Biology 3UO3 - 2012

Animal Physiology

Physical Principles of Gas Exchange

<u>Readings:</u>

Chapter 39:

pgs. 485-494

Please note this change!

Office hours:

When: **Wednesdays** 10-11am

(students in Wednesday morning lab section can email me to arrange alternative time)

Where: LSB-532

Email: paluzzi@mcmaster.ca

Gas exchange

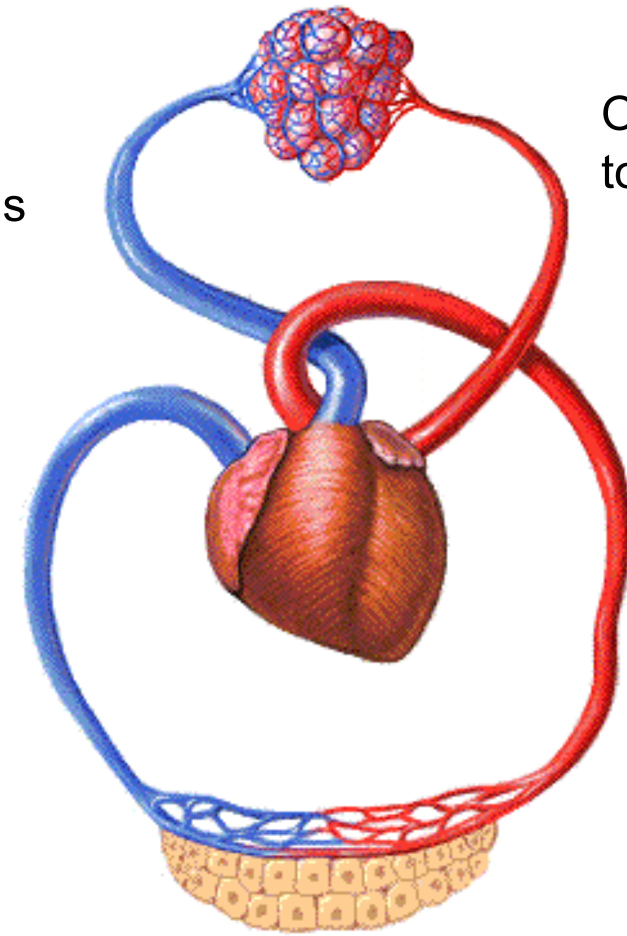
- Refers to the diffusion of O_2 and CO_2 between the alveoli and the pulmonary capillaries in the lungs

- Also O_2 and CO_2 diffusion between the systemic capillaries and cells throughout the body

Goals for today's lecture:

- Overview pulmonary circulation
- Apply gas law relationships – between partial pressure, solubility, and concentration – to gas exchange
- Explore factors that influence external and internal respiration

Gas exchange circuit



What you need to know (ie review)

- Anatomy of the respiratory zone
  - Beyond the terminal bronchioles are the structures of the respiratory zone
  - Alveoli are tiny thin-walled sacs where gas exchange occurs

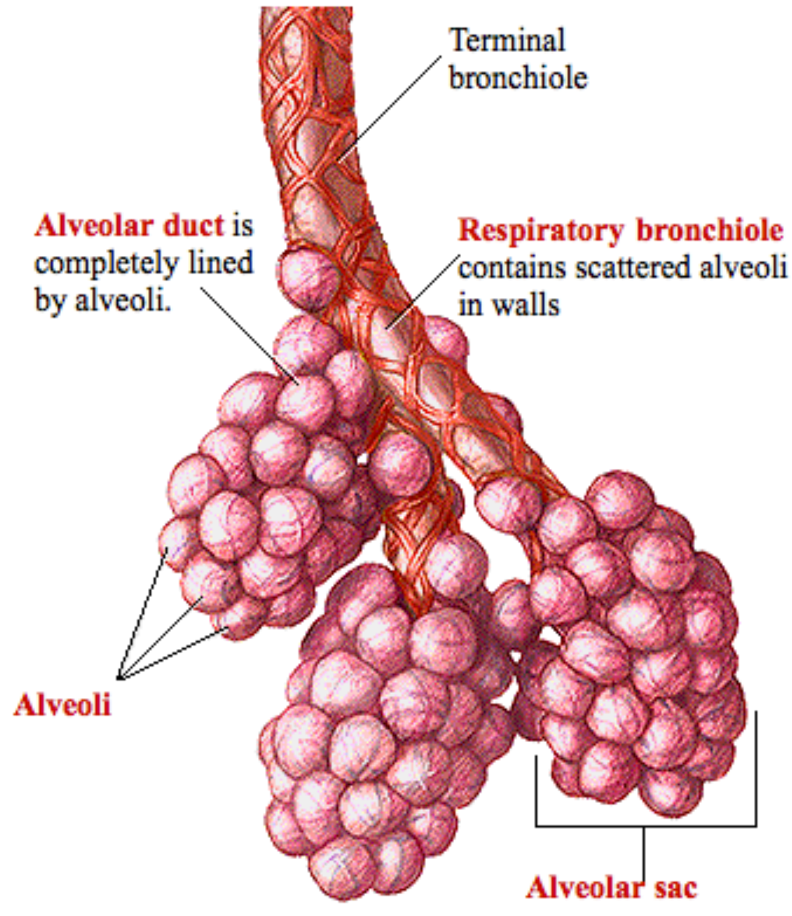


Figure similar to 39-7

What you need to know (ie review)

- Respiratory bronchioles have scattered alveoli and lead into alveolar ducts that are completely lined with alveoli

