Pulmonary Gas Diffusion

Physical principles of gas exchange

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Lecture Objectives:

1. Review Dalton's law & Henry's law and understand their application to partial pressure of gasses in airways and blood.
2. Identify the values of PO_2 and PCO_2 in inspired air, alveolar air, and expired air. And identify the PO_2 and PCO_2 of arterial and venous blood.
3. Discuss and describe the diffusion of O_2 and CO_2 through the alveolar capillary membrane and list the factors affecting the rate of gas diffusion (Fick's law of diffusion).
4. Distinguish between perfusion limitation and diffusion limitation of gas transfer in the lung.
5. Define oxygen diffusing capacity and describe the rationale and technique for the use of carbon monoxide to determine diffusing capacity.
6. List main causes leading to decreased diffusion capacity of the lung.

Physics of Gas Diffusion and Gas Partial Pressures:

1. The Simple diffusion of a gas occurs from the high-concentration area toward the low-concentration area (i.e. it follows the concentration gradient). In a mixture of gases the rate of diffusion of each gas in the mixture is directly proportional to the **partial pressure** of that gas.
2. The partial pressures of individual gases in a mixture are designated by the symbols PO_2, PCO_2, PN_2, PHe, and so forth. The same symbols are used to describe the partial pressure of dissolved gases.

Physics of Gas Diffusion and Gas Partial Pressures (cont.):

3. The number of dissolved molecules of a gas depends on the **solubility coefficient** of that gas. A gas with high water solubility, like CO_2, large number of molecules can be dissolved without building up excess partial pressure within the solution. Conversely, in the case of molecules with low solubility, like O_2, high partial pressure will develop with fewer dissolved molecules (**Henry's law**).

$$Partial\ pressure = \frac{Concentration\ of\ dissolved\ gas}{Solubility\ coefficient}$$

The concentration is expressed in volume of gas dissolved in each volume of water.

The solubility coefficients for important respiratory gases at body temperature	
Oxygen	0.024
Carbon dioxide	0.57
Carbon monoxide	0.018
Nitrogen	0.012
Helium	0.008

Note: CO_2 is more than 20 times as soluble as O_2

Physics of Gas Diffusion and Gas Partial Pressures (cont.):

4. In the alveolus, the direction of diffusion of a gas is determined by the difference of the partial pressures of that gas across the alveolar membrane. For the O_2, it diffuses and dissolves into the blood as its partial pressure is greater in the alveolar air. Alternatively, the net diffusion of CO_2 occurs toward the alveolar air as its partial pressure is greater in the dissolved state in the blood.
5. At normal body temperature, 37°C, the partial pressure of water vapor in the alveolar gas mixture is 47 mmHg. It is designated as PH_2O.

Physical factors affecting the rate of gas diffusion (Fick's law)

1. The partial pressure difference (direct relationship)
2. The solubility of the gas in the fluid (direct relationship). The greater the solubility of the gas, the greater the number of molecules available to diffuse for any given partial pressure difference.
3. The cross-sectional area of the fluid or surface area of the respiratory membrane (direct relationship). The greater the cross-sectional or surface area of the diffusion pathway, the greater the total number of molecules that diffuse decreases. Emphysema and removal of an entire lung decreases the total surface area of the respiratory membrane.
4. The distance through which the gas must diffuse (inverse relationship). The greater the distance the molecules must diffuse, the longer it will take the molecules to diffuse the entire distance. Some pulmonary diseases cause fibrosis of the lungs and can increase the thickness of some portions of the respiratory membrane (↑distance) → impair gaseous exchange.

Physical factors affecting the rate of gas diffusion (cont.)

5. The molecular weight of the gas (inverse relationship). The kinetic movement of the molecules is inversely proportional to the square root of the molecular weight. The greater the velocity of kinetic movement, the greater the rate of diffusion of the gas.
6. The temperature of the fluid (direct relationship). This factor does not need to be considered since body temperature remains reasonably constant.

$$Diffusion\,rate\,(D) \propto \frac{\Delta P \times A \times S}{d \times \sqrt{MW}}$$

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.

