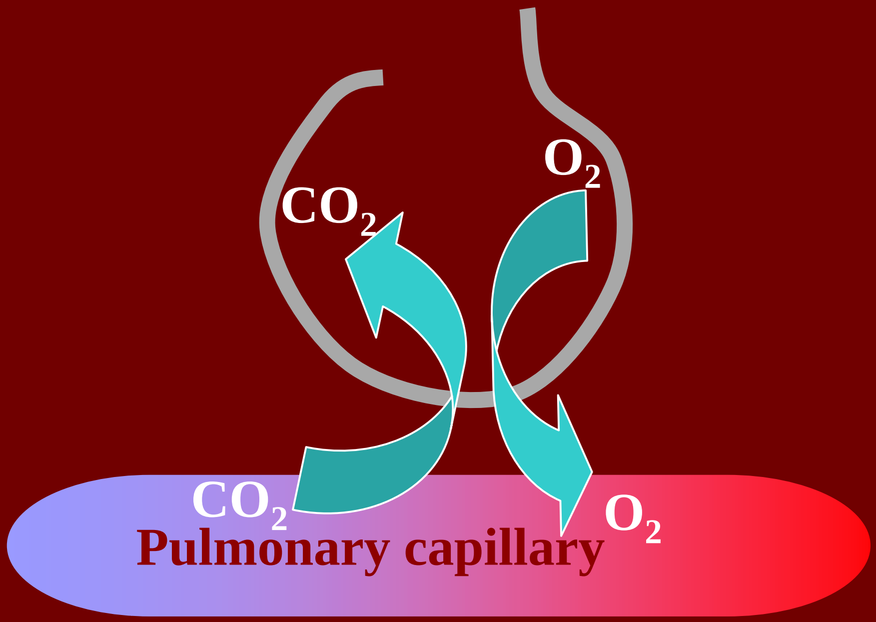
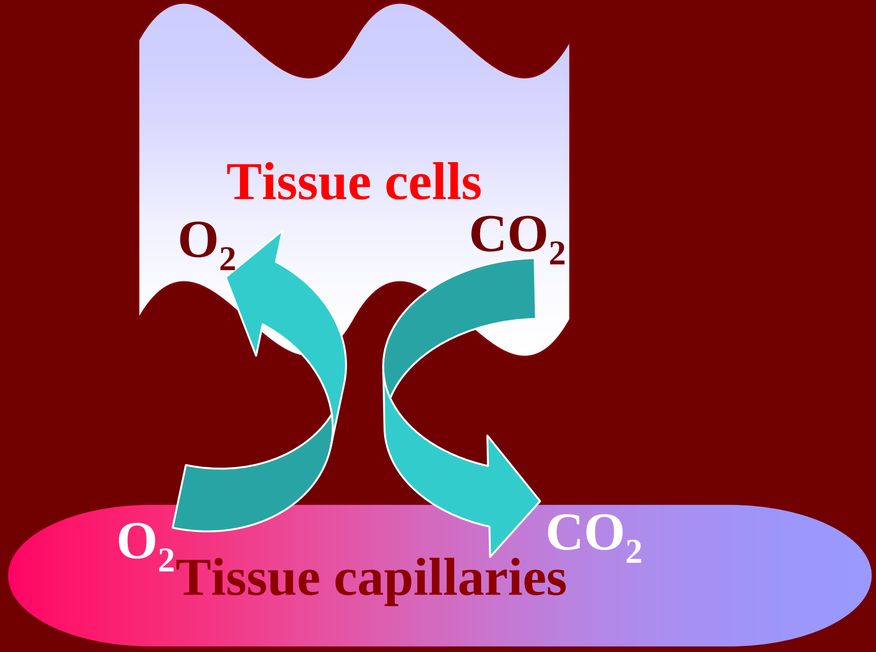
Gas exchange

Pulmonary gas exchange

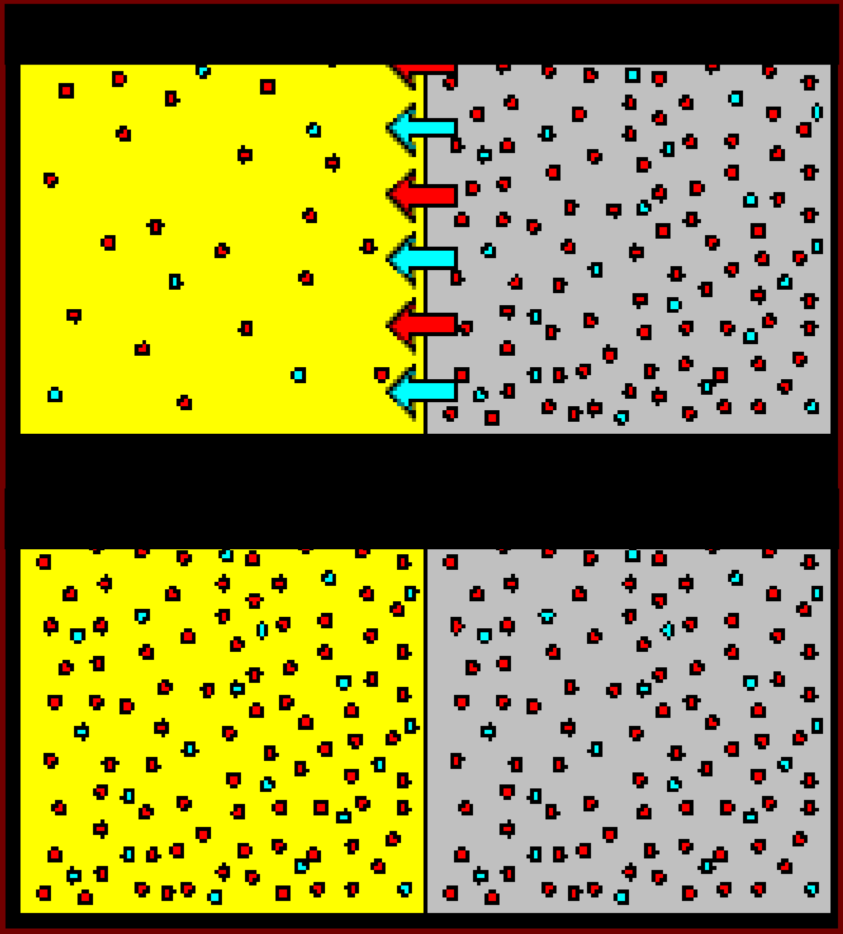


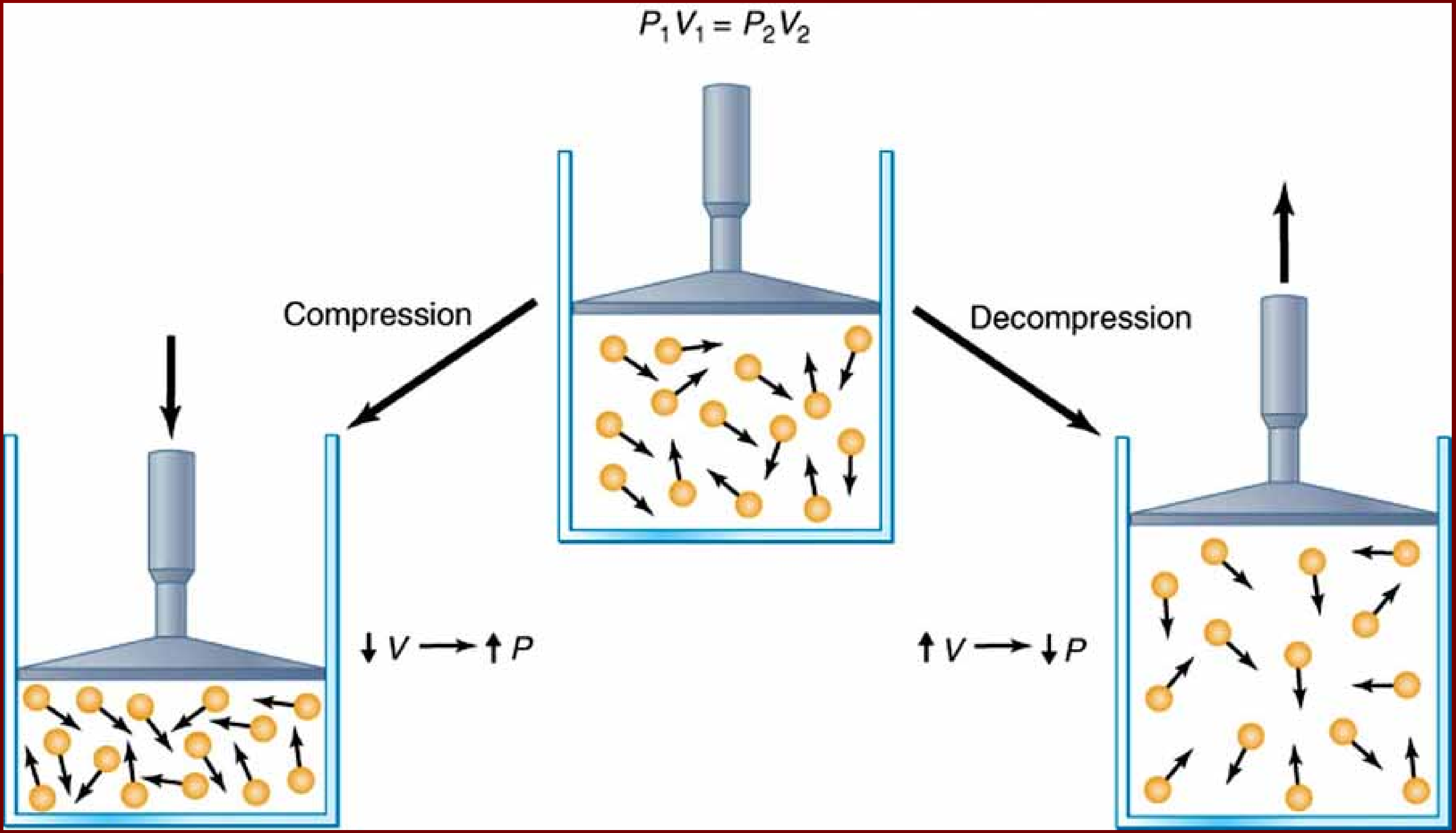
Tissue gas exchange



Physical principles of gas exchange

- Diffusion: continuous random motion of gas molecules.
- Partial pressure: the individual pressure of each gas, eg. Po_2