- Alveolar ducts end in alveolar sacs

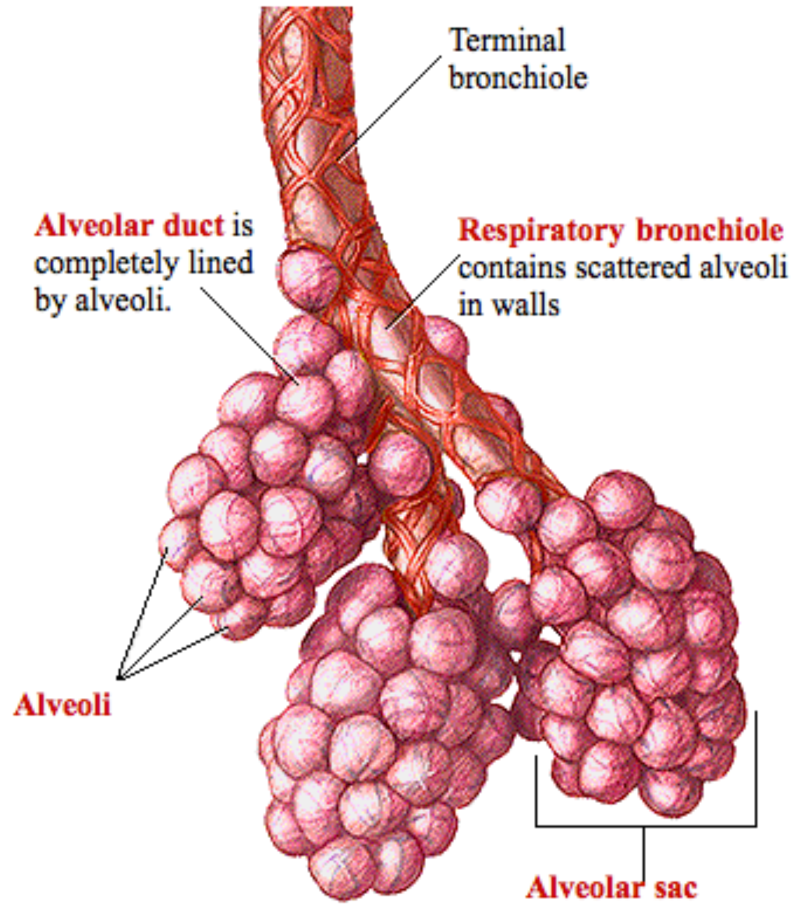
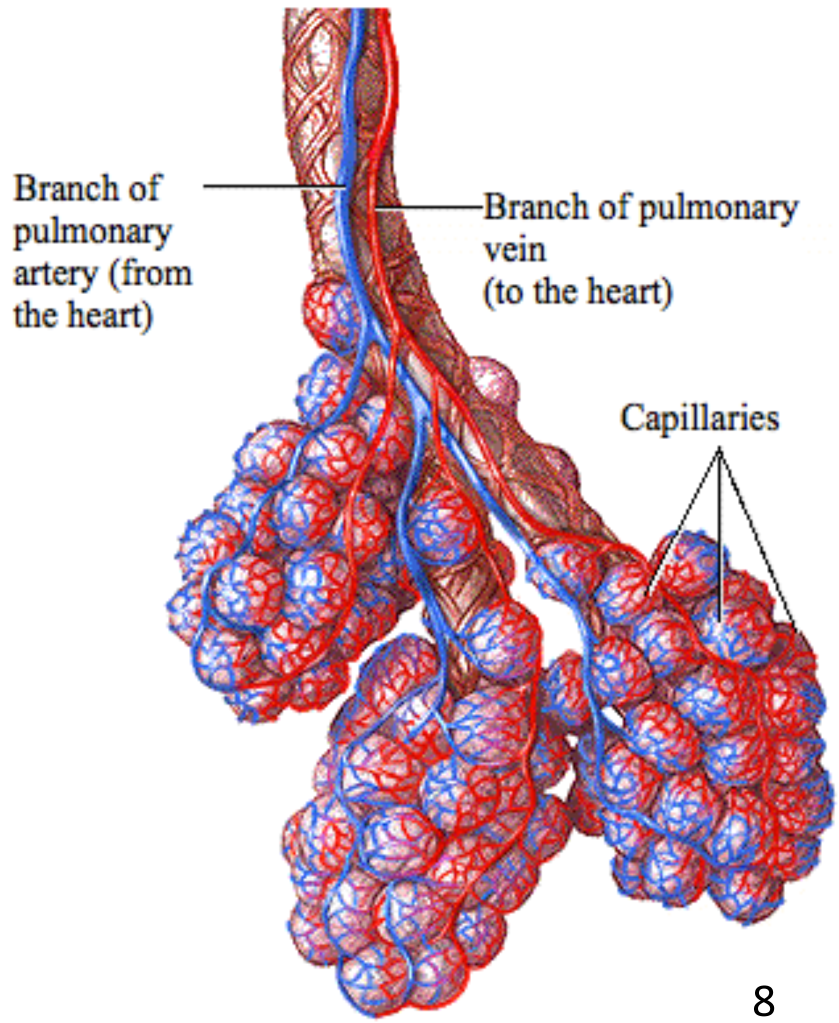


Figure similar to 39-7

Alveoli and pulmonary capillaries

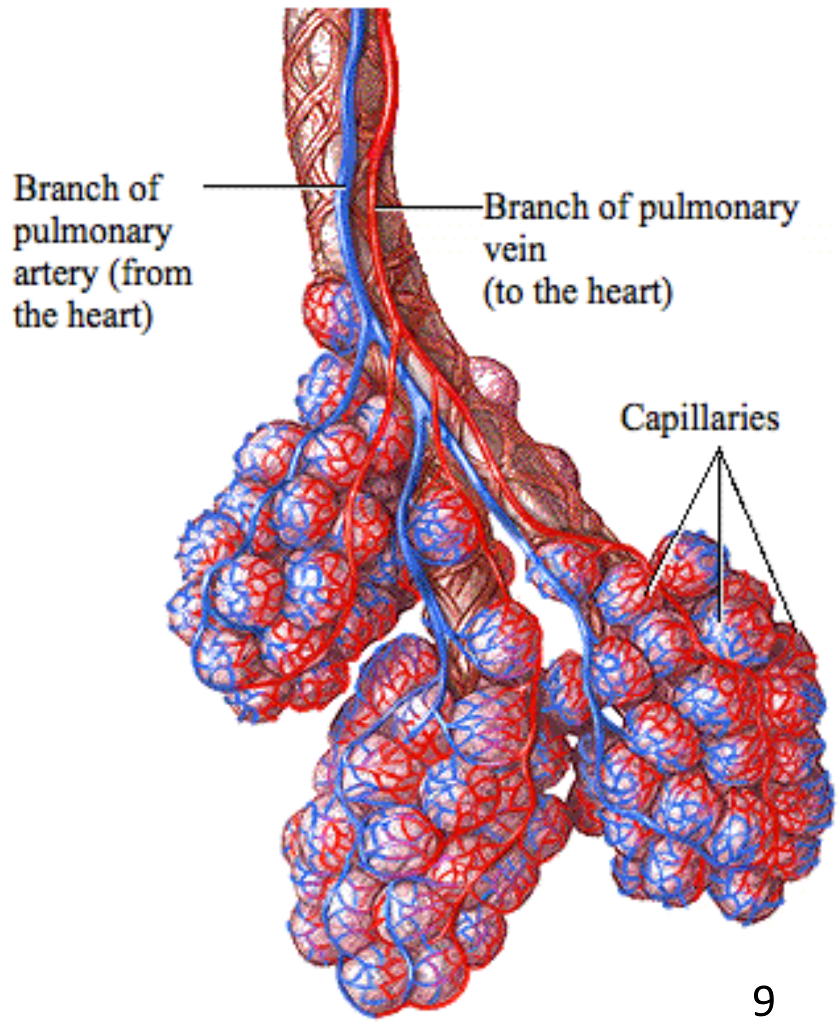
- Pulmonary arteries carry blood low in O_2 for gas exchange at the alveolar capillaries

