Gas exchange and gas transfer

Respiratory block

PHYSIOLOGY 438 TEAMWORK

- Red: important
- Black: in male / female slides
- Pink: in female slides only
- Blue: in male slides only
- Yellow: notes
- Gray: extra information
- Textbook: Guyton + Linda

Editing file

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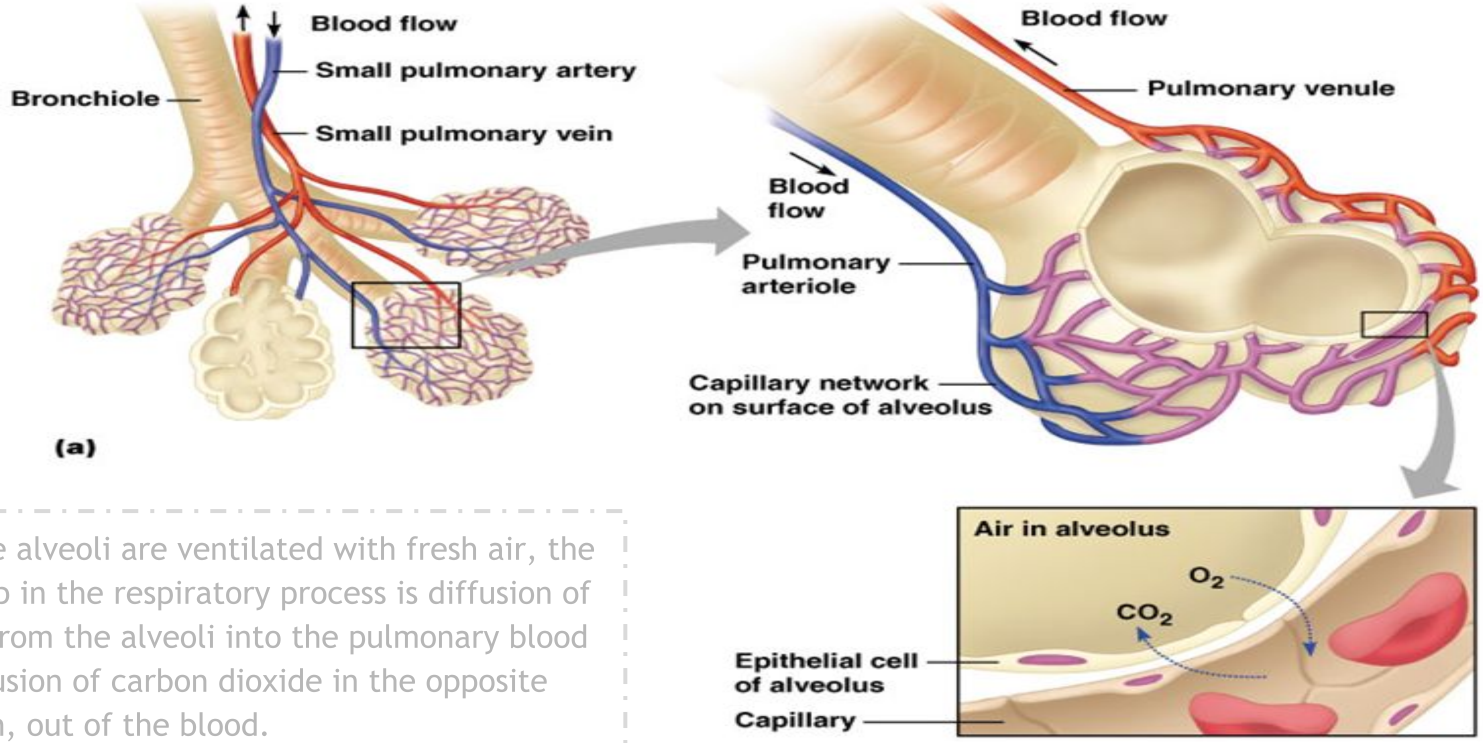
Objectives