Physical factors affecting the rate of gas diffusion (cont.)

Note:

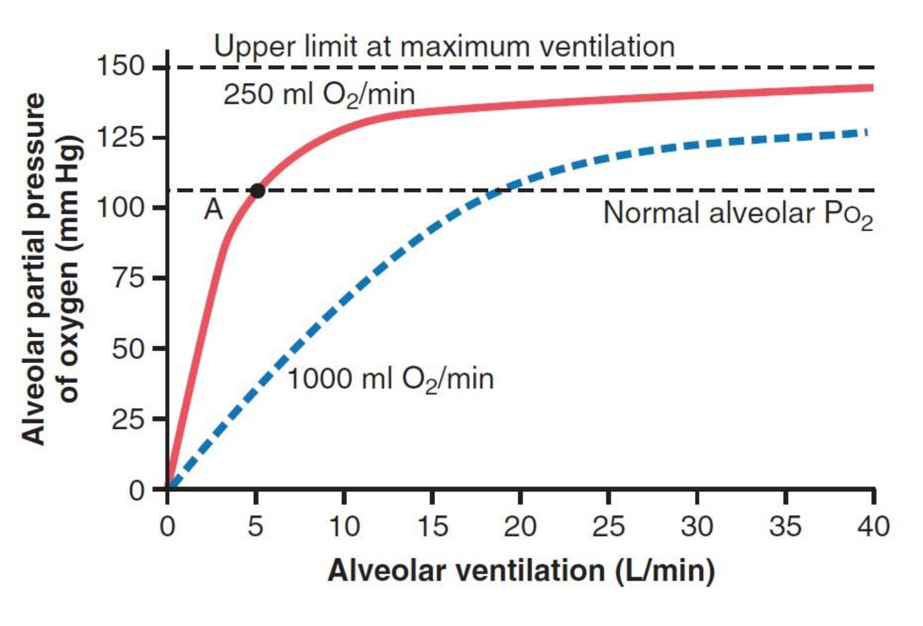
1. The ***diffusion coefficient*** of the gas is determined by ***two*** factors, namely, S/$\sqrt{MW}$. This means that the relative rates at which different gases at the same partial pressure levels will diffuse are proportional to their diffusion coefficients.
2. If the diffusion coefficient for O_2 is assumed as 1, then, the relative diffusion coefficient for CO_2 is 20.3. Therefore, for a given pressure difference, CO_2 diffuses about 20 times as rapidly as O_2.
3. Since both oxygen and carbon dioxide are ***highly lipid soluble***, then the major limitation to the movement of these gases in tissues is the rate at which the gases can diffuse through the tissue water instead of through the cell membranes.

Partial Pressures of Respiratory Gases (in mm Hg) as They Enter and Leave the Lungs (at Sea Level)

	Atmospheric Air	Humidified Air	Alveolar Air	Expired Air
N_2	597 (78.62)	563.4 (74.09)	569 (74.9)	566 (74.5)
O_2	159 (20.84)	149.3 (19.67)	104 (13.6)	120 (15.7)
CO_2	0.3 (0.04)	0.3 (0.04)	40 (5.3)	27 (3.6)
H_2O	3.7 (0.50)	47 (6.20)	47 (6.2)	47 (6.2)
Total	760 (100)	760 (100)	760 (100)	760 (100)