- *Alveolar capillaries is a dense network surrounding each alveolus*



Alveoli and pulmonary capillaries

- Abundant blood supply allows for efficient exchange of O_2 and CO_2
- Blood leaves the capillaries via the pulmonary veins, which transport oxygenated blood back to the heart



Net diffusion of a gas in one direction

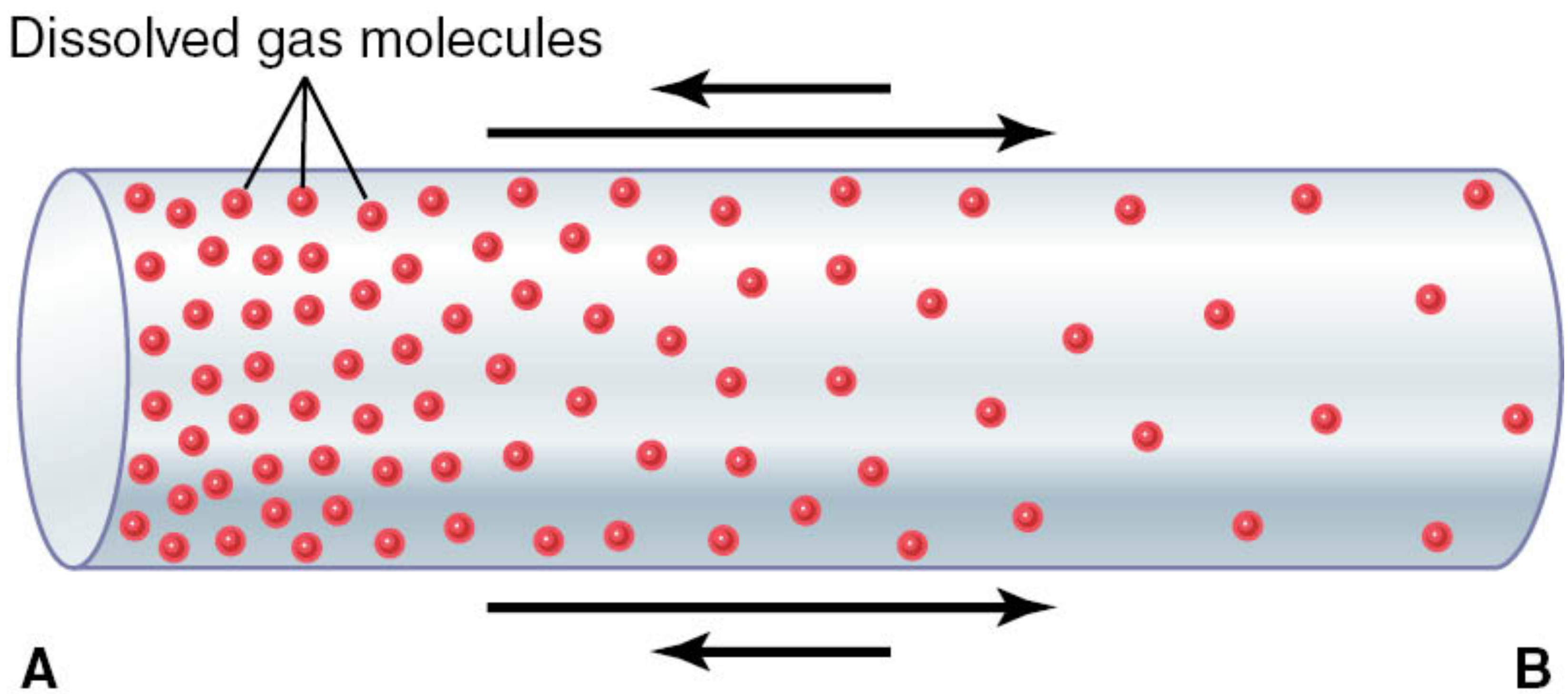


Figure 39-1

Dalton's Law

- In a mixture of gases, total pressure equals the sum of the partial pressures

- To understand gas exchange, we first must study the air we breath

- Atmosphere is a mixture of gases:

O_2 = 20.9%, CO_2 = 0.04%, N_2 = 78.6%, H_2O = 0.46%

Dalton's Law

- The combined partial pressure of these gases equals atmospheric pressure (760 mm Hg)

- Partial pressures for atmospheric gases:
  - O_2 → 20.9% x 760 = 158.8 P_{O2}
  - CO_2 → 0.04% x 760 = 0.3 P_{CO2}
  - N_2 → 78.6% x 760 = 597.4 P_{N2}
  - H_2O → 0.46% x 760 = 3.5 P_{H2O}

Effects of high altitude on partial pressure

- Atmospheric pressure decreases with increasing altitude

- At the summit of Mt. Logan, atmospheric pressure is 356 mm Hg
  - O_2 → 20.9% x 356 = 74 P_{O2}
  - CO_2 → 0.04% x 356 = 0.14 P_{CO2}
  - N_2 → 78.6% x 356 = 279.8 P_{N2}
  - H_2O → 0.46% x 356 = 1.64 P_{H2O}