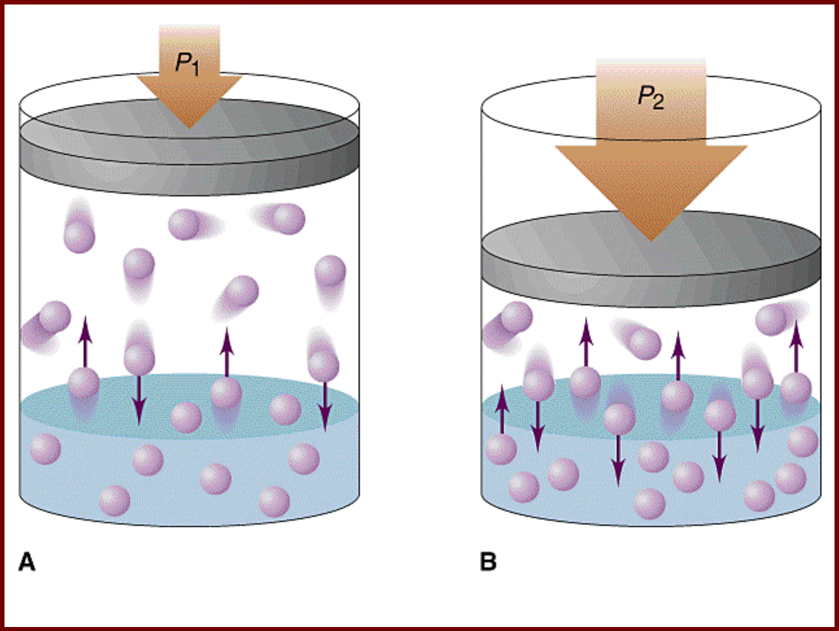


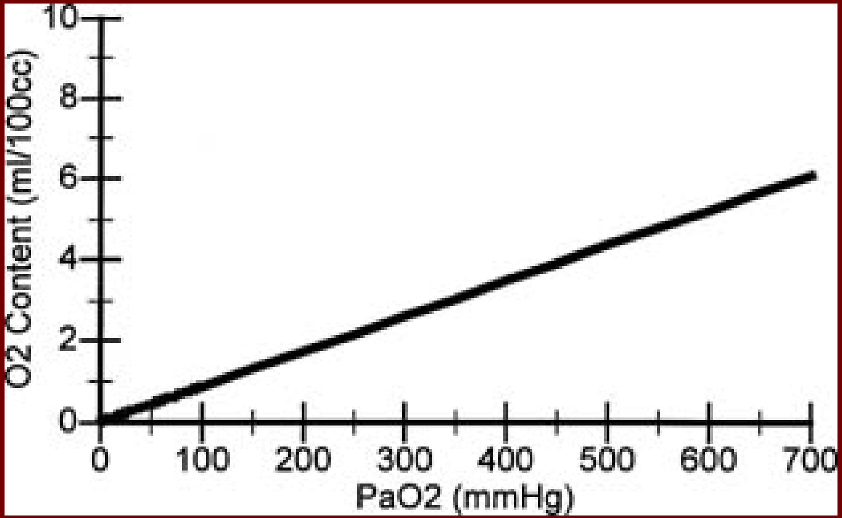
Boyle's law states that the **pressure** of a fixed number of gas molecules is inversely proportional to the **volume** of the container.

Laws governing gas diffusion

- Henry's law:

  The amount of dissolved gas is directly proportional to the partial pressure of the gas





Laws governing gas diffusion

- Graham's Law

When gases are dissolved in liquids, the relative rate of diffusion of a given gas is proportional to its solubility in the liquid and inversely proportional to the square root of its molecular mass

$$\frac{\text{diffusion rate of } CO_2}{\text{diffusion rate of } O_2} = 22\sqrt{\frac{32}{44}} = 19$$

Laws governing gas diffusion

- Fick's law

The net diffusion rate of a gas across a fluid membrane is proportional to the difference in partial pressure, proportional to the area of the membrane and inversely proportional to the thickness of the membrane

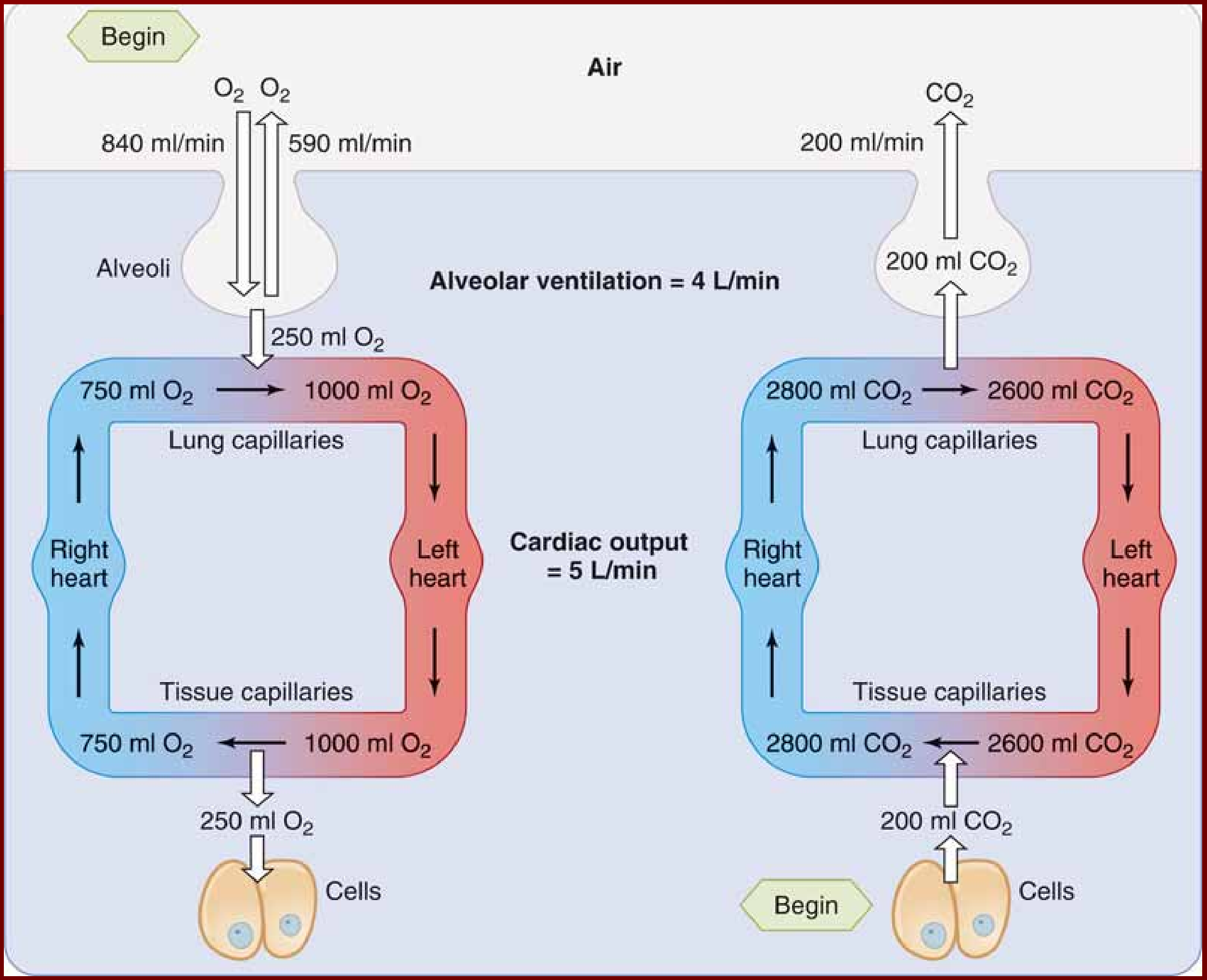
Factors affecting gas exchange

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

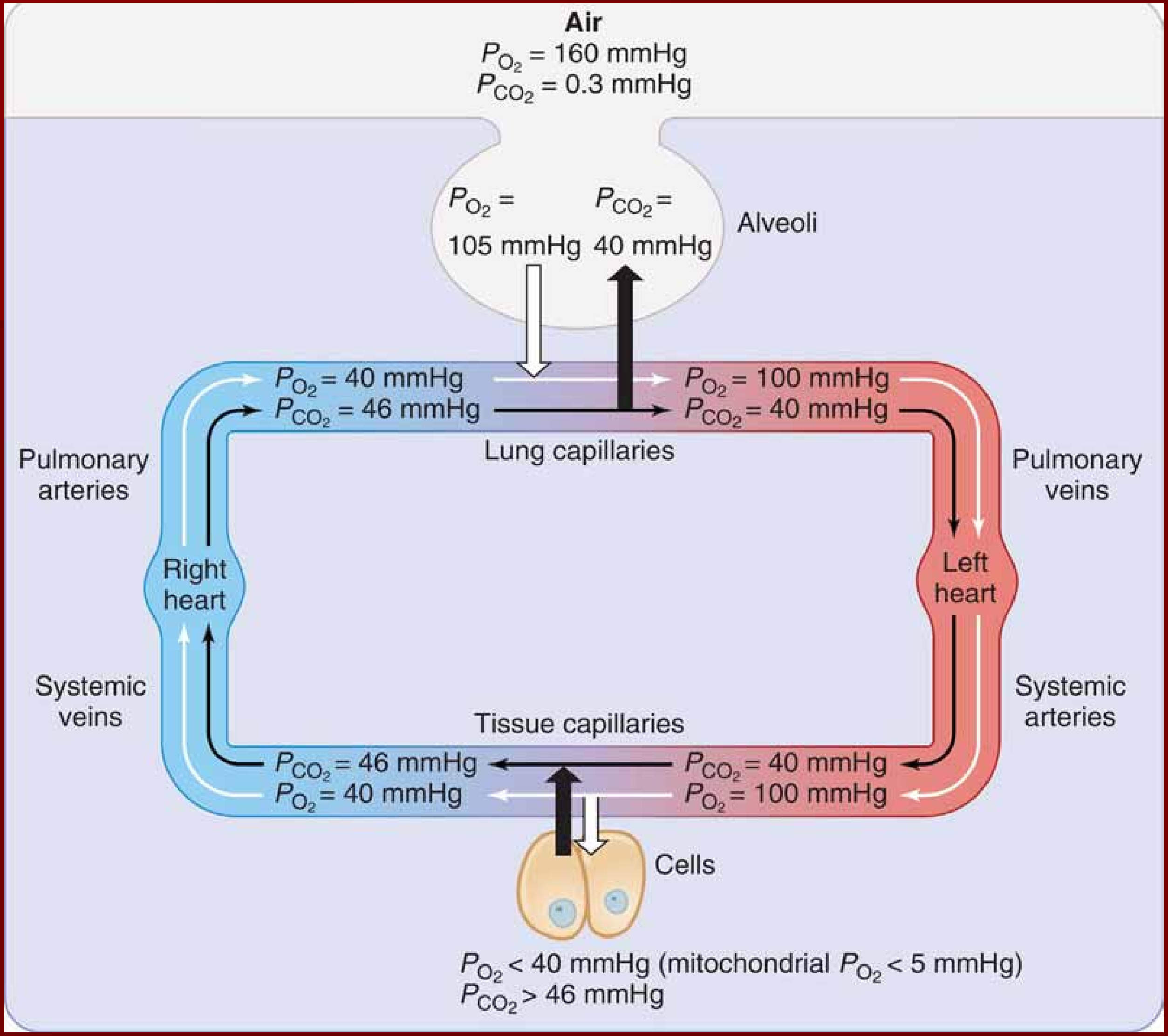
D:	Rate of gas diffusion
ΔP:	Difference of partial pressure
S:	Solubility of the gas
T:	Absolute temperature
A:	Area of diffusion
d:	Distance of diffusion
MW:	Molecular weight

Gas partial pressure (mmHg)

	Atmosphere	Alveoli	Arterial	Venous	Tissue
Po_2	159	104	100	40	30
Pco_2	0.3	40	40	46	50

