AN INTRODUCTION TO GAS EXCHANGE

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OBJECTIVES

1. Distinguish between the following terms: minute, alveolar and dead space ventilation; and anatomic, alveolar and physiologic dead space.

2. Specify the partial pressures of CO_2 and O_2 in the alveoli, mixed venous and arterial blood in normal individuals.

3. Using the alveolar ventilation equation, discuss the factors that determine the partial pressure of carbon dioxide in the alveoli and define the terms hyperventilation and hypoventilation.

4. Be able to calculate the P_{AO_2} using the simplified alveolar-air equation.

5. Using Fick's Law of Diffusion, specify the key factors that affect the exchange of oxygen across the alveolar capillary membrane.

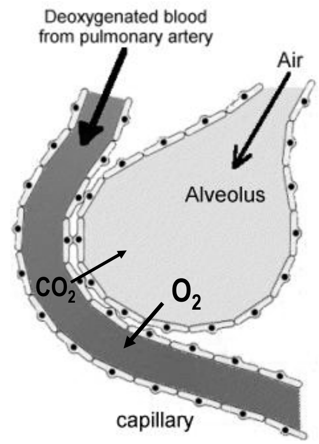
Gas exchange in the lungs takes place in the airways with alveoli– in the respiratory zone

Gas exchange depends on--

1. Alveolar ventilation ($\dot{V}A$)

2. The process of diffusion

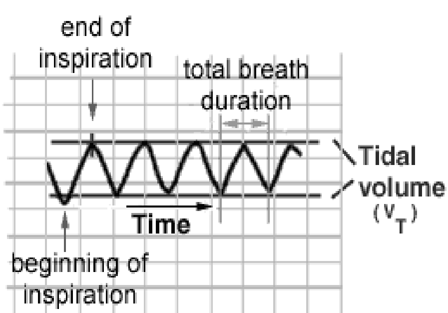
3. Alveolar perfusion ($\dot{Q}$)



BREATHING QUANTIFIED

Minute Ventilation [$\dot{V}_E$]

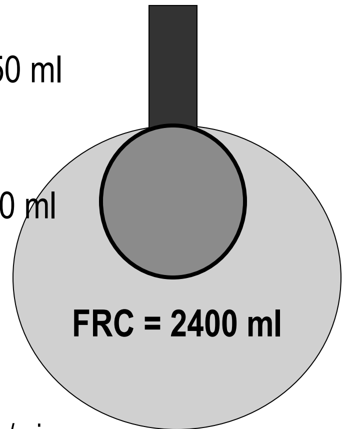
$\dot{V}_E = V_T$ X respiratory rate (RR)



$\dot{V}_E = V_T$ X RR
= 500 ml X12 b/min
= 6000 ml/min
= 6 L/min

Minute Ventilation = Alveolar + Dead Space Ventilation

V_T 500 ml { V_{DS}= 150 ml ; V_A= 350 ml }



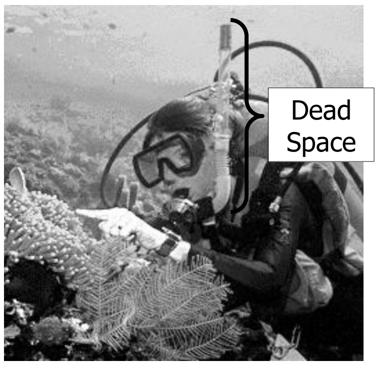
$\dot{V}_E = V_T \times RR$ = 500 ml X12 b/min= 6.0 L/min

$\dot{V}_A = V_A \times RR$ = 350 ml X12 b/min= 4.2 L/min

$\dot{V}_{DS} = V_{DS} \times RR$ = 150 ml X12 b/min=1.8 L/min

Breathing Pattern	Tidal Volume (ml)	Breathing Frequency (breaths/min)	Minute Ventilation (ml/min)	Dead Space Ventilation (ml/min)	Alveolar Ventilation (ml/min)
normal quiet breathing	500	12	6000	150X12=1800	4200
shallow & fast	150	40	6000	150X40=6000	0
deep & slow	1000	6	6000	150X6=900	5100

Consider the added dead space of:



snorkeling tube

volume regulated ventilator

Dead Space Ventilation [$\dot{V}_{DS}$]

Includes ventilation of both--

1. the anatomic dead space: the portion of the breath that enters and leaves the conducting zones of the airways [nose$\rightarrow$ terminal bronchioles]

2. the alveolar dead space: air that reaches the alveoli but does not participate in gas exchange