5959 meters above sea level

Effects of high altitude on partial pressure

- At lower atmospheric pressure, fewer O_2 molecules available

- Hence, gasp for breath at higher altitudes

5959 meters above sea level

Pressures of gases dissolved in water and tissues

- Gases dissolved in water or body tissues exert pressure since molecules are moving randomly
- Some molecules are physically or chemically attracted to water molecules, while others are repelled

Henry's Law

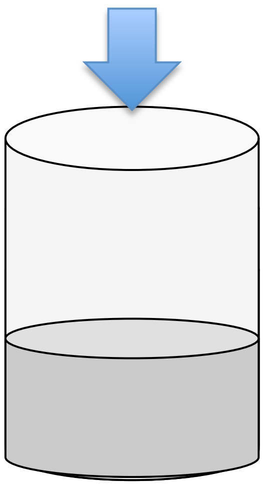
- Within the lungs, O_2 and CO_2 diffuse between the alveolar air and the blood

- This diffusion is governed by Henry's law which states that the amount of gas dissolving in a liquid is proportional to
  - The partial pressure of the gas, and
  - The solubility of the gas

Henry's Law

- Within a container of constant volume with both air and liquid, O_2 is at equilibrium between air and liquid

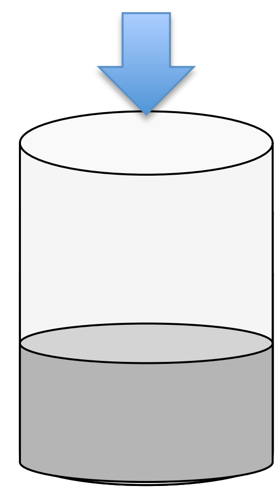
- Increased pressure causes O_2 to move more into the liquid, forming a new equilibrium



Henry's Law

Diffusion of CO_2

- With an equivalent increase in pressure, more CO_2 dissolves in the liquid



- CO_2 is much more soluble in liquid than O_2 (> 20 times)

Sites of gas exchange

- Blood low in O_2 pumped from the right side of the heart via pulmonary arteries to the lungs

- **External respiration:**
  - CO_2 diffuses into alveoli
  - O_2 diffuses into the pulmonary capillaries

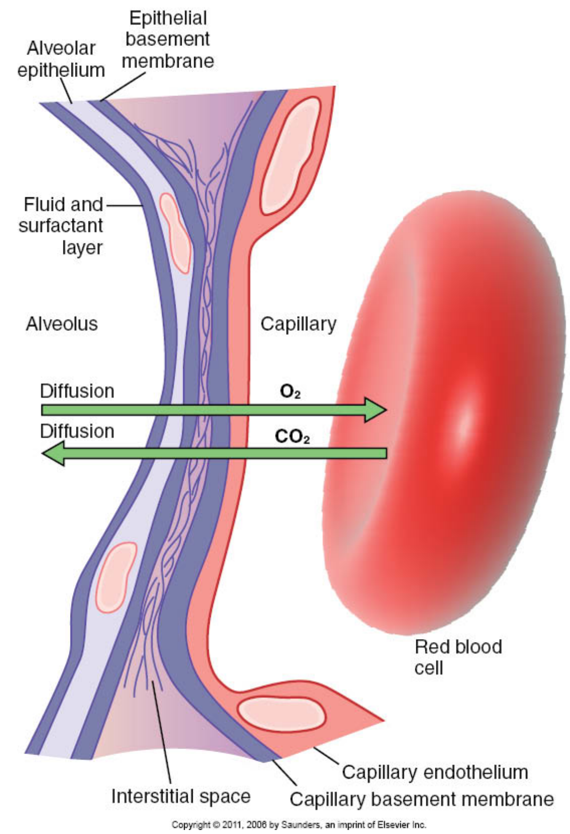


Figure 39-9

Factors influencing external respiration

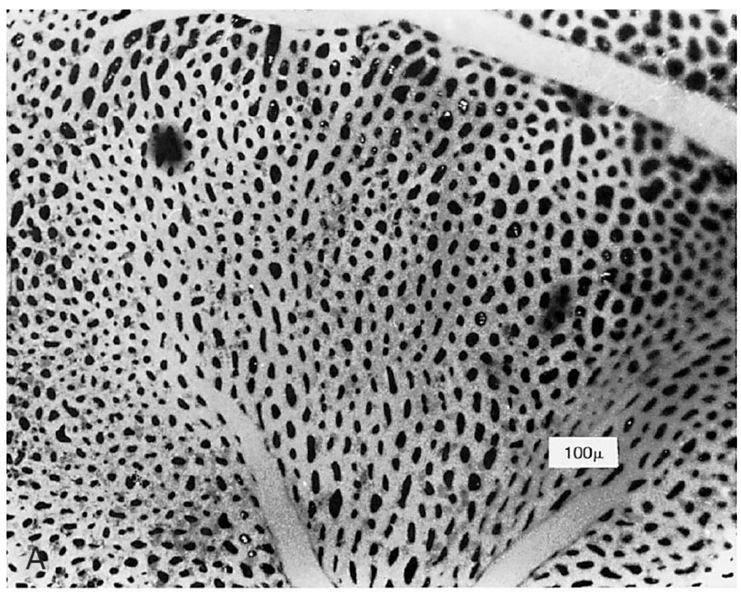
Efficient external respiration depends on three main factors:

i. Surface area and structure of the respiratory membrane
ii. Partial pressure gradients between alveoli and capillaries
iii. Matching alveolar airflow to pulmonary capillary blood flow

External respiration: surface area and structure of respiratory membrane

- Total surface area of the respiratory membrane ~70 m^2 (750 ft^2)
- Only 60-140 mL of blood in pulmonary capillaries, therefore exchange of O_2 and CO_2 is very rapid

Figure 39-8



(From Maloney JE, Castle BL: Pressure-diameter relations of capillaries and small blood vessels in frog lung. Respir Physiol 7:150, 1969. Reproduced by permission of ASP Biological and Medical Press, North-Holland Division.)

