioxide excretion, 200 and 800 ml/min. One curve represents a normal rate of carbon dioxide excretion of 200 ml/min. At the normal rate of alveolar ventilation of 4.2 L/min, the operating point for alveolar $PCO_2$ is at point A in Figure 39-5 (i.e., 40 mm Hg).

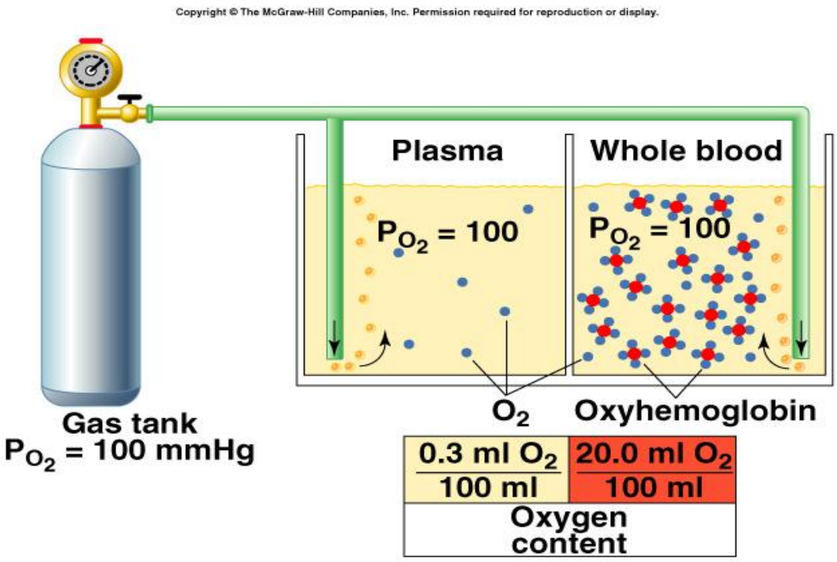
Two other facts are also evident from Figure 39-5 : First,*the alveolar $PCO_2$ increases directly in proportion to the rate of carbon dioxide excretion*, as represented by the fourfold elevation of the curve (when 800 milliliters of $CO_2$ are excreted per minute). Second, *the alveolar $PCO_2$ decreases in inverse proportion to alveolar ventilation*. Therefore, the concentrations and partial pressures of both oxygen and carbon dioxide in the alveoli are determined by the rates of absorption or excretion of the two gases and by the amount of alveolar ventilation.

# Oxygen and Carbon dioxide Transport

# Objectives

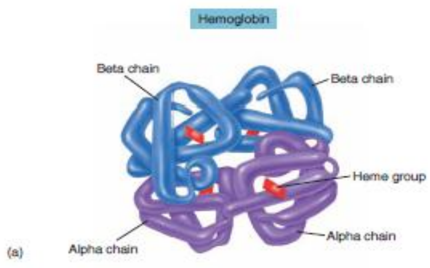
1. Understand the forms of oxygen transport in the blood, the importance of each.
2. Differentiate between O2 capacity, O2 content and O2 saturation.
3. Describe (Oxygen- hemoglobin dissociation curve)
4. Define the P50 and its significance.
5. How DPG, temperature, $H^+$ ions and $PCO_2$ affect affinity of $O_2$ for Hemoglobin and the physiological importance of these effects.
6. Describe the three forms of carbon dioxide that are transported in the blood, and the chloride shift.

# Forms of O2 transport



## Transport of O2 and CO2 in the blood and body fluids

- $O_2$ is mostly transported in the blood bound to hemoglobin
- If the $P_{O2}$ increases Hb binds $O_2$
- If $P_{O2}$ decreases Hb releases $O_2$
- O2 binds to the heme group on hemoglobin, with 4 oxygens /Hb



# Terminology

$O_2$ content: amount of $O_2$ in blood (mL $O_2$/100 mL blood)

$O_2$-binding capacity: maximum amount of $O_2$ bound to hemoglobin (mL $O_2$/100 mL blood) measured at 100% saturation.