Anatomic DS + Alveolar DS = Physiologic DS

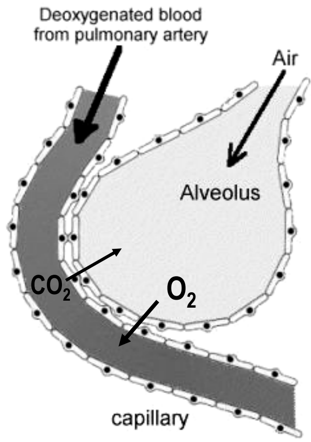
Gas Exchange in the Lungs takes place in the Airways with Alveoli– in the Respiratory Zone

Gas exchange depends on--

1. Alveolar ventilation ($\dot{V}A$)

2. The process of diffusion
[partial pressure gradients]

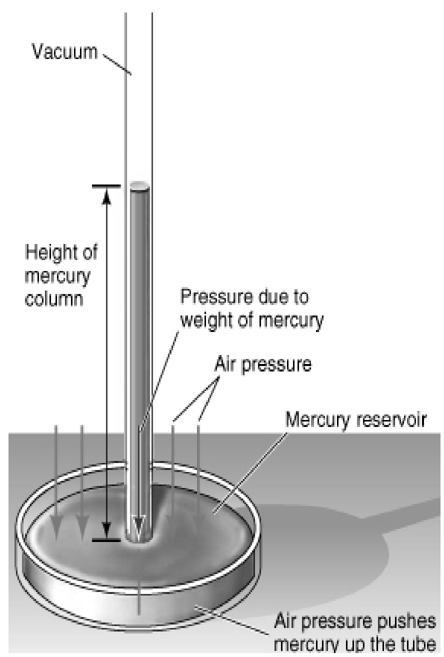
3. Alveolar perfusion ($\dot{Q}$)



AIR: A MIXTURE OF GASES

Barometric pressure [P_B] is the total pressure exerted by this mixture of gases.

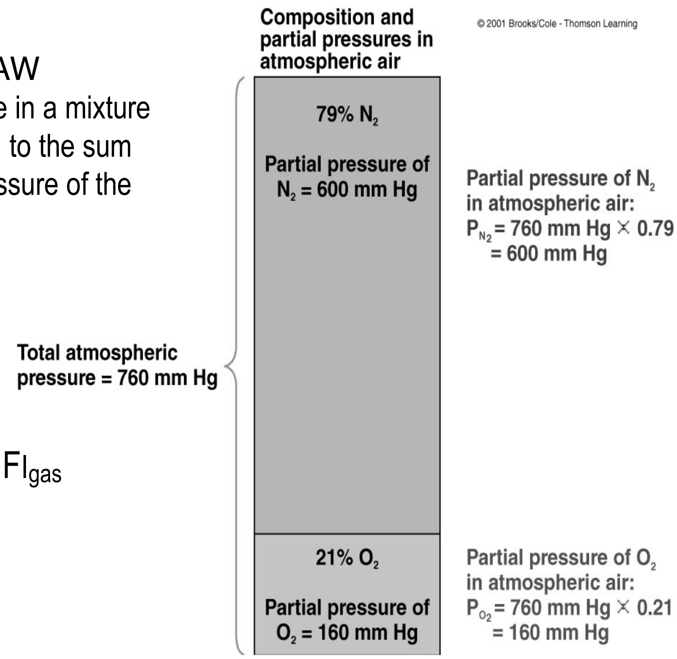
At sea level P_B = 760 mmHg.



DALTON'S LAW

the total pressure in a mixture of gases is equal to the sum of the partial pressure of the individual gases.

$$P_{gas} = P_B \times FI_{gas}$$



What happens to the partial pressure of oxygen with inspiration?

PO_2 = 160 mmHg
PCO_2 = 0
P_{H2O} = 0

dry air at sea level

$$P_{gas} = P_B \times FI_{gas}$$

PO_2 = 150
PCO_2 = 0
P_{H2O} = 47

conducting airways
[heated & humidified]