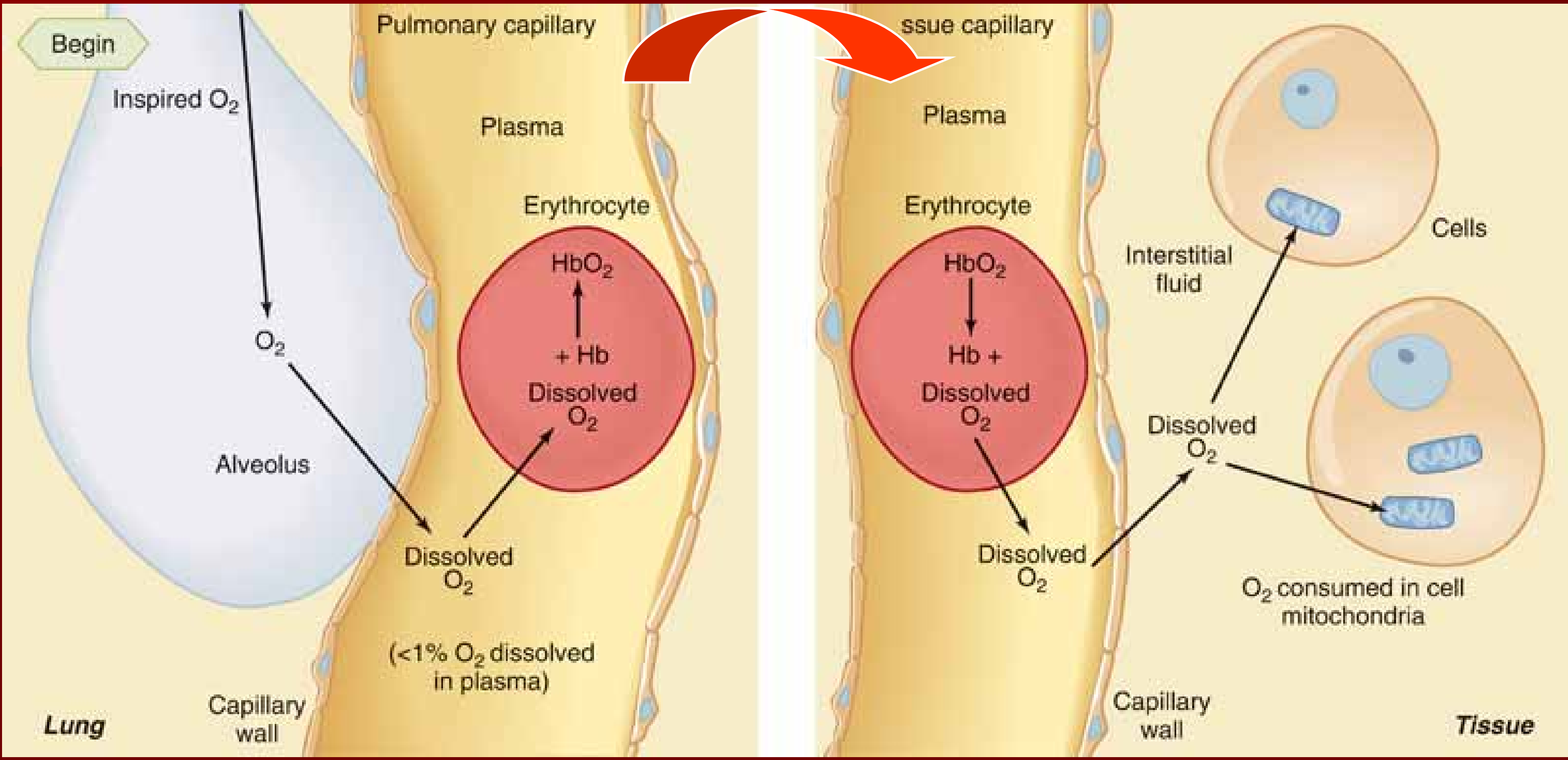


In the lungs, the concentration gradients favor the diffusion of oxygen toward the blood and the diffusion of carbon dioxide toward the alveolar air; owing to the metabolic activities of cells, these gradients are reversed at the interface of the blood and the active cells.



Changes in the concentration of dissolved gases are indicated as the blood circulates in the body. Oxygen is converted to water in cells; cells release carbon dioxide as a byproduct of fuel catabolism.

Diffusion of gases in liquid



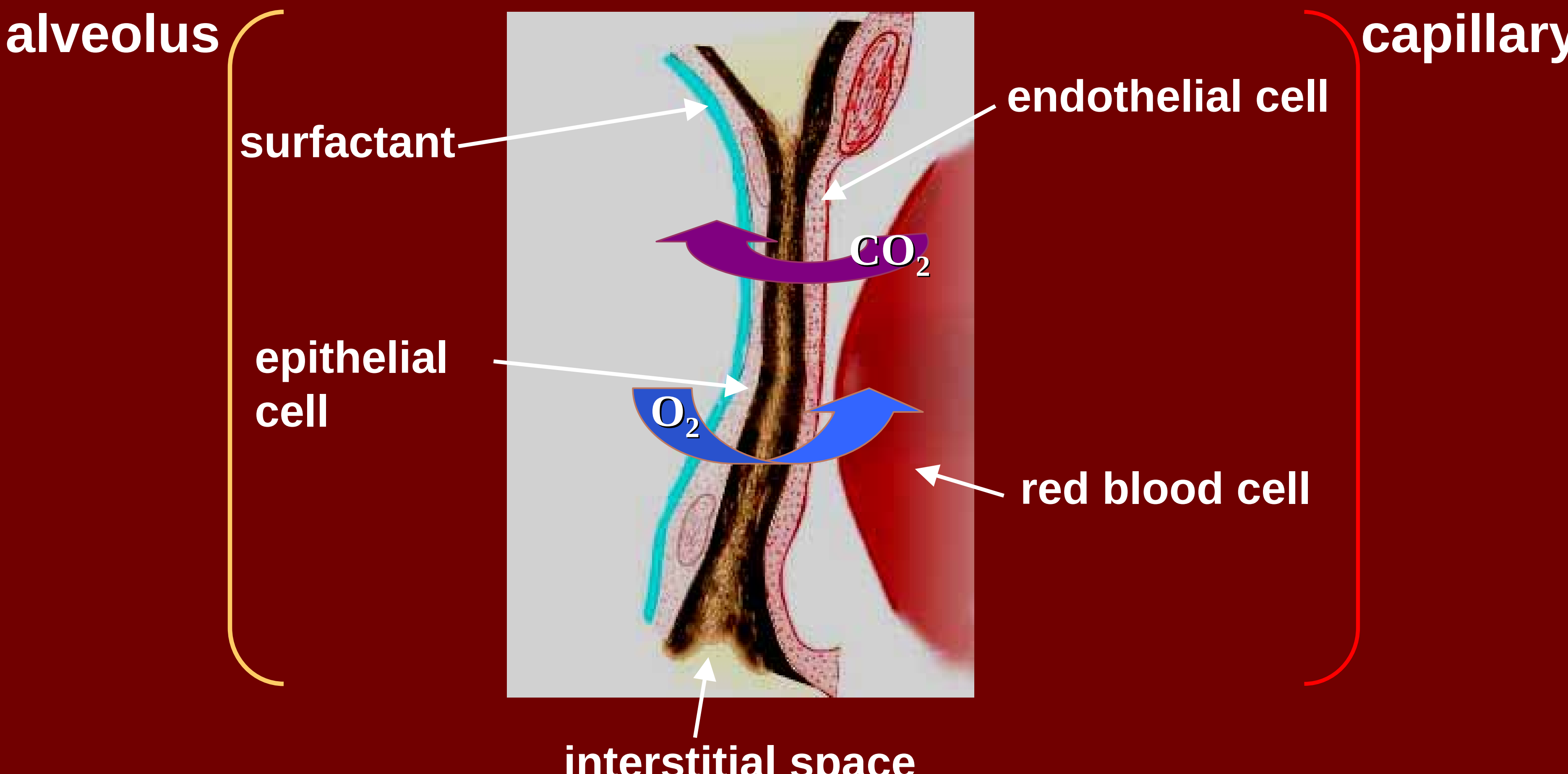
Oxygen movement in the lungs and tissues;
Movement of inspired air into the alveoli is by bulk flow;
All movement across membranes are by diffusion.

Factors that affect the velocity of pulmonary gas exchange

- Thickness of respiratory membrane
- Surface area of respiratory membrane
- The diffusion coefficient of the gas
- The pressure difference of the gas between the two sides of the membrane

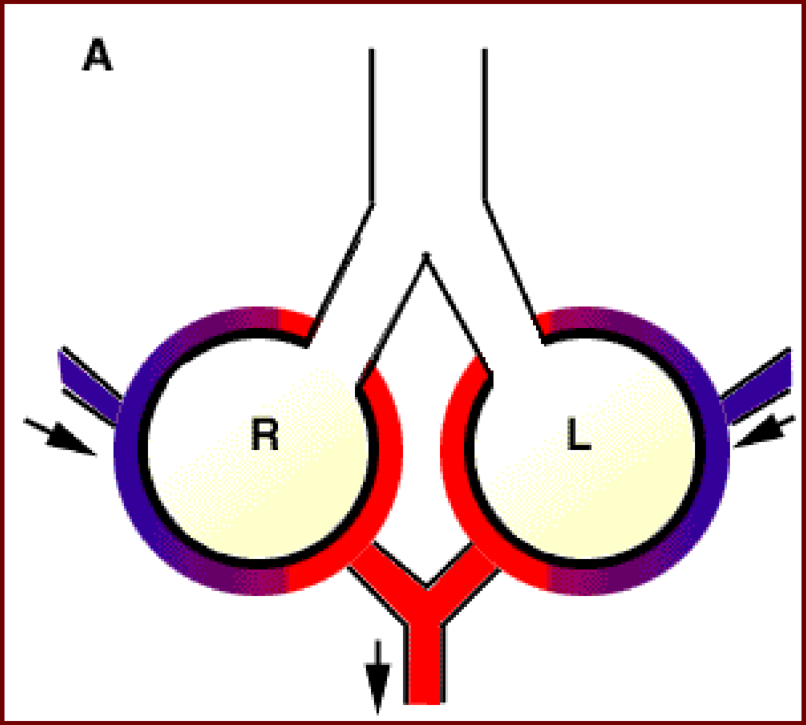
Respiratory membrane

- Is the structure through which oxygen diffuse from the alveolus into the blood, and carbon dioxide in the opposite direction.