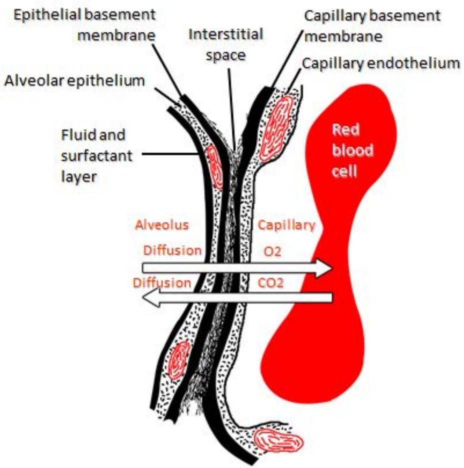
1. Define partial pressure of a gas
2. Understand that the pressure exerted by each gas in a mixture of gases is independent of the pressure exerted by the other gases (Dalton's Law)
3. Understand that gases in a liquid diffuse from higher partial pressure to lower partial pressure (Henry's Law)
4. Describe 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.

Gas exchange through the respiratory membrane



After the alveoli are ventilated with fresh air, the next step in the respiratory process is diffusion of oxygen from the alveoli into the pulmonary blood and diffusion of carbon dioxide in the opposite direction, out of the blood.

Composition of alveolar air and its relation to atmospheric air:



- The dry atmospheric air enters the respiratory passage is humidified before it reaches the alveoli.
- Alveolar air is partially replaced by atmospheric air with each breath.
- O_2 is constantly absorbed from the alveolar air.
- CO_2 constantly diffuses from the pulmonary blood into the alveoli.

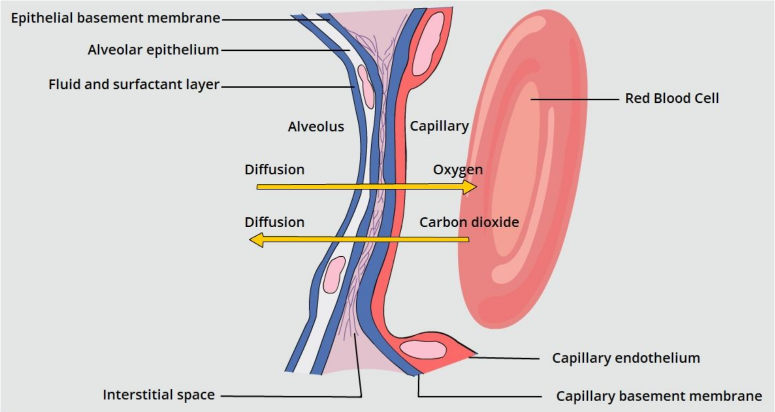
Respiratory Unit and Layers of Respiratory Membrane

- **Respiratory unit** (respiratory lobule):

a unit consisting of a respiratory bronchiole, alveolar ducts, atria, and alveoli.

- The total number of alveoli in the human body is around 300 million, with each having an average diameter of 0.2mm.
- The extremely thin walls of these alveoli form part of the **Respiratory Membrane**, whose thickness inversely affects the rate of gas diffusion.

The following figures show the layers of the respiratory membrane:



Respiratory Membrane Layers

- Fluid-surfactant layer
- Alveolar epithelium
- Epithelial basement membrane
- Interstitial space
- Capillary basement membrane
- Capillary endothelium

Partial pressure of gases (in a mixture)

- In respiratory physiology, there is a mixture of gases mainly of O_2, N_2, and CO_2.
- The pressure of gas is caused by the constant kinetic movement of gas molecules against the surface.

★ Explanation:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Pressure is caused by multiple impacts of moving molecules against a surface. Therefore, the pressure of a gas acting on the surfaces of the respiratory passages and alveoli is proportional to the summated force of impact of all the molecules of that gas striking the surface at any given instant

- The rate of diffusion of each of these gases is directly proportional with the partial pressure of the gas.