$$P_{gas} = [P_B - P_{H20}] \times FI_{gas}$$

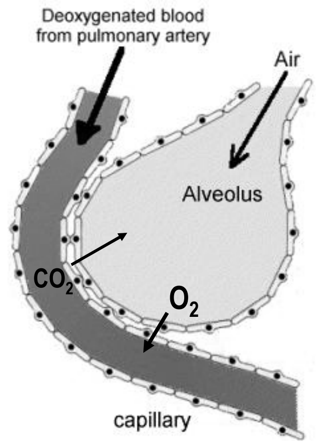
PO_2 = 100
PCO_2 = 40
P_{H2O} = 47

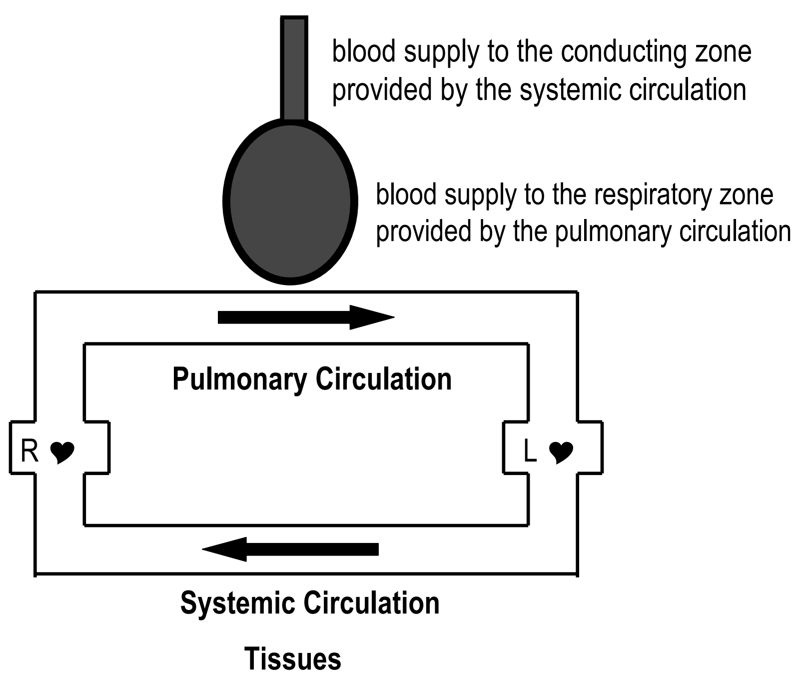
the alveoli
[diluted, mixed in FRC]

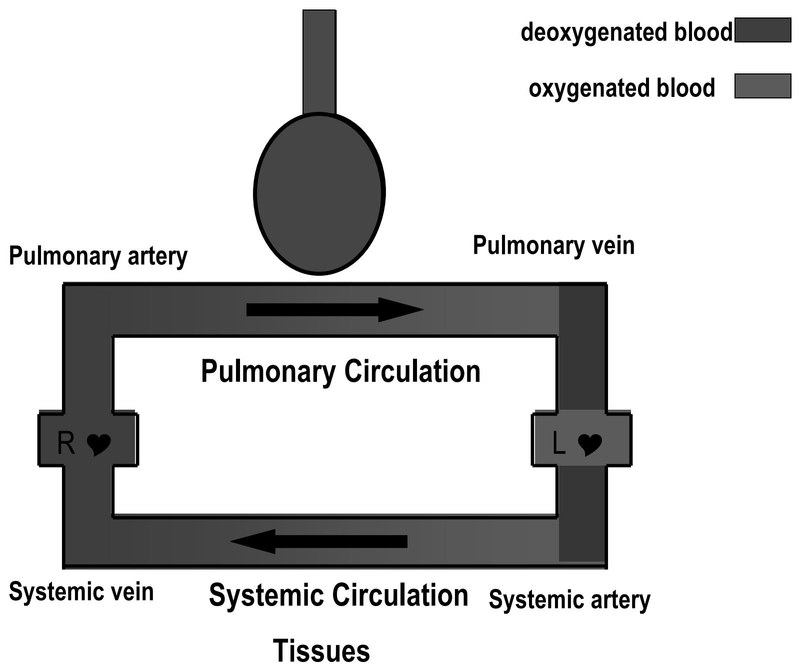
Gas Exchange in the Lungs takes place in the Airways with Alveoli– in the Respiratory Zone