External respiration: partial pressures

- Partial pressure gradients influence gas exchange between alveoli and pulmonary capillaries

- Note the difference in partial pressures in alveoli are different than the atmosphere

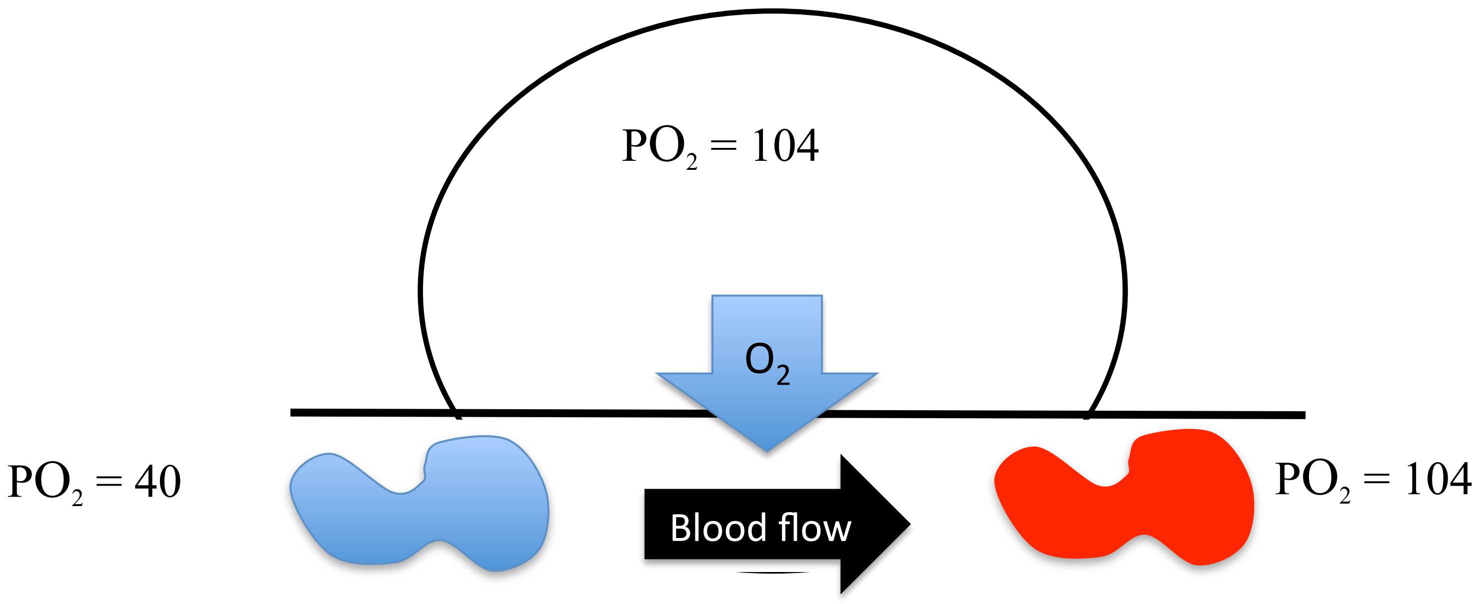
	Alveoli	Atmosphere
PO2	104	159
PCO2	40	0.3
PH2O	47	3.5

External respiration: partial pressures

- Difference in partial pressures is caused by a combination of factors
  - Humidification of inhaled air moving into the respiratory passageways
  - Gas exchange between alveoli and pulmonary capillaries
  - Mixing of new and old air since only ~10% exchange of air with each breath

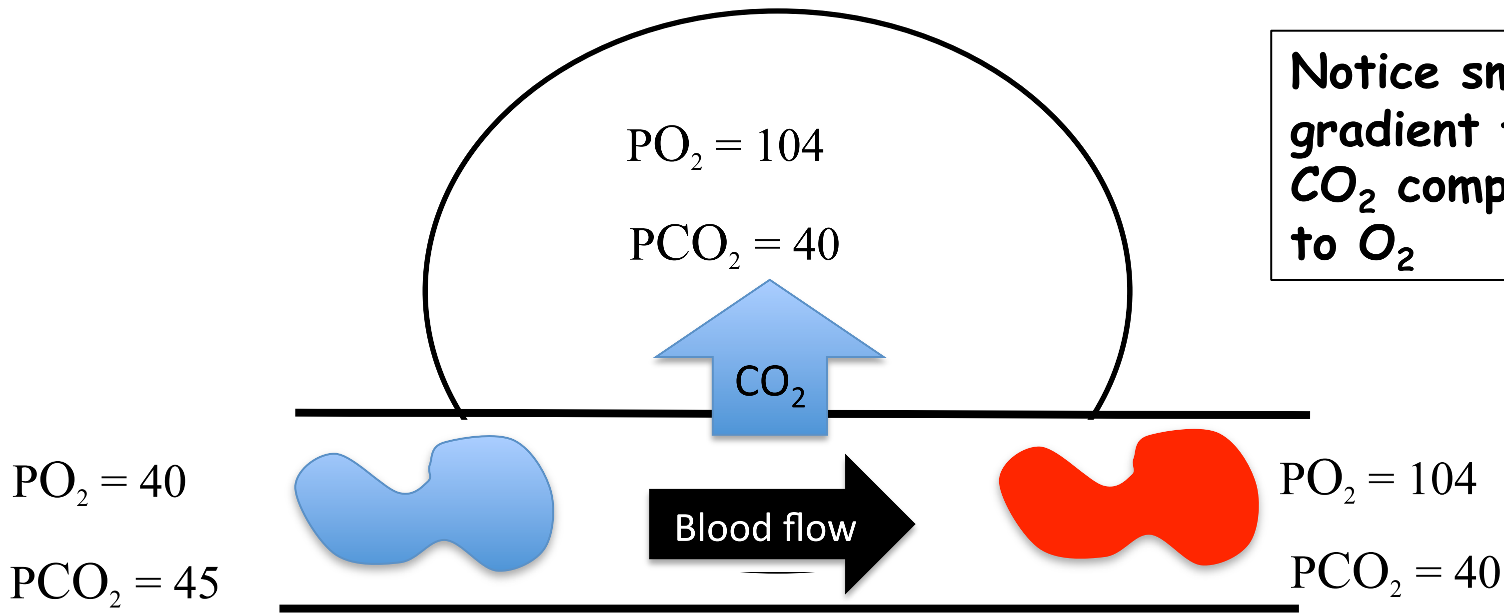
External respiration: loading O_2 into the blood