★ Explanation:

Ideal gas law

$$PV = nRT \rightarrow P = \frac{nRT}{V}$$

$$c = \frac{n}{V}$$

concentration formula

$$P = CRT$$

so,

pressure ∝ ~~concentration~~

and since

~~concentration~~ ∝ rate of diffusion

pressure ∝ rate of diffusion

P = Pressure (mmHg)
R = Gas constant (no unit)
n = NO. of molecules (mol)
V = Volume (L)
T = temperature (K)

★ **Pressure of gases dissolved in water and tissue:**

The pressure of gases dissolved in fluid is similar to their pressure in the gaseous phase and they exert their own individual partial pressure.

From Guyton

Explanation of Partial pressure of gases (in a mixture)

The concept of partial pressure can be explained as follows:
Consider air, which has an approximate composition of 79% nitrogen and 21% oxygen. The total pressure of this mixture at sea level averages 760 mmHg. 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% of the 760 mmHg is caused by nitrogen (600 mmHg) and 21% by O_2 (160 mm Hg).
- ➔ Thus, the "partial pressure" of nitrogen in the mixture is 600 mmHg, and the "partial pressure" of O_2 is 160 mmHg; 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 PO_2, PCO_2, PN_2, and so forth.

Diffusion of Gases Between the Gas Phase in Alveoli and Blood

The partial pressure of each gas in the alveolar respiratory gas mixture tends to force molecules of that gas into solution in the blood of the alveolar capillaries. Conversely, the molecules of the same gas that are already dissolved in the blood are bouncing randomly in the fluid of the blood, and some of these bouncing molecules escape back into the alveoli. The rate at which they escape is directly proportional to their partial pressure in the blood.

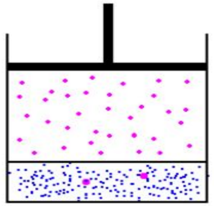
But in which direction will net diffusion of the gas occur?
The answer is that net diffusion is determined by the difference between the two partial pressures. If the partial pressure is greater in the gas phase in the alveoli, as is normally true for oxygen, then more molecules will diffuse into the blood than in the other direction. Alternatively, if the partial pressure of the gas is greater in the dissolved state in the blood, which is normally true for CO_2, then net diffusion will occur toward the gas phase in the alveoli.

laws of gases

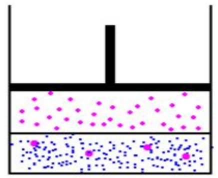
Henry's Law

Gas solubility is proportional to the gas partial pressure. If the temperature stays constant increasing the pressure will increase the amount of dissolved gas.

Gases diffuse from high pressure to low pressure.



Low pressure equilibrium
Low concentration



Double the pressure equilibrium
Double the concentration

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

Dalton's Law

of Partial Pressures

It states that the total pressure exerted by a mixture of gases is the sum of partial pressure of each individual gas present.

$$P_{total} = P_1 + P_2 + P_3 + . . .$$

★

Factors that affect the rate of gas diffusion through the respiratory membrane

Female's slides only

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

- ★ D: diffusion rate
- ★ P: Partial pressure differences
- ★ A: Surface area for gas exchange
- ★ S: Solubility of gas
- ★ d: Diffusion distance
- ★ MW: Molecular weight

- **The diffusion rate of the specific gas:**

Diffusion coefficient for the transfer of each gas through the respiratory membrane depends on:

- ❑ Directly on its solubility (S) through the membrane CO_2 solubility > O_2
- ❑ Inversely on the square root of its molecular weight (MW).
- ❑ The Diffusion Coefficient = $S/\sqrt{MW}$ directly proportional
- ❑ Inversely proportional to The thickness of the respiratory membrane

SO ➔ **CO_2 diffuses 20 times as rapidly as O_2.**

If we have respiratory failure which gas will be affected first? O_2

➔ from Guyton:

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:

Oxygen	0.024
Carbon dioxide	0.57
Carbon monoxide	0.018
Nitrogen	0.012
Helium	0.008

From this table, one can see that CO_2 is more than 20 times as soluble as O_2. Therefore, the partial pressure of CO_2 (for a given concentration) is less than one twentieth that exerted by O_2.