Percent saturation: % of heme groups bound to $O_2$

$$\%\ \text{saturation of Hb} = \frac{\text{oxygen content}}{\text{oxygen capacity}} \times 100$$

Dissolved $O_2$: Unbound $O_2$ in blood (mL $O_2$/100 mL blood).

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## Cont…transport of oxygen in arterial blood

- When blood is 100% saturated with O2: each gram of Hb carry 1.34 ml O2 So O2 content = 15g Hb x 1.34 O2=20 ml.
  But when the blood is only 97% saturated with O2:each 100 ml blood contain 19.4 ml O2).
- Amount of oxygen released from the hemoglobin to the tissues is 5ml O2 per each 100ml blood.
  So O2 content in venous blood =19.4-5= 14.4 ml.
- During strenuous exercise the oxygen uptake by the tissue increases 3 folds so 15 ml O2 is given /100 ml blood
  So O2 content in venous blood =19.4-15=4.4 ml O2 /100ml blood.
  At rest tissues consume 250 ml O2 /min and produce 200ml CO2

**Reversible Combination of Oxygen with Hemoglobin**

The chemistry of hemoglobin is presented in Chapter 32, where it was pointed out that the oxygen molecule combines loosely and reversibly with the heme portion of hemoglobin. When $PO_2$ is high, as in the pulmonary capillaries, oxygen binds with the hemoglobin, but when $PO_2$ is low, as in the tissue capillaries, oxygen is released from the hemoglobin. This is the basis for almost all oxygen transport from the lungs to the tissues.

**Maximum Amount of Oxygen That Can Combine with the Hemoglobin of the Blood.**

The blood of a normal person contains about 15 grams of hemoglobin in each 100 milliliters of blood, and each gram of hemoglobin can bind with a maximum of 1.34 milliliters of oxygen (1.39 milliliters when the hemoglobin is chemically pure, but impurities such as methemoglobin reduce this). Therefore, 15 times 1.34 equals 20.1, which means that, on average, the 15 grams of hemoglobin in 100 milliliter of blood can combine with a total of about 20 milliliters of oxygen if the hemoglobin is 100 percent saturated. This is usually expressed as *20 volumes percent*. The oxygen-hemoglobin dissociation curve for the normal person can also be expressed in terms of volume percent of oxygen, as shown by the far right scale inFigure 40-8, instead of percent saturation of hemoglobin.

**Figure 40-9** Effect of blood $PO_2$ on the quantity of oxygen bound with hemoglobin in each 100 milliliters of…Amount of Oxygen Released from the Hemoglobin When Systemic Arterial Blood Flows Through the Tissues.

The total quantity of oxygen *bound with hemoglobin* in normal systemic arterial blood, which is 97 percent saturated, is about 19.4 milliliters per 100 milliliters of blood. This is shown in Figure 40-9. On passing through the tissue capillaries, this amount is reduced, on average, to 14.4 milliliters ($PO_2$ of 40 mm Hg, 75 percent saturated hemoglobin). Thus, *under normal conditions, about 5 milliliters of oxygen are transported from the lungs to the tissues by each 100 milliliters of blood flow*.

Transport of Oxygen During Strenuous Exercise.

During heavy exercise, the muscle cells use oxygen at a rapid rate, which, in extreme cases, can cause the muscle interstitial fluid $PO_2$ to fall from the normal 40 mm Hg to as low as 15 mm Hg. At this low pressure, only 4.4 milliliters of oxygen remain bound with the hemoglobin in each 100 milliliters of blood, as shown in Figure 40-9. Thus, 19.4 − 4.4, or 15 milliliters, is the quantity of oxygen actually delivered to the tissues by each 100 milliliters of blood flow. Thus, three times as much oxygen as normal is delivered in each volume of blood that passes through the tissues.