Gas exchange depends on--

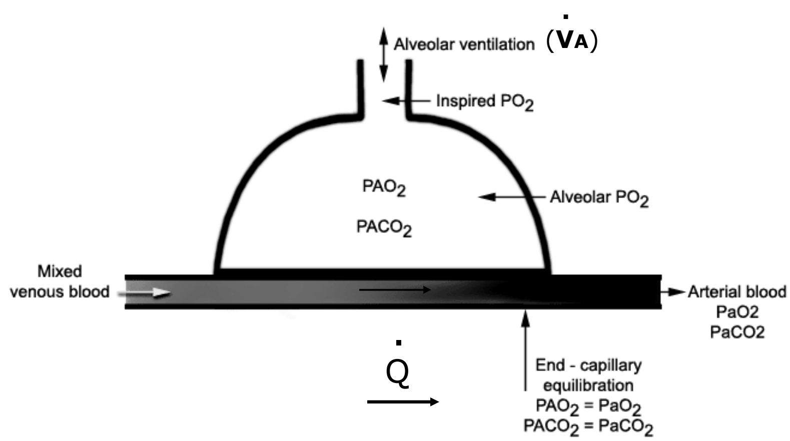
1. Alveolar ventilation ($\dot{V}_A$)
2. The process of diffusion
3. **Alveolar perfusion ($\dot{Q}$)**





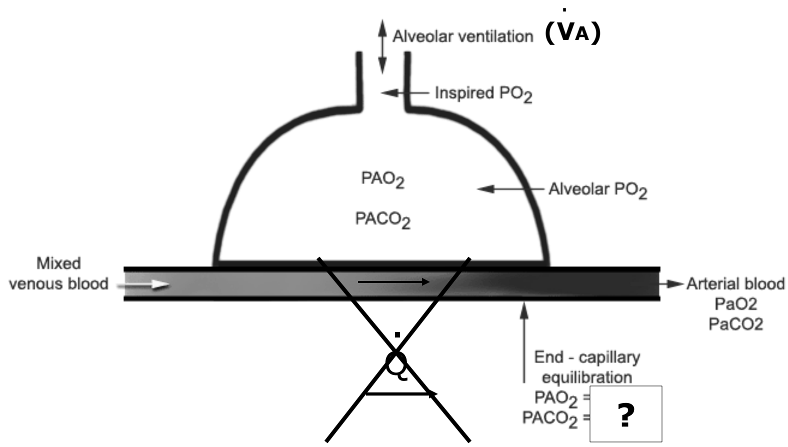


THE SIGNIFICANCE OF THE PARTIAL PRESSURE OF ALVEOLAR GASES

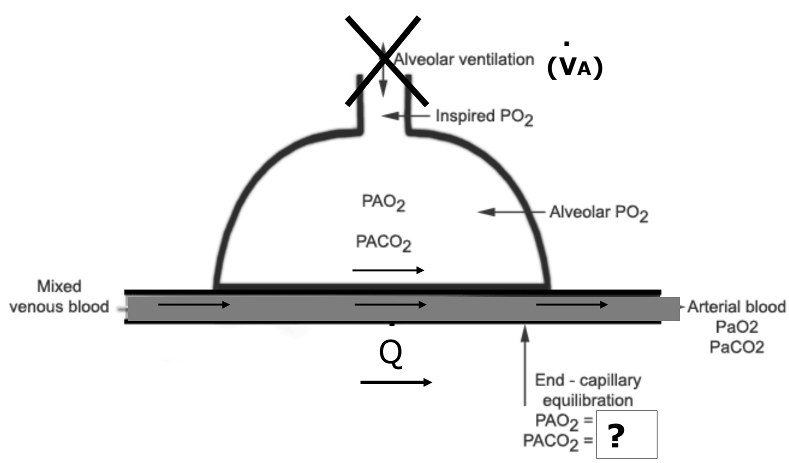


Blood gases– gas in solution exerts pressure (tension) equivalent to the partial pressure of the gas in gas phase in equilibrium with the liquid

THE SIGNIFICANCE OF PULMONARY BLOOD FLOW (PERFUSION) IN THE COMPOSITION OF ALVEOLAR GASES



THE SIGNIFICANCE OF ALVEOLAR VENTILATION IN THE COMPOSITION OF ALVEOLAR GASES



Two key equations in medicine describe the factors that determine the partial pressures of CO_2 & O_2 in alveolar air--

1) P_ACO_2: Alveolar Ventilation Equation

2) P_AO_2: Alveolar Air Equation

ALVEOLAR VENTILATION EQUATION

$$P_ACO_2 \propto \frac{\dot{V}CO_2}{\dot{V}A}$$

$$P_ACO_2 = P_aCO_2$$

In healthy adults the average $Pa\mathbf{CO_2}$ is maintained at 40 mmHg.