Factors that affect the rate of gas diffusion through the respiratory membrane

ΔP

Partial pressure differences:

The pressure difference between the two sides of the membrane **(between the alveoli and the blood)**.

- ★ When the pressure of the gas in the alveoli is greater than the pressure of the gas in the blood as for O_2
  - ➔ **net diffusion from the alveoli into the blood occurs.**
- ★ When the pressure of the gas in the blood is greater than the pressure in the alveoli as for CO_2
  - ➔ **net diffusion from the blood into the alveoli occurs.**

A

Surface area of the membrane:

range ($50\text{-}100 m^2$) average ($70 m^2$)

- ★ Removal of an **entire lung** decreases the surface area to **half** normal.
- ★ In **emphysema** with dissolution of the alveolar wall decreases S.A. to **5-folds** because of loss of the alveolar walls.

d

The thickness of the respiratory membrane **(Diffusion distance):**

- ★ increasing in the thickness of the respiratory membrane e.g. edema
  - ➔ decreases the rate of diffusion.

Thickness will decrease during exercise, therefore the rate of diffusion increases.

Partial pressures of respiratory gases as they enter and leave the lungs (at sea level)

Female's slides only

	Atmospheric Air* (mm Hg)		Humidified Air (mm Hg) in dead space		Alveolar Air (mm Hg)		Expired Air (mm Hg)	
N_2	597.0	(78.62%)	563.4	(74.09%)	569.0	(74.9%)	566.0	(74.5%)
★ O_2	159.0	(20.84%)	149.3	(19.67%)	104.0	(13.6%)	120.0	(15.7%)
★ CO_2	0.3	(0.04%)	0.3	(0.04%)	40.0	(5.3%)	27.0	(3.6%)
★ H_2O	3.7	(0.50%)	47.0	(6.20%)	47.0	(6.2%)	47.0	(6.2%)

★ Oxygen concentration in the atmosphere is **21%**

- ➔ So **partial O_2 pressure (PO_2) in atmosphere** =760 mmHg (1 ATM) 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 mmHg**
- ➔ This mixes with high CO_2 levels from residual volume in the alveoli to arrive at PCO_2 of **40 mmHg in the alveoli.**

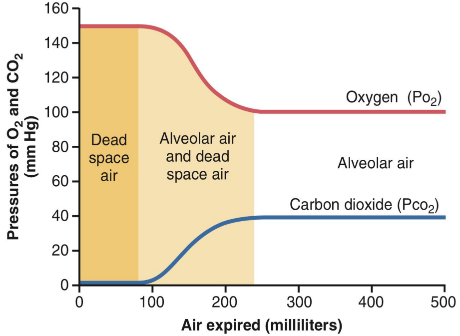


Figure 40-6. Oxygen and carbon dioxide partial pressures (*Po_2* and *Pco_2*) in the various portions of normal expired air.

Male's slides only

We recommend for girls to read this slide

PO_2 and PCO_2 Levels and Diffusion Routes

- Cells use oxygen in metabolic activities all the time, which means that the PO_2 inside cells and its surrounding interstitial fluid would decrease.
- This causes a partial pressure difference with the blood in surrounding tissue capillaries, leading to net diffusion of O_2 into the interstitial fluid.
- This deoxygenated blood circulates back into the heart and into the lungs, where the PO_2 of alveolar air causes O_2 to diffuse into the pulmonary capillaries.

- The same mechanism happens with CO_2 but in the opposite direction, because cells produce CO_2 instead of consuming it like it does with O_2

	PO_2	PCO_2
Alveoli	104 mmHg	40 mmHg
Pulmonary capillaries - Tissue capillaries*	40 mmHg - 95 mmHg	45 mmHg - 40 mmHg
Interstitial fluid	40 mmHg	45 mmHg
Cells	23 mmHg	46 mmHg

(arrows indicate diffusion)

*the change in partial pressure between tissue and pulmonary capillaries is caused by accumulation of gas as the blood circulates the body.