- O_2 diffuses along its partial pressure gradient, from the alveolus into the blood, until equilibrium is reached



External respiration: unloading CO_2 into the alveolus

- CO_2 diffuses along its partial pressure gradient, from the blood into the alveolus, until equilibrium is reached



Notice small gradient for CO_2 compared to O_2

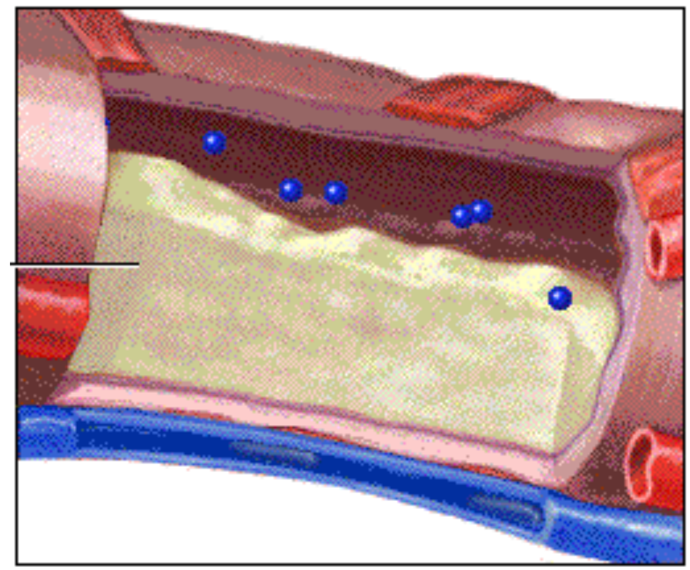
Ventilation-perfusion coupling: effect of PO_2

- Efficient gas exchange is maintained by ventilation-perfusion coupling

- This ensures alveolar airflow is proportional to pulmonary capillary blood flow

Ventilation-perfusion coupling: effect of PO_2

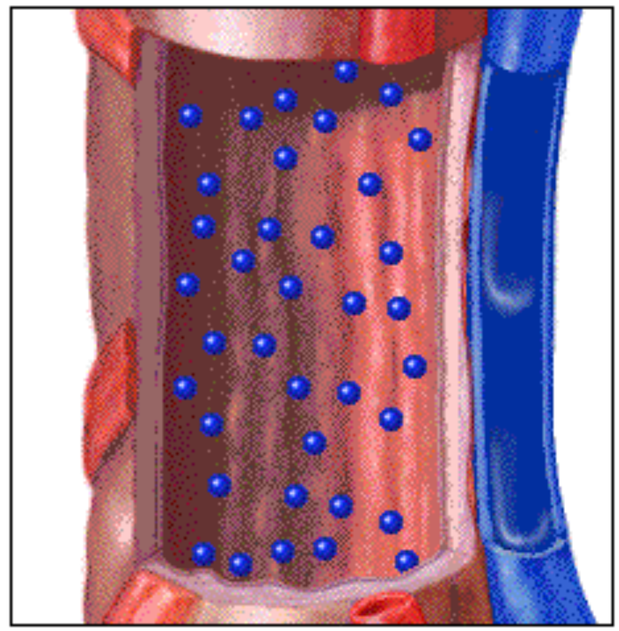
- If airflow is restricted to a bronchiole (e.g. due to mucus), the resulting low PO_2 causes the local arterioles to vasoconstrict



- Blood flow redirected to alveoli with higher airflow and higher O_2 availability for diffusion into blood

Ventilation-perfusion coupling: effect of PO_2

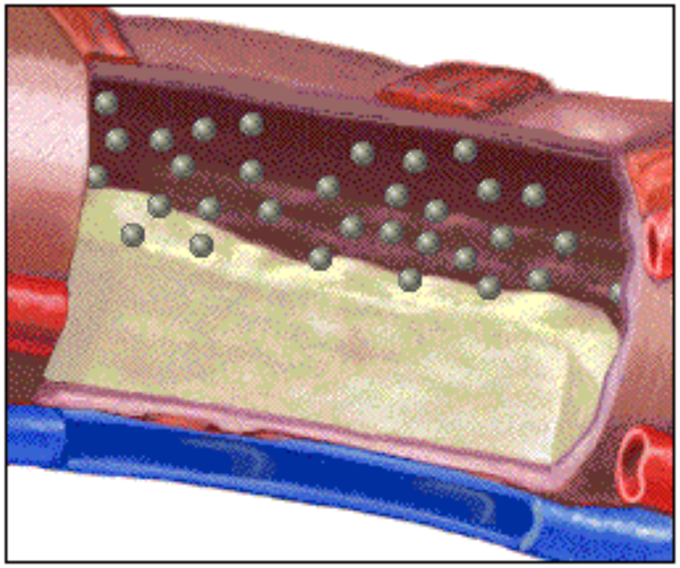
- In region of high air supply relative to the blood supply, the resulting higher PO_2 causes the local arterioles to vasodilate



- This ensures that more blood is brought to alveoli to maximize uptake of O_2

Ventilation-perfusion coupling: effect of PCO_2

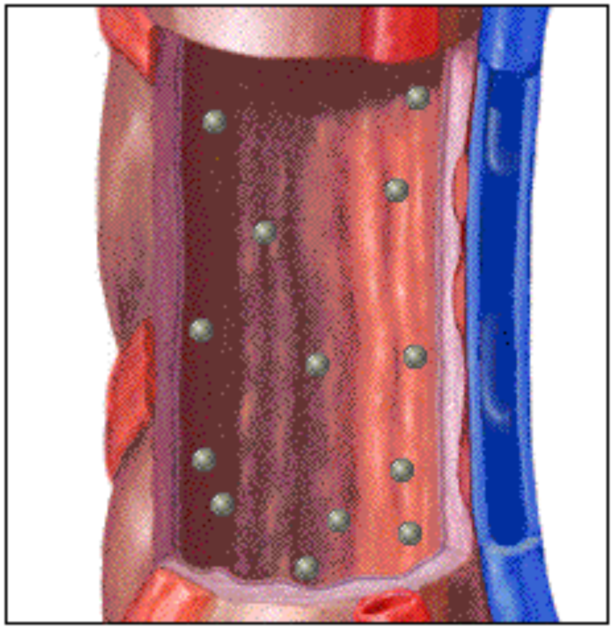
- While arterioles respond to changes in PO_2, bronchioles respond to changes in PCO_2
- When airflow is lower than normal, PCO_2 rises causing bronchioles to dilate
- This ensures the elimination of excess CO_2 in the alveoli