Ventilation-perfusion ratio

- Alveolar ventilation (V) = 4.2 L
- Pulmonary blood flow (Q) = 5 L
- V/Q = 0.84 (optimal ratio of air supply and blood supply)



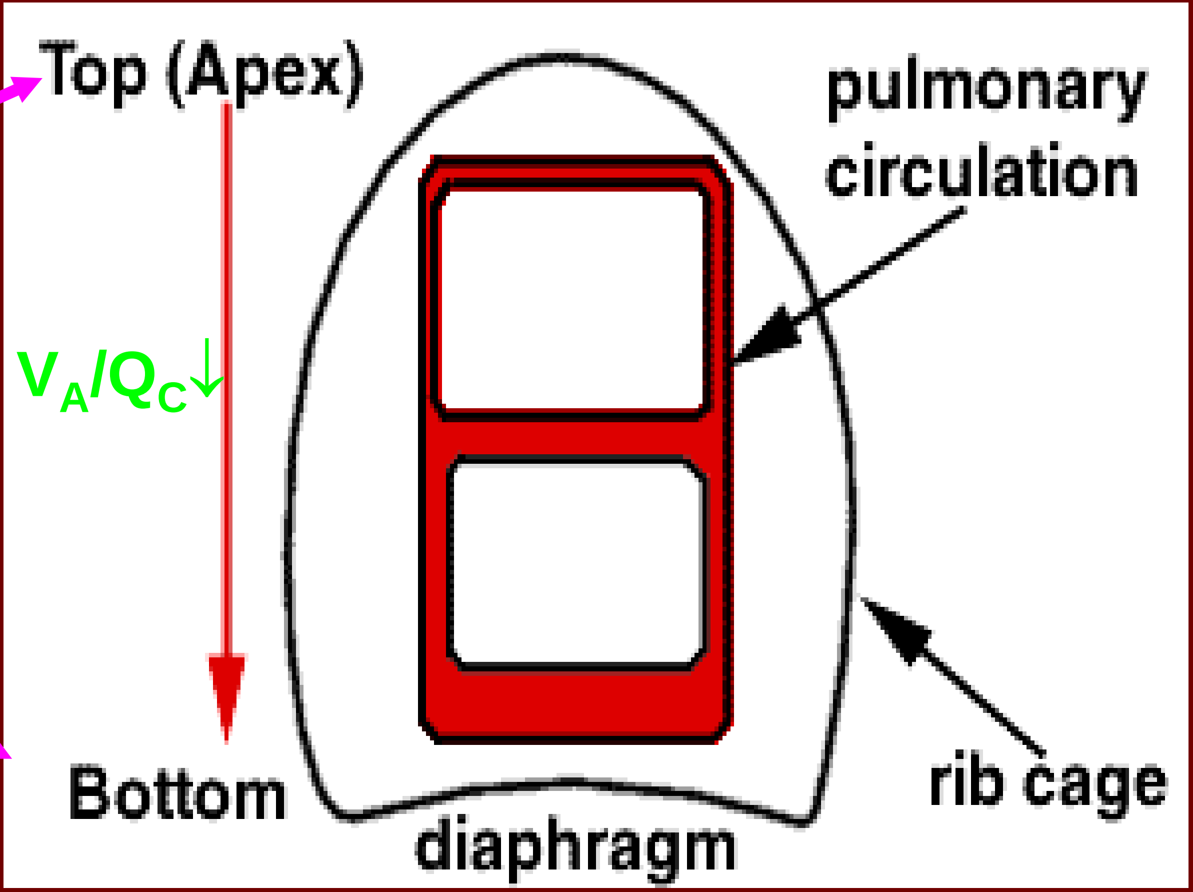
Ventilation-perfusion ratio

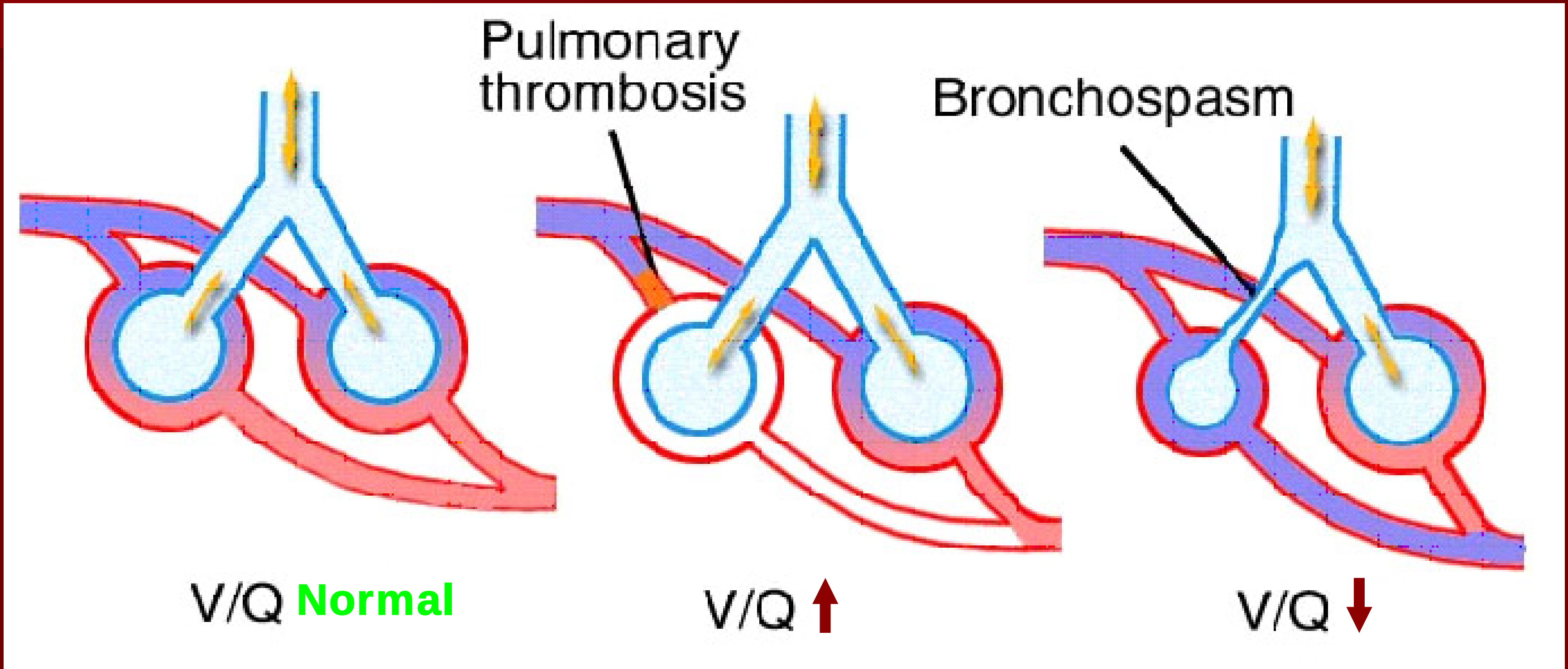
Effect of gravity on V/Q

Physiologic dead space

$V_A/Q_C\downarrow$

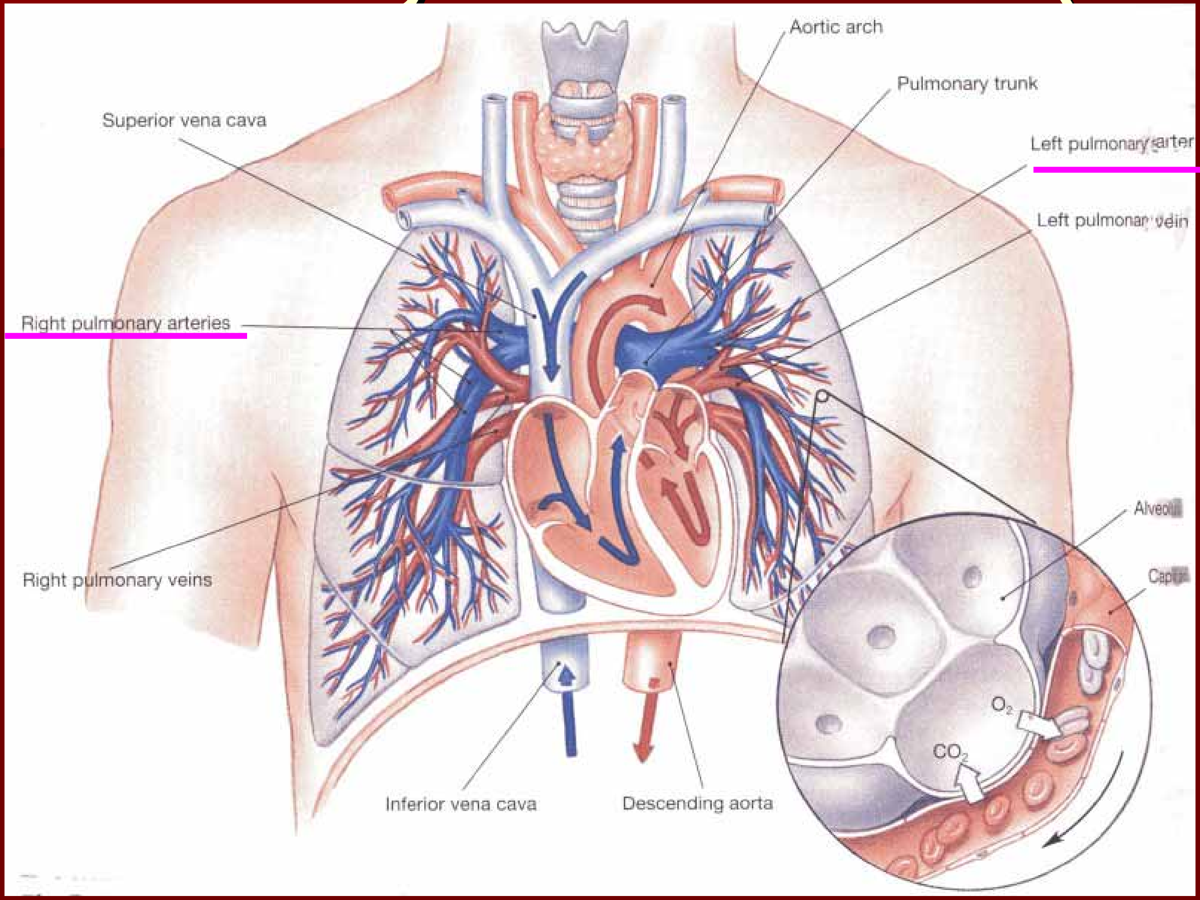
Physiologic shunt





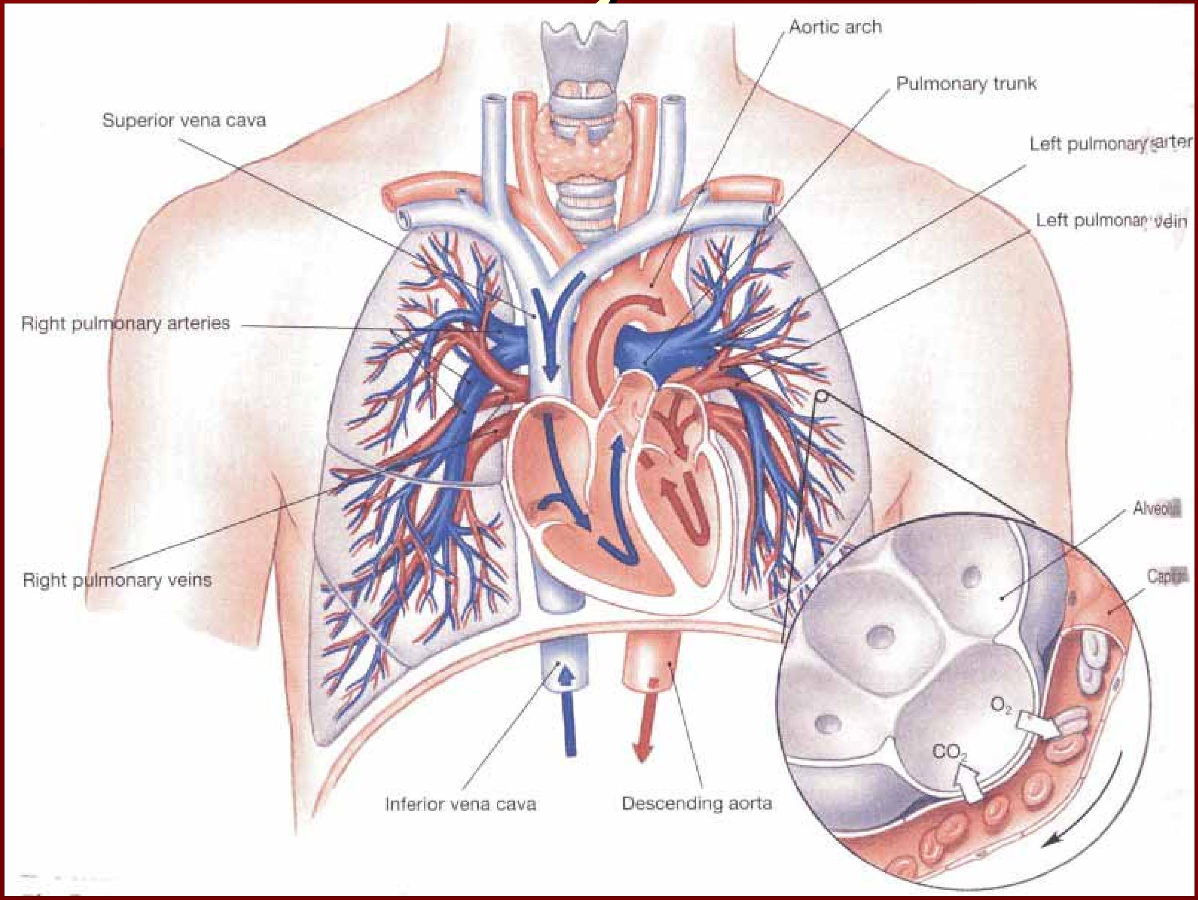
Mismatching of the air supply and blood supply in individual alveoli. The main effect of ventilation-perfusion inequality is to decrease the Po_2 of systemic arterial blood.