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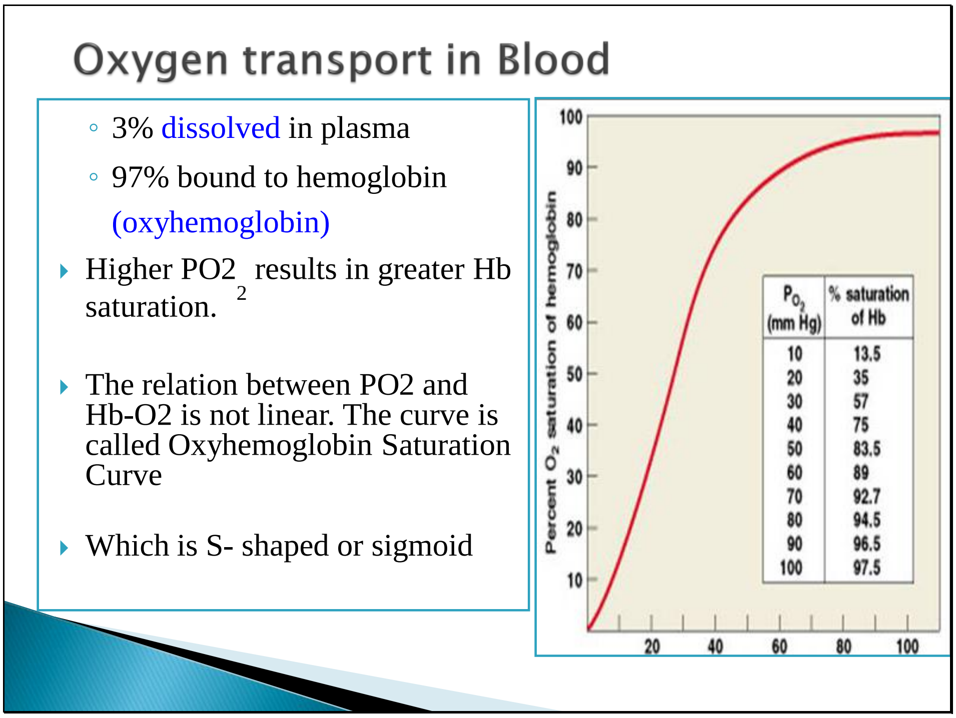


| $P_{O_2}$ (mm Hg) | % saturation of Hb |
|---|---|
| 10 | 13.5 |
| 20 | 35 |
| 30 | 57 |
| 40 | 75 |
| 50 | 83.5 |
| 60 | 89 |
| 70 | 92.7 |
| 80 | 94.5 |
| 90 | 96.5 |
| 100 | 97.5 |

**Role of Hemoglobin in Oxygen Transport**

Normally, about 97 percent of the oxygen transported from the lungs to the tissues is carried in chemical combination with hemoglobin in the red blood cells. The remaining 3 percent is transported in the dissolved state in the water of the plasma and blood cells. Thus, *under normal conditions*, oxygen is carried to the tissues almost entirely by hemoglobin.

**Figure 40-8 Oxygen-hemoglobin dissociation curve.Oxygen-Hemoglobin Dissociation Curve.**

Figure 40-8 shows the oxygen-hemoglobin dissociation curve, which demonstrates a progressive increase in the percentage of hemoglobin bound with oxygen as blood $PO_2$increases, which is called the *percent saturation of hemoglobin*. Because the blood leaving the lungs and entering the systemic arteries usually has a $PO_2$ of about 95 mm Hg, one can see from the dissociation curve that the *usual oxygen saturation of systemic arterial blood averages 97 percent*. Conversely, in normal venous blood returning from the peripheral tissues, the $PO_2$ is about 40 mm Hg, and *the saturation of hemoglobin averages 75 percent*.

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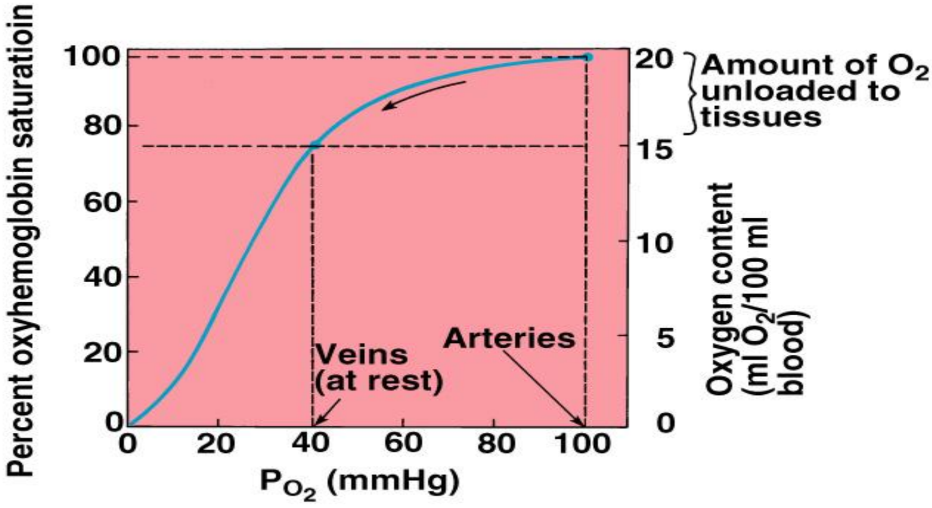
# Oxyhemoglobin Dissociation Curve