Ventilation-perfusion coupling: effect of PCO_2

- When airflow through a bronchiole is high compared to the blood supply, PCO_2 drops causing bronchioles to constrict

- This reduces the airflow so it is proportional to the local blood flow



O_2 concentration and partial pressure in the alveoli

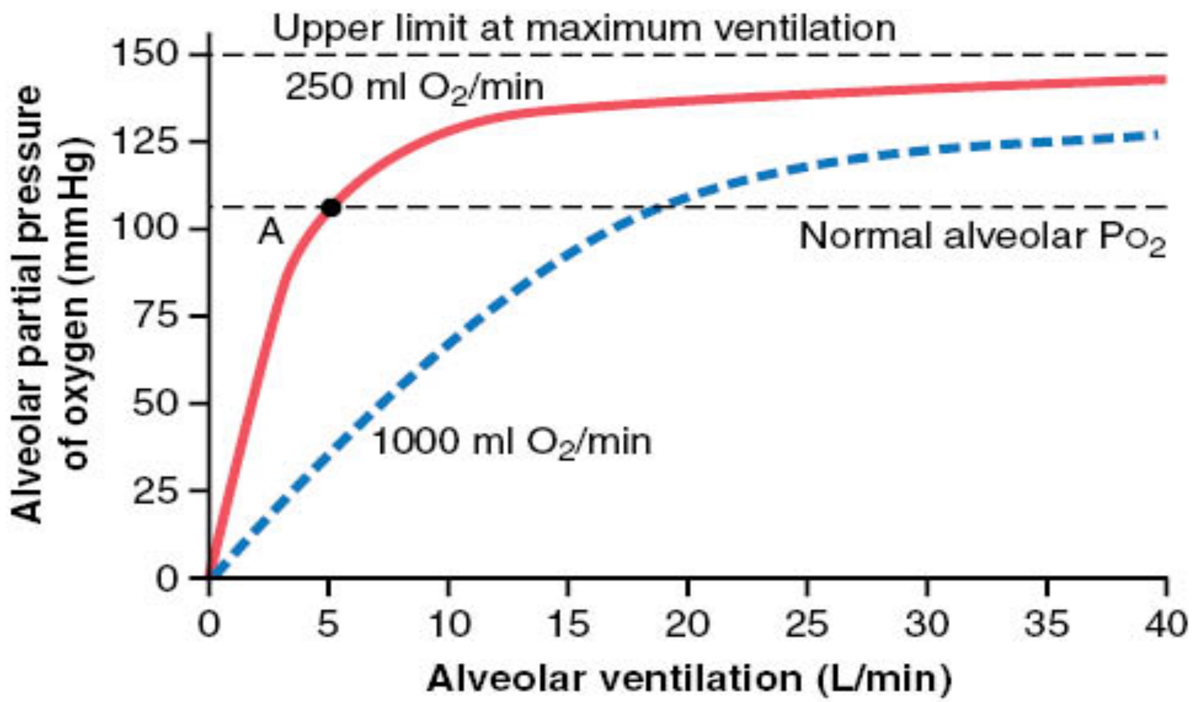


Figure 39-4 Effect of alveolar ventilation on the alveolar PO_2 at two rates of oxygen absorption from the alveoli—250 ml/min and 1000 ml/min. *Point A* is the normal operating point.

CO_2 concentration and partial pressure in the alveoli

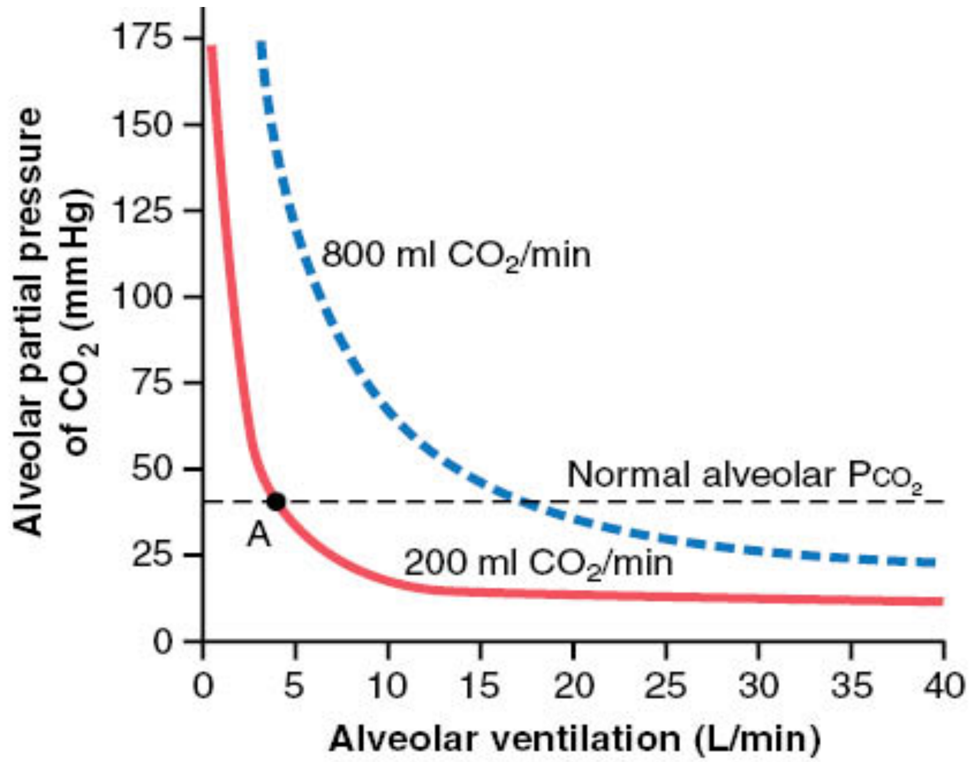


Figure 39-5 Effect of alveolar ventilation on the alveolar PCO_2 at two rates of carbon dioxide excretion from the blood—800 ml/min and 200 ml/min. *Point A* is the normal operating point.