Pulmonary circulation (P136)



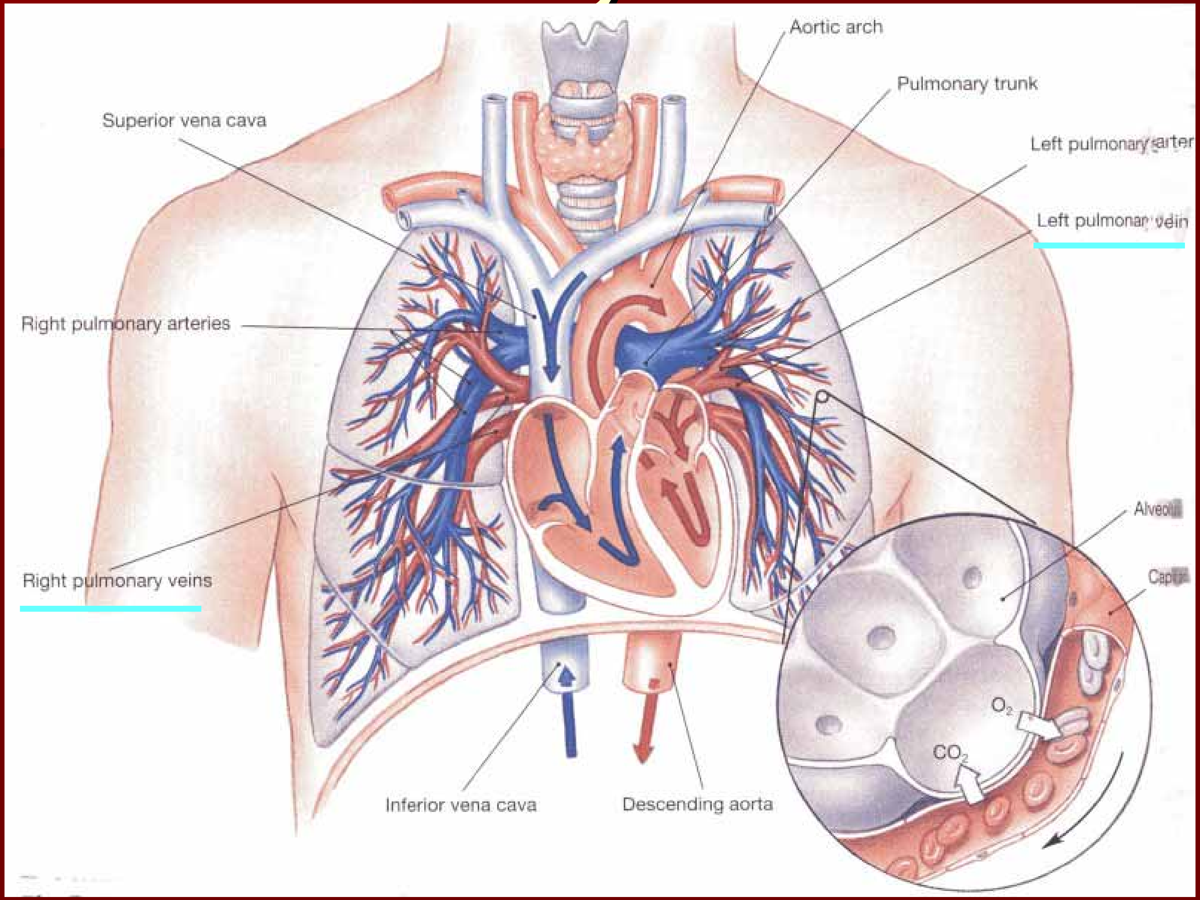
- The pulmonary arteries from the right ventrical branch along with the bronchial tree until they reach the respiratory bronchioles.

Pulmonary circulation



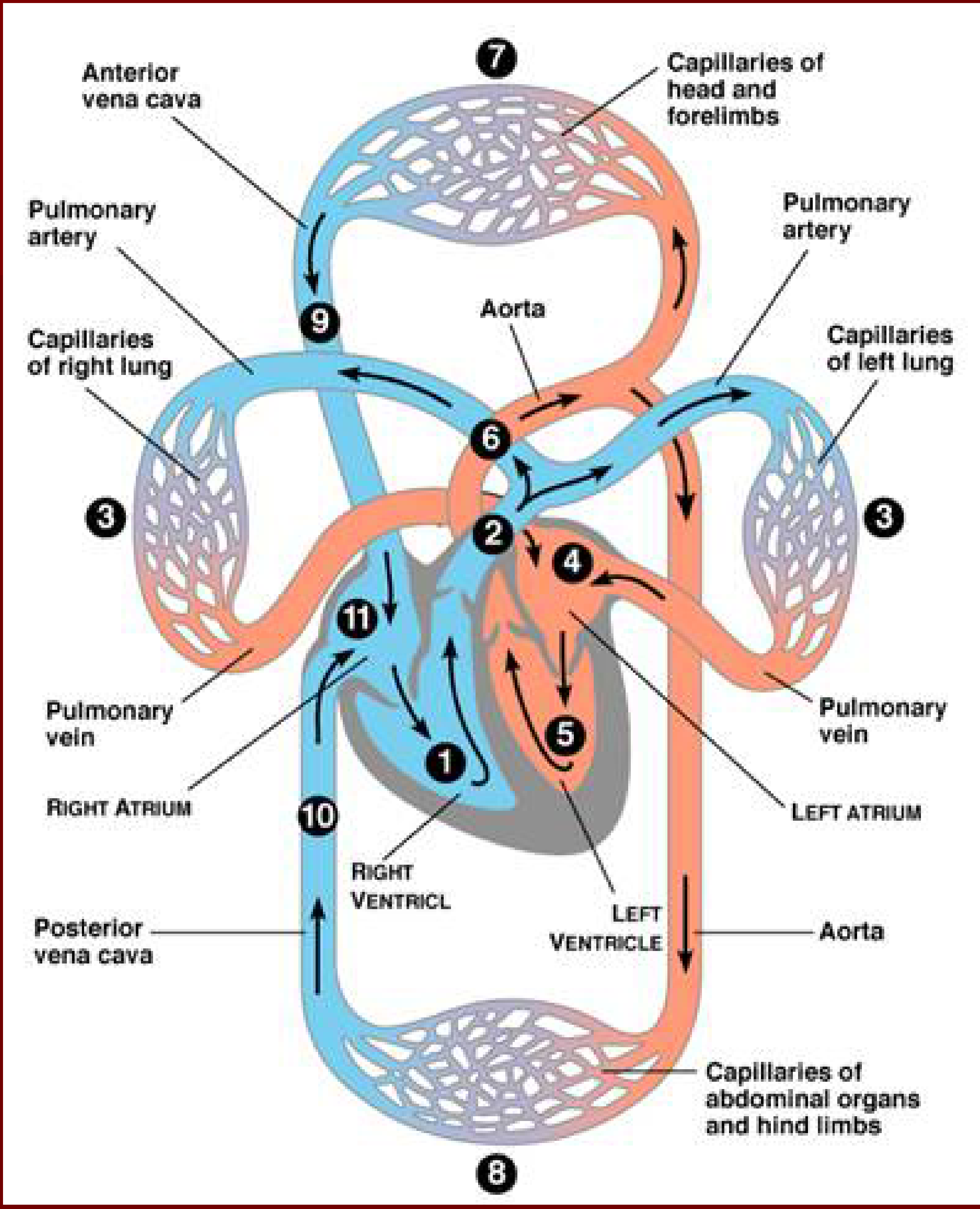
- **The pulmonary capillaries surround the alveoli very densely. The walls of the pulmonary capillaries and the alveoli are very thin and permeable to facilitate gas transport between inspired gas and the blood.**

Pulmonary circulation



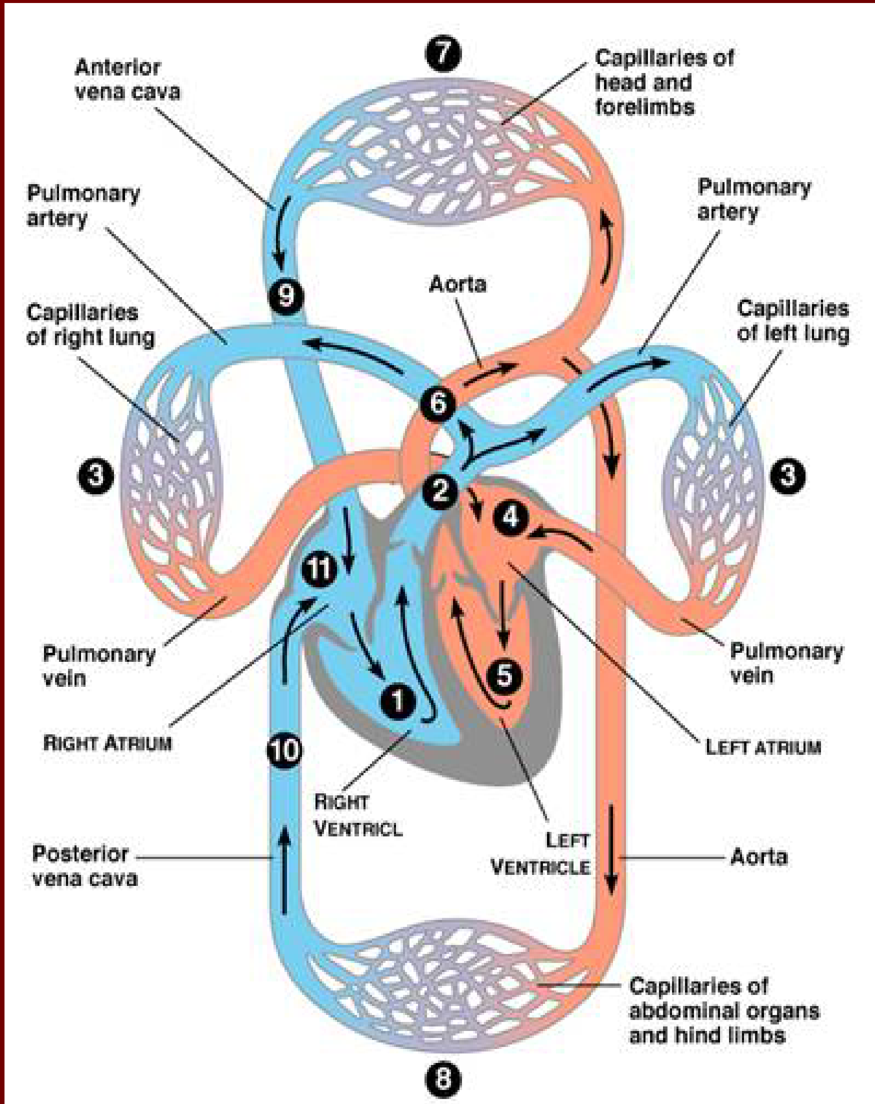
- The pulmonary veins run parallel to their corresponding arteries. Oxygenated blood returns to the left atrium via 6-8 pulmonary veins, thus completing the circulation of blood.