PO_2 and PCO_2 Levels and Diffusion Routes

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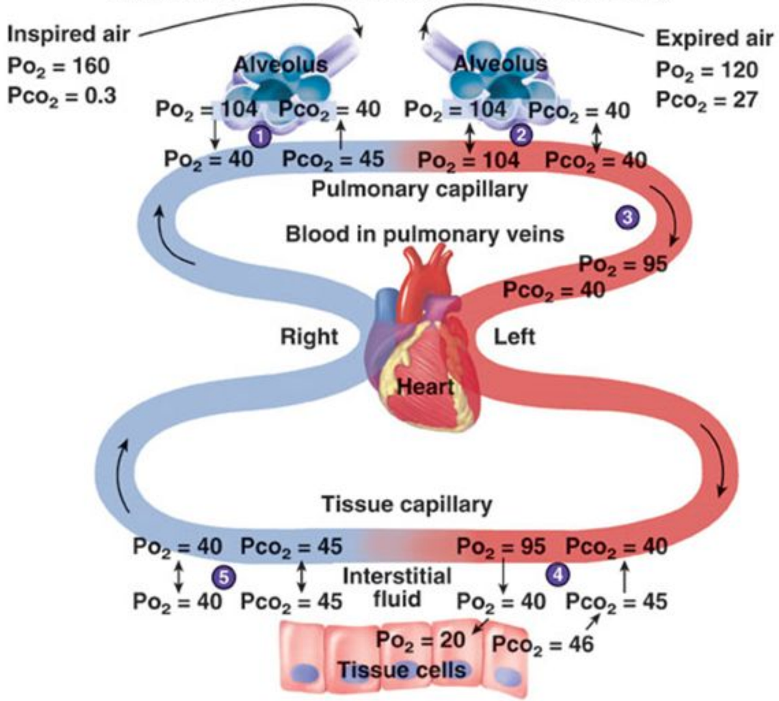
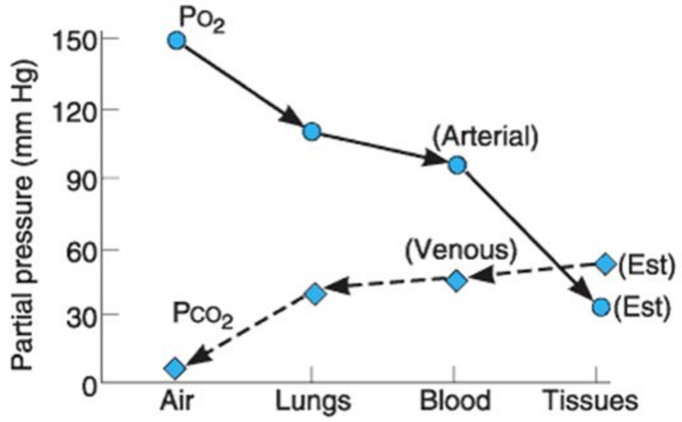


Figure 35–1.



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Summary of PO_2 and PCO_2 values in air, lungs, blood, and tissues, graphed to emphasize the fact that both O_2 and CO_2 diffuse "downhill" along gradients of decreasing partial pressure. (Redrawn and reproduced, with permission, from Kinney JM: Transport of carbon dioxide in blood. Anesthesiology 1960;21:615.)