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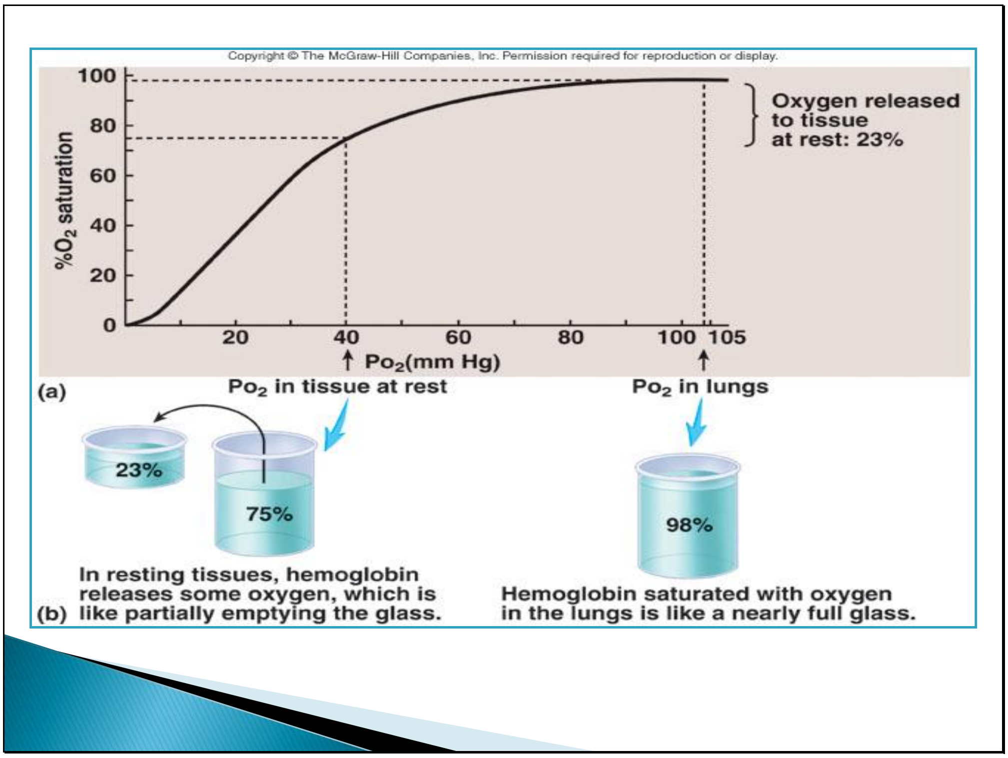

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%O2 saturation
100
80
60
40
20
0
20
40
60
80
100 105
Po2(mm Hg)
Oxygen released to tissue at rest: 23%
(a)
Po2 in tissue at rest
Po2 in lungs
23%
75%
98%
In resting tissues, hemoglobin releases some oxygen, which is like partially emptying the glass.
(b)
Hemoglobin saturated with oxygen in the lungs is like a nearly full glass.

## Factors that shift the O2- Hb dissociation curve

- The position of the dissociation curve can be determined by measuring the P50
- **P50:** The arterial PO2 at which 50% of the Hb is saturated with O2, normally P50= 26.5
- **Decreased P50** means increased affinity of Hb to O2 or shift of the curve to left
- **Increased P50** means decreased affinity or shift of the curve to right