- Pulmonary circulation: The right ventricle fills and then contracts, pushing the blood into the pulmonary artery which leads to the lungs. In the lung capillaries, the exchange of carbon dioxide and oxygen takes place. The fresh, oxygen-rich blood enters the pulmonary veins and then returns to the heart, re-entering through the left atrium. The oxygen-rich blood then passes through a one-way valve into the left ventricle.



Respiration and blood circulation

- Systemic circulation: The oxygen-rich blood in the left ventricle will exit the heart through the main artery, called the aorta. The left ventricle's contraction forces the blood into the aorta and the blood begins its journey throughout the body. The veins bring waste-rich blood back to the heart, entering the right atrium throughout two large veins called vena cavae. The right atrium fills with the waste-rich blood and then contracts, pushing the blood through a one-way valve into the right ventricle.



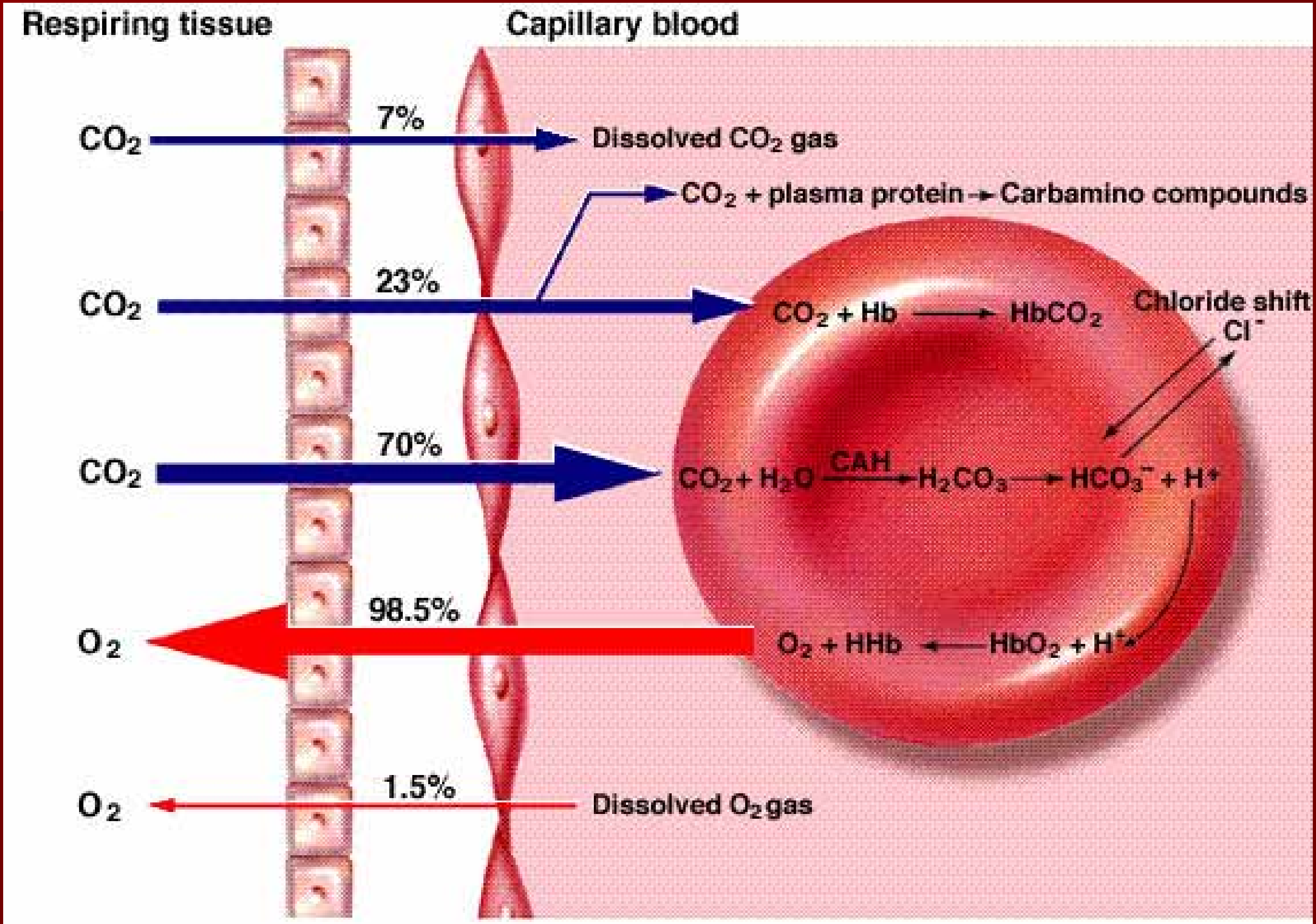
Gas transport in the blood

- Respiratory gases are transported in the blood in two forms:
  - Physical dissolution
  - Chemical combination

Alveoli **Blood** **Tissue**

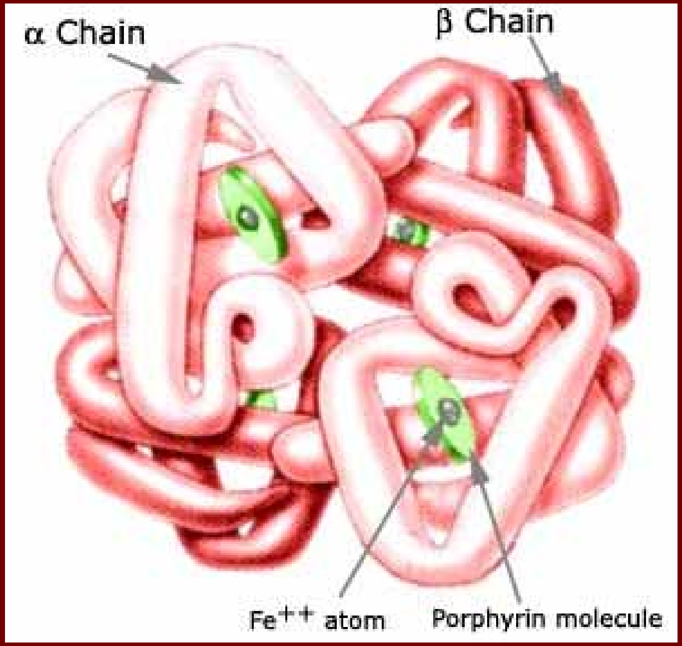
O_2 → dissolve → combine → dissolve → O_2

CO_2 ← dissolve ← combine ← dissolve ← CO_2

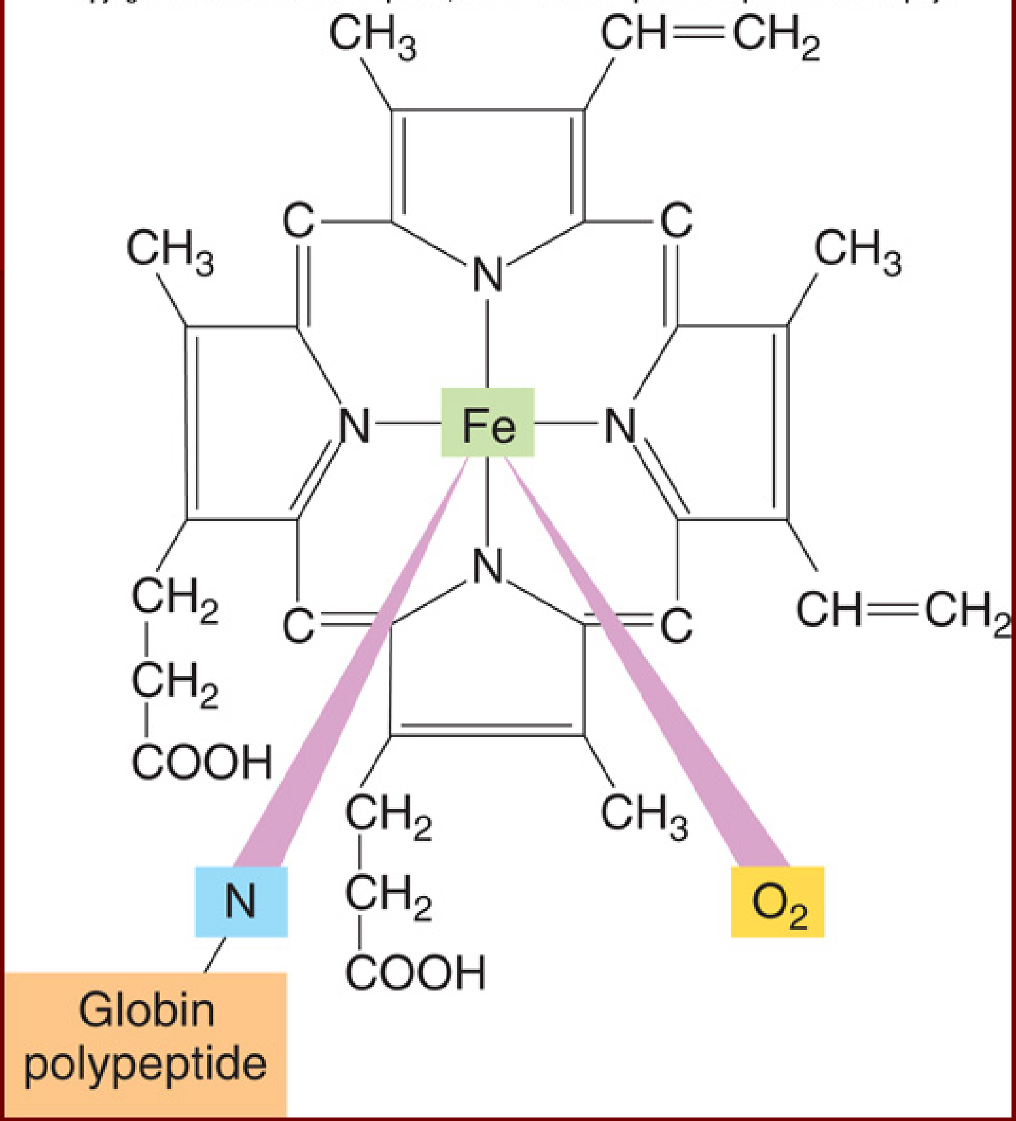


Respiring tissue
Capillary blood
CO_2
7%
Dissolved CO_2 gas
CO_2 + plasma protein → Carbamino compounds
CO_2
23%
CO_2 + Hb → $HbCO_2$
Chloride shift
Cl^-
CO_2
70%
$CO_2 + H_2O \xrightarrow{CAH} H_2CO_3 \rightarrow HCO_3^- + H^+$
O_2
98.5%
O_2 + HHb ← HbO_2 + H^+
O_2
1.5%
Dissolved O_2 gas