Sites of gas exchange

- O_2 rich blood leaves the lungs via pulmonary veins to the left side of the heart to be pumped into the systemic circuit

- **Internal respiration:**
  - O_2 diffuses into cells from systemic capillaries
  - CO_2 diffuses into systemic capillaries from cells

Internal respiration

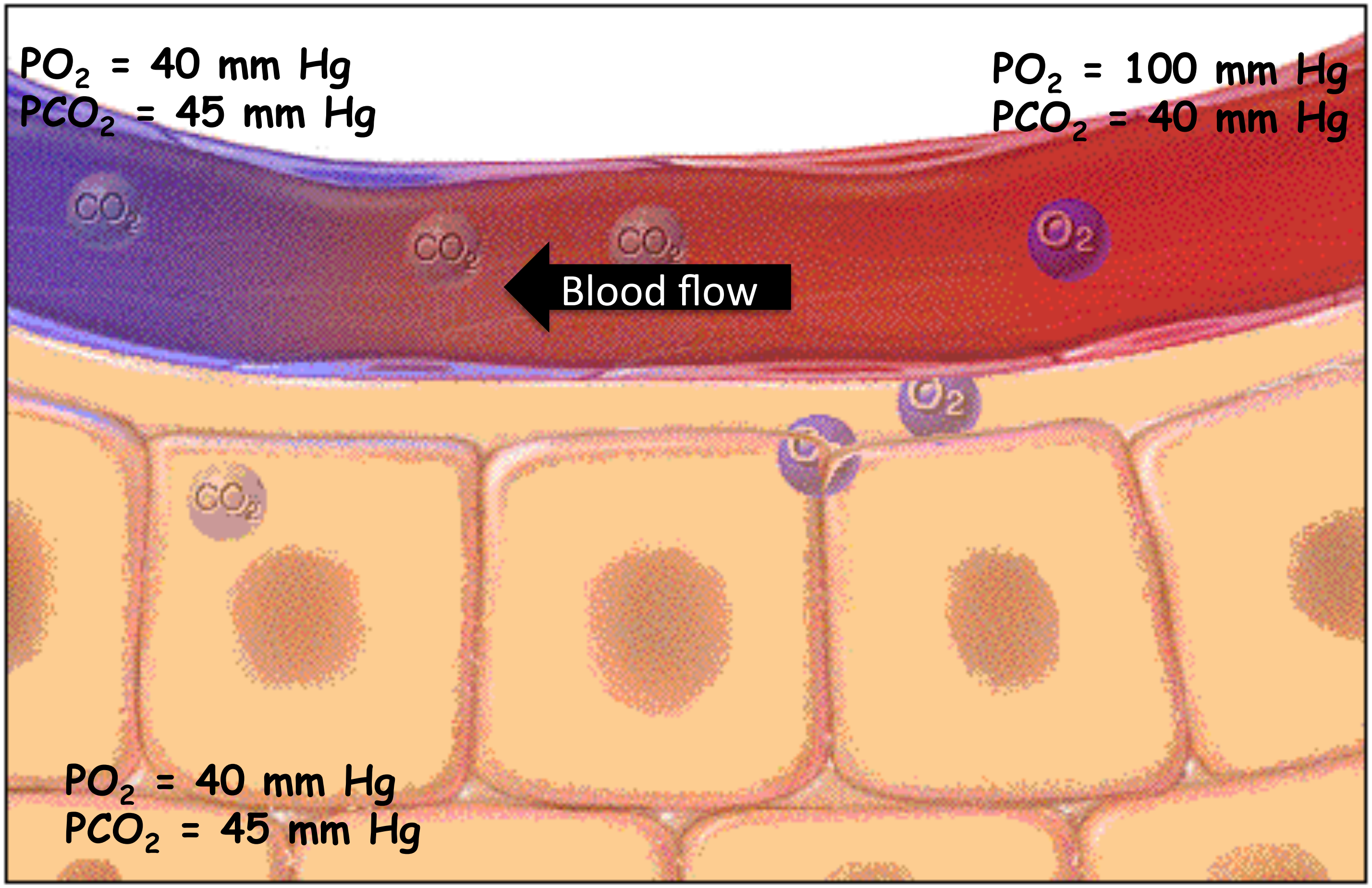
- Like external respiration, internal respiration depends on several factors:

  i. Surface area available for diffusion (varies in different tissues)
  ii. As in the lungs, gases diffuse along their partial pressure gradients
  iii. Rate of blood flow in a specific tissue, which can vary (e.g. metabolic rate of tissue)

Internal respiration: O_2 and CO_2 exchange

- In relatively inactive organs, the tissue cells have a PO_2 = 40 mm Hg and PCO_2 = 45 mm Hg
- Blood entering the systemic capillary has PO_2 = 100 mm Hg and PCO_2 = 40 mm Hg
- Notice the difference in PO_2 compared to what was observed for alveolar PO_2

Internal respiration: O_2 and CO_2 exchange



Summary

- Gas laws show the relationship between partial pressure, solubility and concentration of gases
- Gases diffuse along their partial pressure gradients from regions of high partial pressure to low partial pressure

Summary

- External respiration: O_2 loads into the capillaries from the alveoli and unloads CO_2 from the capillaries into the alveoli

- Internal respiration: O_2 unloads from systemic capillaries into cells and CO_2 loads from cells to systemic capillaries

Summary

- Efficient gas exchange depends on several factors including surface area, partial pressure gradients, blood flow and airflow
- Importantly, during external respiration, ventilation-perfusion coupling ensures optimum gas exchange by maintaining airflow and blood flow in proper proportions