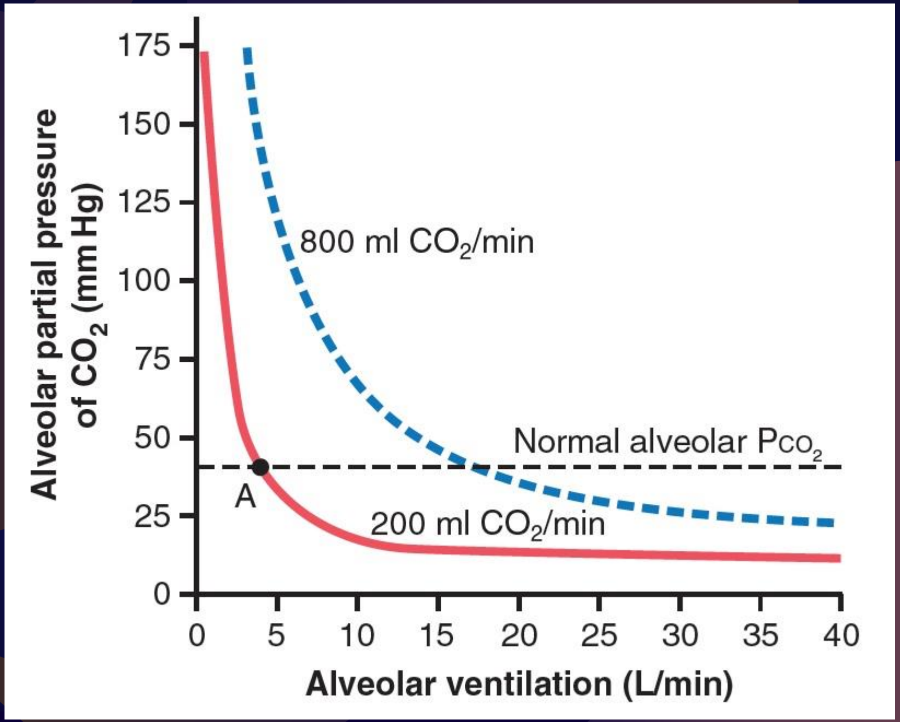
Oxygen concentration and P_{AO_2}

- P_{AO_2} is determined by (1) the rate of absorption of O_2 into the blood and (2) the rate of entry of new O_2 into the lungs by the ventilatory process.
- Red curve → O_2 absorption at a rate of 250 ml/min (rest level)
- Blue curve → O_2 absorption at a rate of 1000 ml/min (exercise)
- Note that the rate of alveolar ventilation increases fourfold to maintain the alveolar PO_2 at the normal value of 104 mmHg.



Carbone dioxide concentration and P_{ACO_2}

- P_{ACO_2} is determined by (1) the rate of excretion of CO_2 into the blood and (2) the rate of removal of CO_2 from the alveoli by ventilation.
- Red curve → normal rate of CO_2 excretion of 200 ml/min (rest level)
- Blue curve → CO_2 excretion rate of 800 ml/min (exercise)
- Note that (1) the alveolar PCO_2 increases directly in proportion to the rate of CO_2 excretion, as represented by the fourfold elevation of the curve, and (2) the alveolar PCO_2 decreases in inverse proportion to alveolar ventilation. The operating point for alveolar PCO_2 is at point A in the figure (i.e., 40 mmHg).



Diffusing Capacity of the Respiratory Membrane

- The diffusion capacity of a gas is the volume of that gas that will diffuse through the membrane each minute for a partial pressure difference of 1 mmHg.
- The time courses for the red blood cell to moves through the pulmonary capillary takes about 0.75 s.
- Under typical resting conditions, the capillary PO_2 virtually reaches that of alveolar gas when the red cell is about <u>one-third of the way</u> along the capillary. Therefore, O_2 transfer (from alveolus to blood) is perfusion limited and not diffusion limited.
- The diffusing capacity for O_2 under resting conditions averages 21 ml/min/mmHg. This capacity increases during exercise.