Transport of oxygen

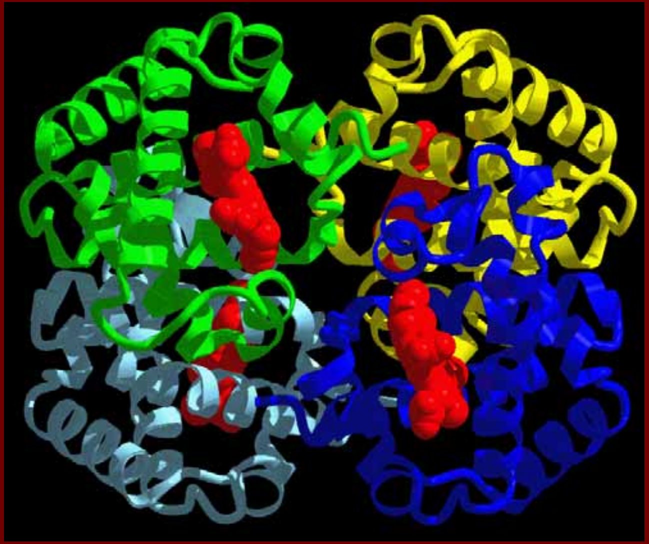


- Forms of oxygen transported
  - Chemical combination: 98.5%
  - Physical dissolution: 1.5%
- Hemoglobin (Hb) is essential for the transport of O_2 by blood



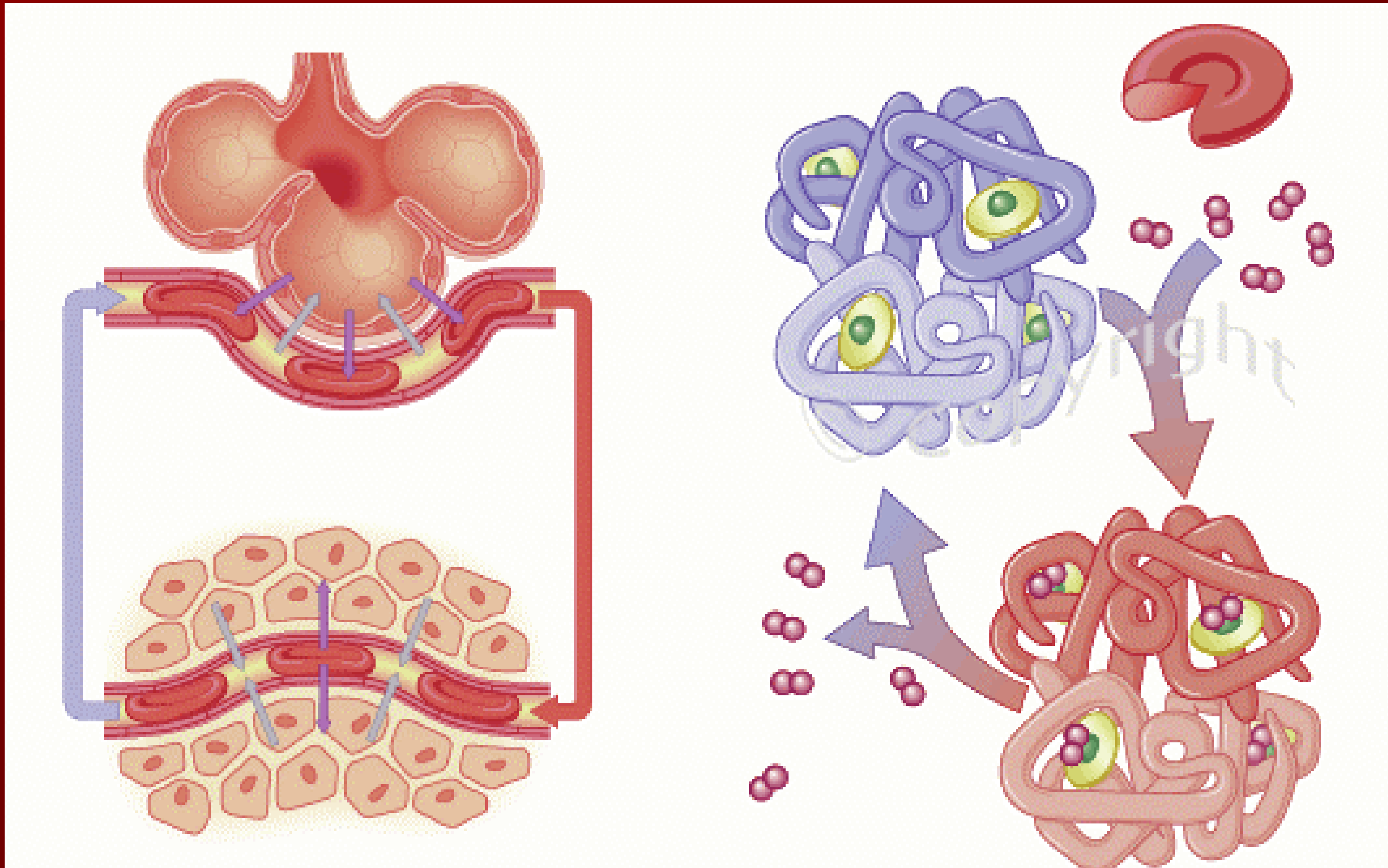
Hemoglobin is the gas-transport molecule inside erythrocytes.

- Normal adult hemoglobin is composed of four subunits linked together, with each subunit containing a single heme -- the ring-like structure with a central iron atom that binds to an oxygen atom.



Two forms of Hb

- Deoxygenated state (deoxyhemoglobin) -- when it has no oxygen
- Oxygenated form (oxyhemoglobin) -- carrying a full load of four oxygen atoms



$$Hb + O_2 \underset{\text{Low } PO_2}{\overset{\text{High } PO_2}{\rightleftharpoons}} HbO_2$$

Cooperativity of Hb

- Deoxy-hemoglobin is relatively uninterested in oxygen, but when one oxygen attaches, the second binds more easily, and the third and fourth easier yet.

- The same process works in reverse: once fully loaded hemoglobin lets go of one oxygen, it lets go of the next more easily, and so forth.

- Oxygen capacity
  - The maximal capacity of Hb to bind O_2 in a blood sample
- Oxygen content
  - The actual binding amount of O_2 with Hb
- Oxygen saturation
  - Is expressed as O_2 bound to Hb devided by the maximal capacity of Hb to bind O_2
  - (O_2 content / O_2 capacity) x 100%

Hb>50g/L ---→Cyanosis

- Cyanosis is a physical sign causing bluish discoloration of the skin and mucous membranes.
- Cyanosis is caused by a lack of oxygen in the blood.
- Cyanosis is associated with cold temperatures, heart failure, lung diseases, and smothering. It is seen in infants at birth as a result of heart defects, respiratory distress syndrome, or lung and breathing problems.

Cyanosis

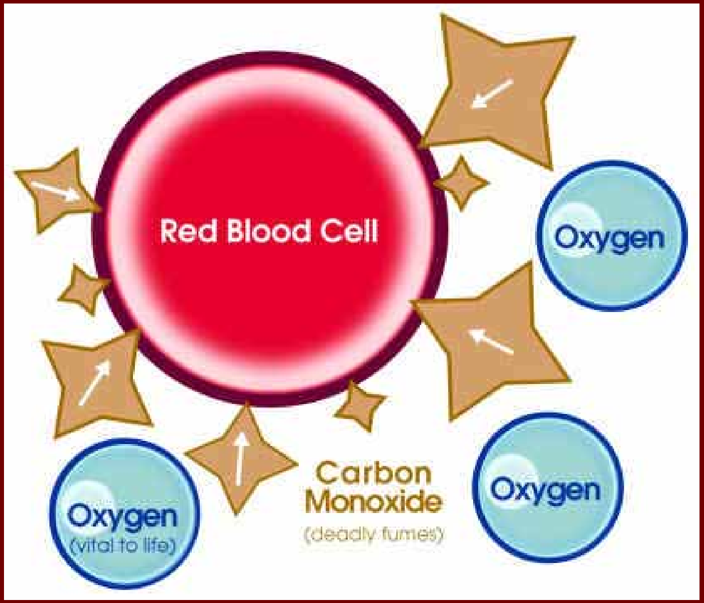
- Hb>50g/L

Hypoxia

- Definition: Hypoxia is a state of oxygen deficiency in the body which is sufficient to cause an impairment of function.
- Hypoxia is caused by the reduction in partial pressure of oxygen, inadequate oxygen transport, or the inability of the tissues to use oxygen.