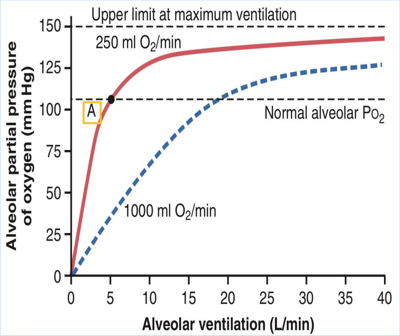
The partial pressure of oxygen in the inspired air starts as 160mmHg and decreases gradually as it pass around the systemic circulation, because most of it will diffuse in the tissues. finally reaching a concentration of 120mmHg in the expired air. (And the opposite for CO_2)
Due to the pressure differences, gases will diffuse from high pressure area to low pressure areas.

Female's slides only

Gas concentrations in the alveoli

Oxygen

	At resting condition	During exercise
ventilatory rate	4.2 L/min.	must increase 4 times "to maintain the alveolar PO_2 at the normal value of 104 mmHg (A)"
volume enter the pulmonary capillaries	250 ml/min	1000 ml/min (x4 normal volume)



Explanation:

This graph shows the ventilation, absorption through the alveoli, and Oxygen alveolar pressure.

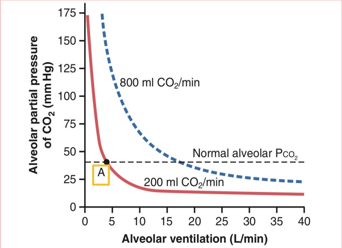
if the absorption increases from 250 to 1000 ml O_2/min , the alveolar pressure would drop. so the body accommodates by increasing the ventilation.

Carbon dioxide

normal rate of excretion from the blood	200ml/min
Normal ventilation	4.2 L/min
normal alveolar PCO_2 operating point (A)	40mmHg.

★ relations

- Alveolar PCO_2 is directly in proportion to the rate of CO_2 excretion
  "increases as represented by the dotted curve for 800ml CO_2 excretion/min."
- Alveolar PCO_2 is inversely proportional to alveolar ventilation



Explanation:

This graph demonstrates excretion, ventilation, and CO_2 pressure in the alveoli.

the more excretion, the higher the CO_2 pressure will be in the alveoli. so the body accommodates by increasing ventilation to get rid of the excess CO_2.

★ recall from the previous lecture:

ventilatory rate: is the total volume of new air entering the alveoli and other adjacent gas exchange areas

Quiz

You don't understand why we choose this answer?
Click here to read the explanations

1- A human experiment is being performed in which forearm blood flow is being measured under a variety of conditions. The forearm is infused with a vasodilator, resulting in an increase in blood flow. Which of the following occurs?

A. Tissue interstitial partial pressure of oxygen (Po_2) will increase
B. Tissue interstitial partial pressure of carbon dioxide (Pco_2) will increase
C. Tissue pH will decrease

2-If alveolar surface area is decreased 50% and pulmonary edema leads to a doubling of diffusion distance, how does diffusion of O_2 compare with normal?

A. 25% increase
B. 25% decrease
C. 50% decrease
D. 75% decrease

3- A person with normal lungs at sea level (760 mmHg) is breathing 50% O_2. What is the approximate alveolar Po_2?

A. 100
B. 159
C. 306
D. 330

4- The forces governing the diffusion of a gas through a biological membrane include the pressure difference across the membrane (ΔP), the cross-sectional area of the membrane (A), the solubility of the gas (S), the distance of diffusion (d), and the molecular weight of the gas (MW). Which changes increase the diffusion of a gas through a biological membrane?

	ΔP	A	S	d	MW
A.	Increase	Increase	Increase	Increase	Increase
B.	Increase	Decrease	Increase	Increase	Increase
C.	Increase	Increase	Increase	Decrease	Decrease
D.	Increase	Decrease	Decrease	Increase	Increase

SAQ

1- what are the Factors that affect the rate of gas diffusion?

2- Why does arterial O_2 pressure decrease to 95?

Answers

1- $D \propto \frac{\Delta P \times A \times S}{d \times \sqrt{MW}}$

2- A small portion of blood (2%) supplies deep lung tissues then joins with arterial blood, thus decreasing the O_2 concentration.

Key answers:
1-A 2-D 3-C 4- C

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