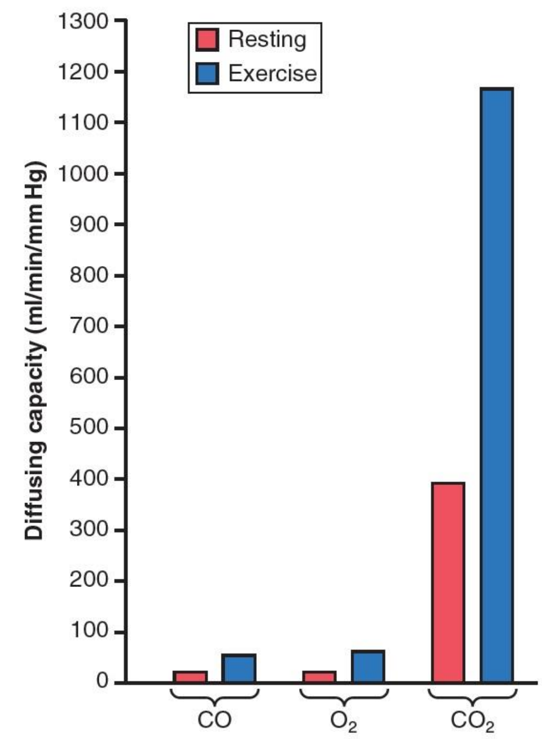


Figure *Diffusing capacities* for carbon monoxide, oxygen, and carbon dioxide in the normal lungs under resting conditions and during exercise.

Diffusing Capacity of the Respiratory Membrane (cont.)

- With severe exercise, the pulmonary blood flow is greatly increased, and the time spent by the red cell in the capillary may be reduced to as little as 0.25 s. However, in normal subjects breathing air, there is still no measurable fall in end-capillary PO_2.
- Since the diffusion coefficient of CO_2 is slightly more than 20 times that of O_2, it can be assumed that a diffusing capacity for CO_2 under resting conditions is about 400 to 450 ml/min/mmHg and during exercise of about 1200 to 1300 ml/min/mmHg.
- Physiologists usually measure carbon monoxide (CO) diffusing capacity instead of O_2 diffusing capacity as it is easier. Oxygen diffusing capacity is obtained by multiplying CO diffusing capacity by a factor of 1.23. The average diffusing capacity for CO in healthy young men at rest is 17 ml/min/mmHg.

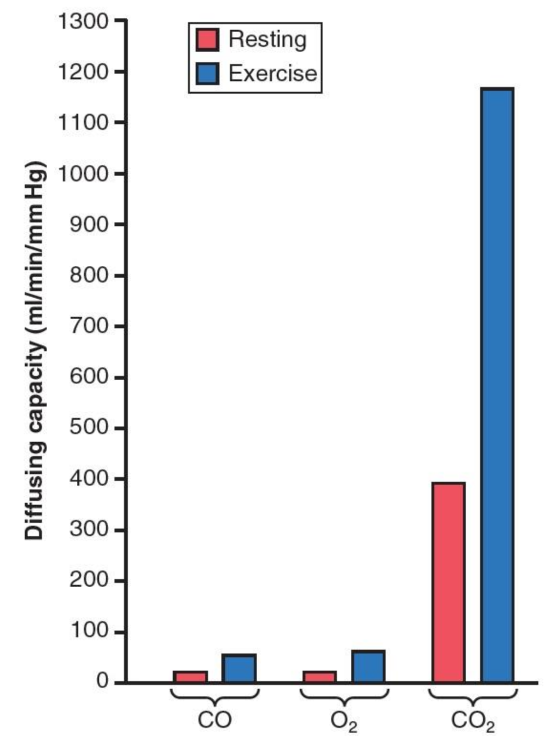


Figure *Diffusing capacities* for carbon monoxide, oxygen, and carbon dioxide in the normal lungs under resting conditions and during exercise.

Test Question:

Q. Concerning the diffusing capacity of the lung:

A. It is best measured with carbon monoxide because this gas diffuses very slowly across the blood-gas barrier.
B. Diffusion limitation of oxygen transfer during exercise is more likely to occur at sea level than at high altitude.
C. Breathing oxygen reduces the measured diffusing capacity for carbon monoxide compared with air breathing.
D. It is decreased by exercise.
E. It is increased in pulmonary fibrosis, which thickens the blood-gas barrier.