Note the correct use of the terms:
hyperventilation *versus* hyperpnea
hypoventilation *versus* hypopnea

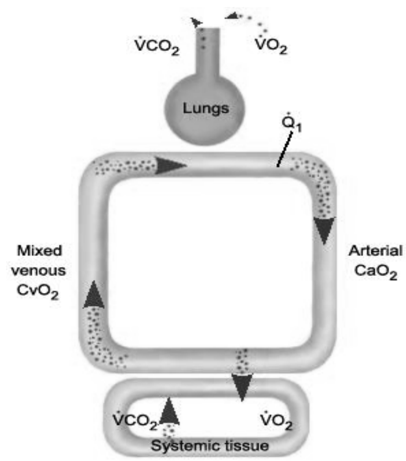
THE RATIO OF CO_2 PRODUCTION TO O_2 CONSUMPTION

At rest:

$\dot{V}CO2$ = 200 ml/min

$\dot{V}O2$ = 250 ml/min

R = $\dot{V}CO2$/ $\dot{V}O2$ = 0.8 values during rest with a mixed diet of carbohydrate & fat



$\dot{V}CO2$/ $\dot{V}O2$ = RER measured at the mouth

$\dot{V}CO2$/ $\dot{V}O2$ = RQ measured at the tissue

R short hand for Respiratory Exchange Ratio [RER] & Respiratory Quotient [RQ]

THE ALVEOLAR AIR EQUATION

$P_AO_2 = P_{in} - P_{out}$

$P_{in} = P_IO_2$

$P_IO_2 = [P_B - P_{H2O}] \times FIO_2$

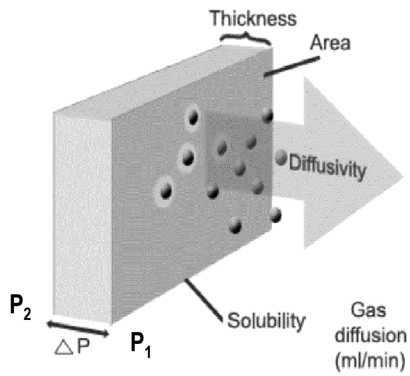
$P_{out} = P_ACO_2 / R$

$$P_AO_2 = [P_B - P_{H2O}] \times FIO_2 - P_ACO_2 / R$$

In Frank's case we can calculate
P_AO_2 = [760 - 47] X 0.21– 48 /0.8 =150 – 48/0.8= 90

We have measured PaO_2 = 60; so we can calculate an A-a gradient for oxygen = 30 mm Hg. What does this signify? Is this healthy?

FICK'S LAW OF DIFFUSION



- Net transfer of a gas molecule down its partial pressure gradient. A passive process that requires a partial pressure gradient
- Transfer across short distances [μm]

$$\dot{V}_{gas}\text{ (ml/min)} \propto \frac{A\,(\Delta P)\,D}{T}$$

$$\Delta P = P_2 - P_1$$

$$D \propto \frac{\text{solubility}}{\sqrt{MW}}$$

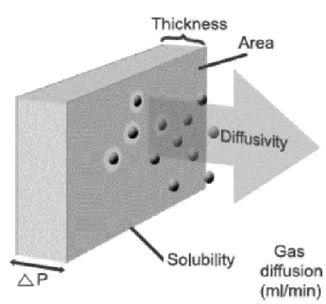
Diffusion of Gases

Surface Area of Barrier Membrane

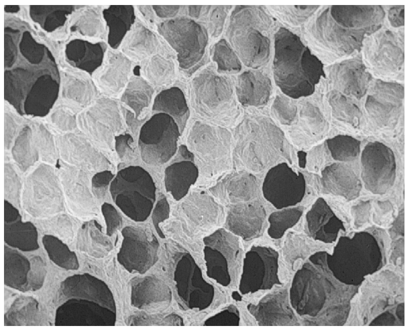
$$\dot{V}_{gas}\text{ (ml/min)} \propto \frac{A\,(\Delta P)\,D}{T}$$

Consider the consequence of changing alveolar capillary membrane surface area [normally 70-100m^2] in:

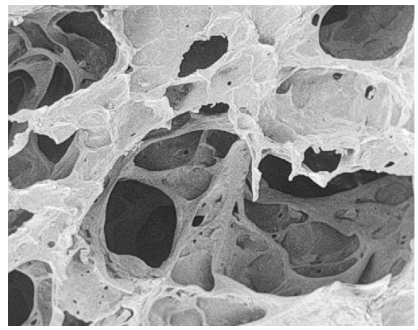
- emphysema



Compare electron micrograph of lungs with different surface areas for gas exchange



normal

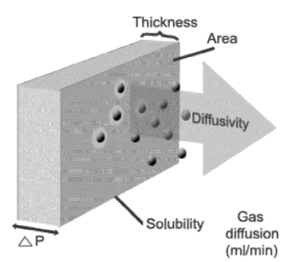


emphysematous

Diffusion of Gases

Thickness of Barrier Membrane

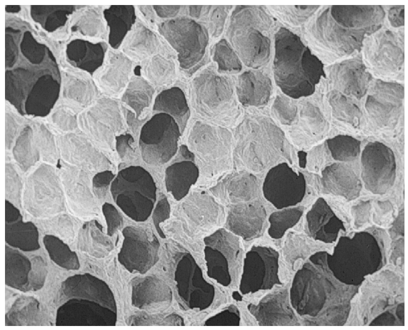
$$\dot{V}_{gas}\,(\text{ml/min}) \propto \frac{A\,(\Delta P)\,D}{T}$$



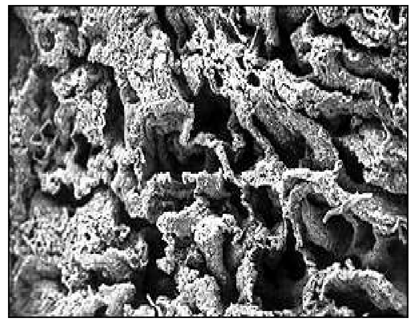
Consider the consequence of an increase in alveolar capillary membrane thickness:

- interstitial or alveolar fibrosis (idiopatic/occupational/allergic/)
- collagen vascular diseases (scleroderma/lupus)
- congestive heart failure (interstitial edema)

Compare electron micrograph of lungs
with different thickness for gas exchange

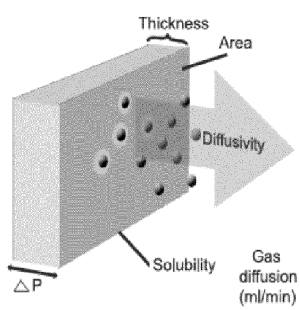


normal lung



fibrotic lung

The Diffusing Capacity of the Lungs or "Transfer Factor"



$$\dot{V}_{gas}\ (ml/min) \propto \frac{A\,(\Delta P)\,D}{T}$$

$$\frac{AD}{T} \propto \frac{\dot{V}_{gas}\ (ml/min)}{\Delta P}$$

$$DL_{gas} \propto \frac{\dot{V}_{gas}\ (ml/min)}{PA_{gas} - Pc_{gas}}$$

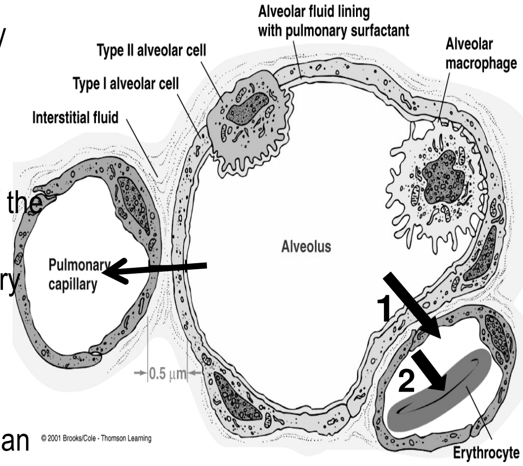
Diffusing Capacity [D_L] of the lung for a given gas is the quantity of gas transferred in unit time per unit pressure difference.

It is typically measured using CO and the measurement is used as an index of adequacy of oxygen transfer across the lungs.

Gases that Combine with Hb, such as O_2, Have two Components Resisting Diffusion

1.The barrier resistance offered by alveolar capillary membrane

2. The resistance offered by the kinetics of the chemical reaction of the gas with the Hb molecule which in turn depends on pulmonary capillary blood volume and the amount of hemoglobin in the blood



Key point: DLCO measure more than the diffusion across the membrane.

The Diffusing Capacity [D_LCO]
an Aid for Clinical Diagnosis

- If we are interested with the adequacy of gas exchange we examine its end products, the partial pressure of arterial blood gases ($PaCO_2$ & PaO_2) by taking an arterial blood gas sample.

  Abnormal $PaCO_2$ values indicate hyper or hypoventilation.

  P_AO_2 can be determined by applying the blood gas values to the alveolar air equation. This in turn allows calculation of $P(A\text{-}a)O_2$ which in turn helps distinguish between different causes of hypoxemia.

- If the diffusing capacity is low we know there is a problem with oxygen transfer but the cause remains unclear and needs additional information.