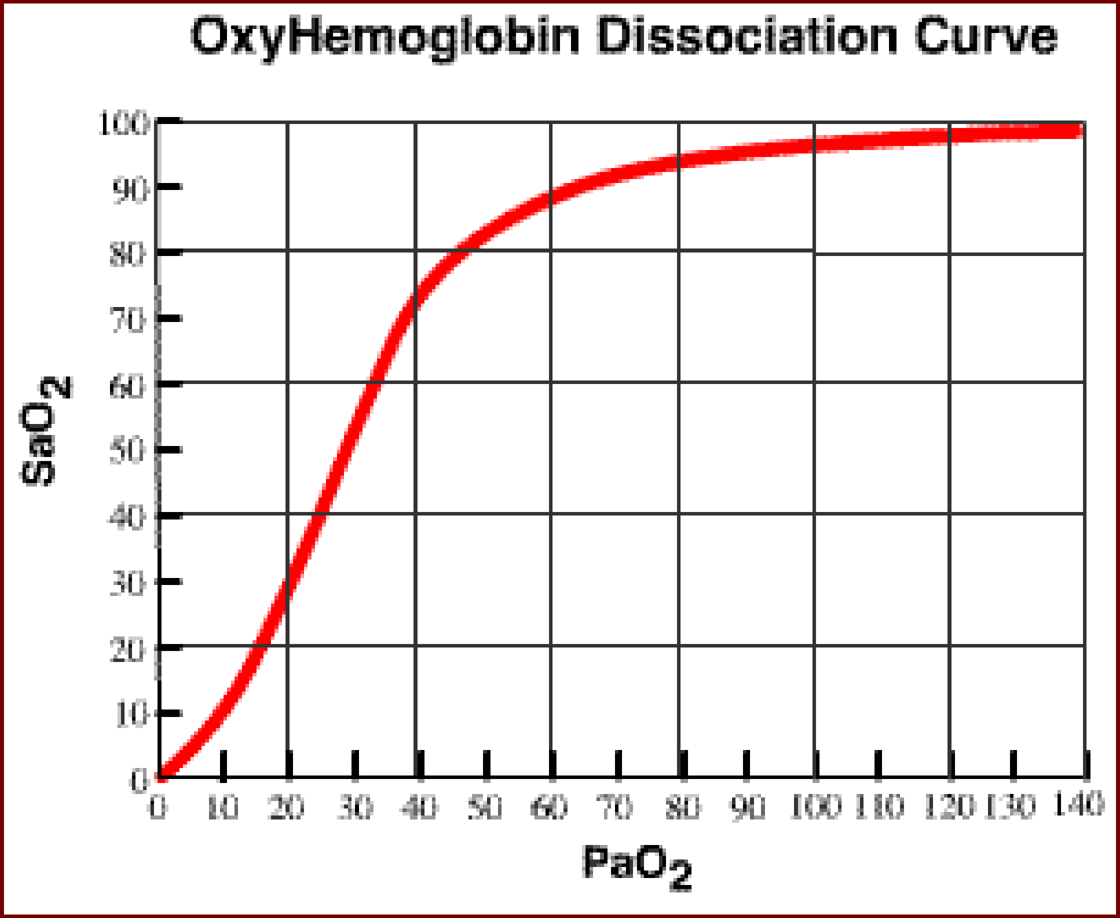
Carbon monoxide poisoning

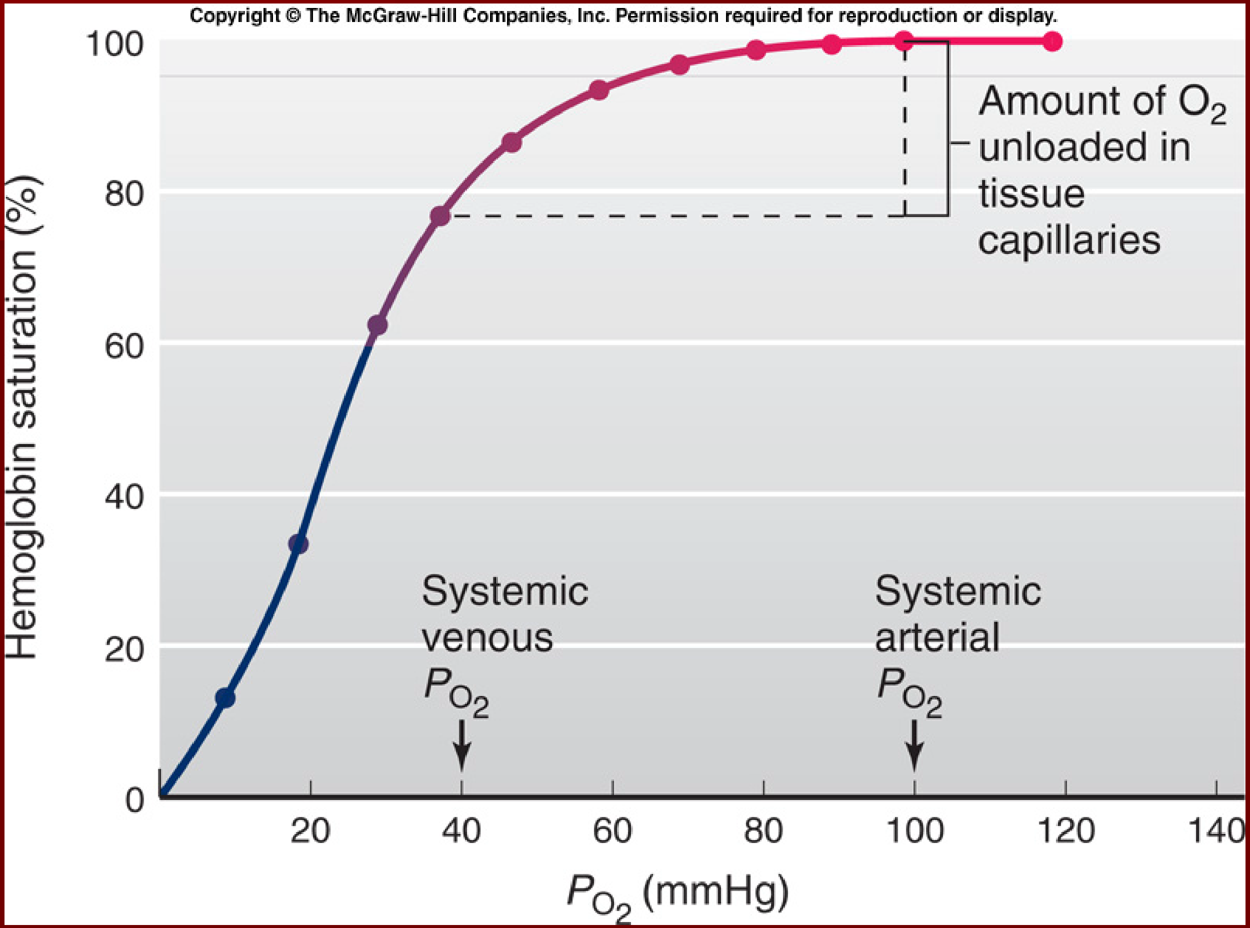
- CO competes for the O_2 sides in Hb
- CO has extremely high affinity for Hb
- Carboxyhemoglobin---20%-40%, fetal.
- A bright or cherry red coloration to the skin



Oxygen-hemoglobin dissociation curve

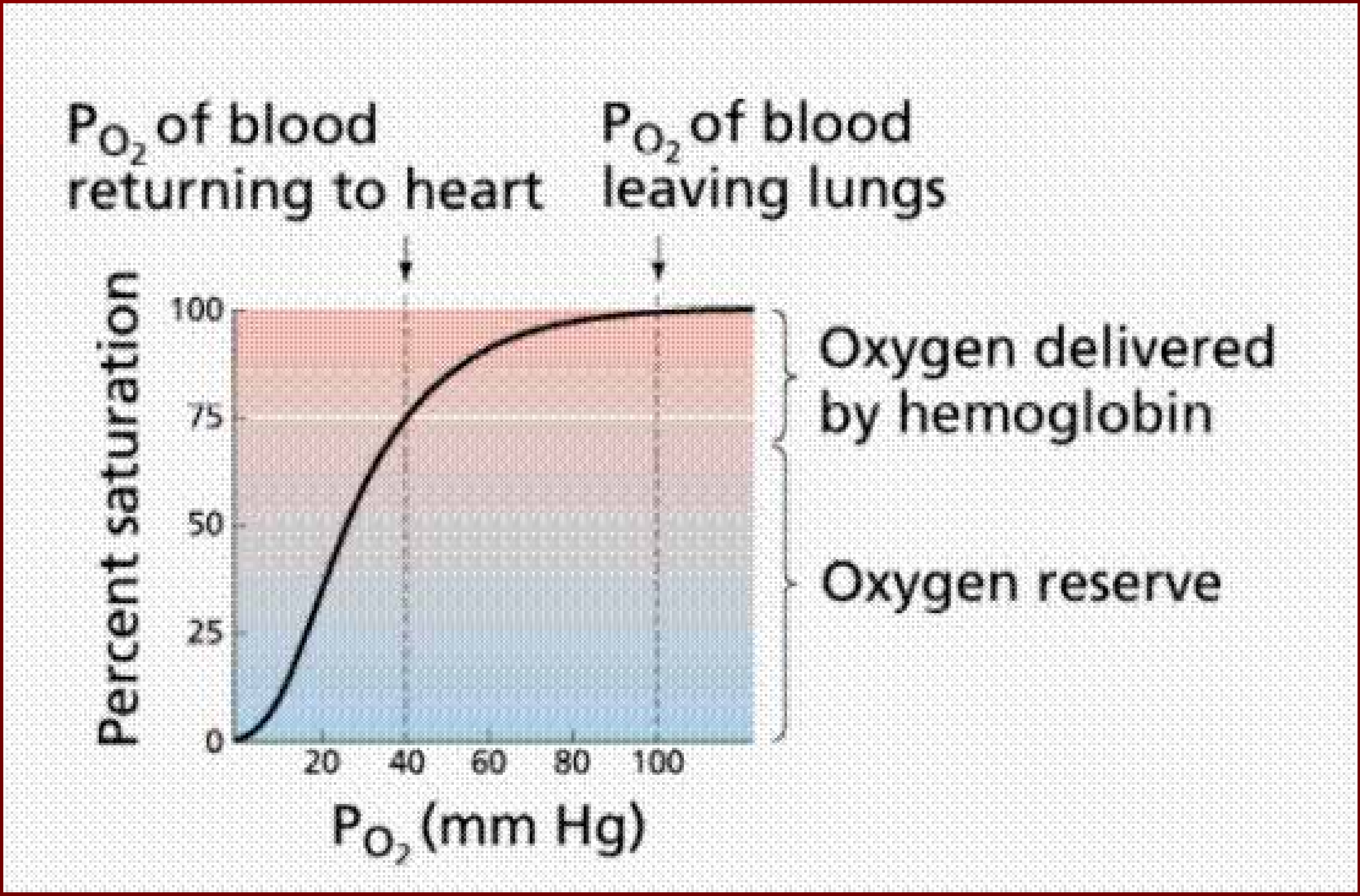
- The relationship between O_2 saturation of Hb and PO_2





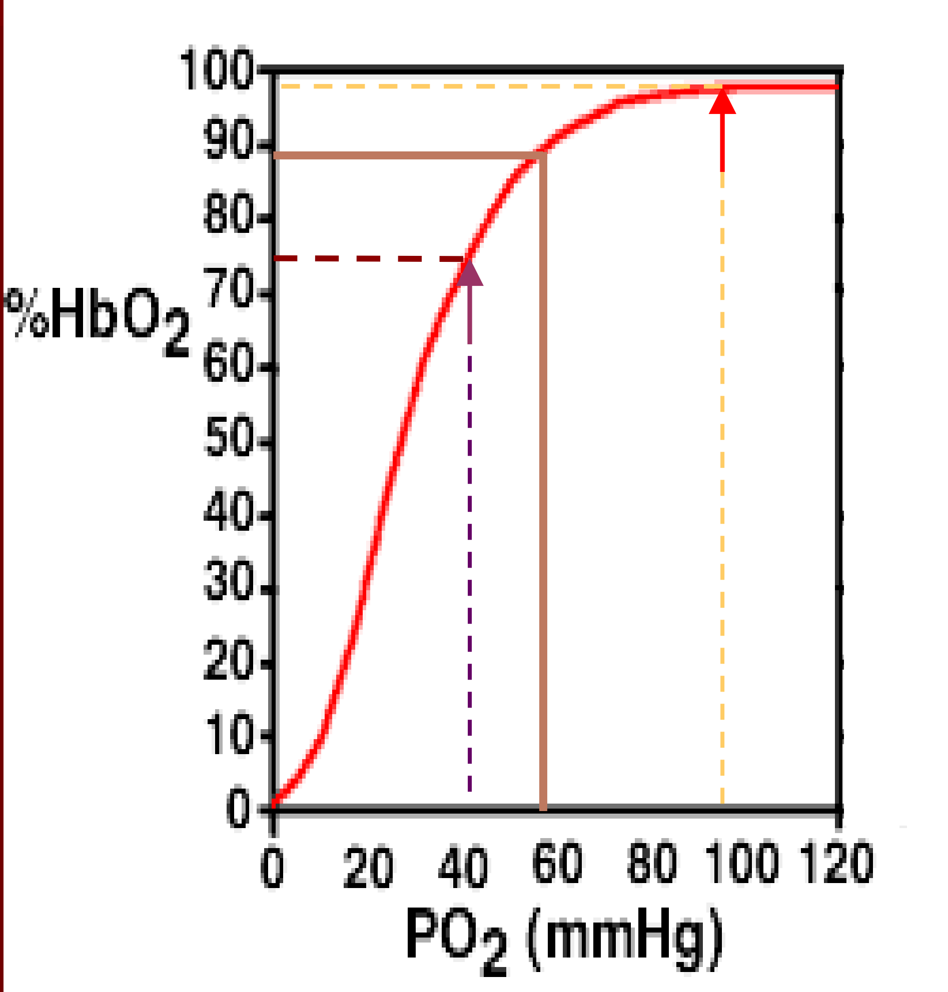
As the concentration of oxygen increases, the percentage of hemoglobin saturated with bound oxygen increases until all of the oxygen-binding sites are occupied (100% saturation).

Note that venous blood is typically 75% saturated with oxygen.


P_{O_2} of blood returning to heart
P_{O_2} of blood leaving lungs
100
75
50
25
0
20
40
60
80
100
Percent saturation
P_{O_2} (mm Hg)
Oxygen delivered by hemoglobin
Oxygen reserve

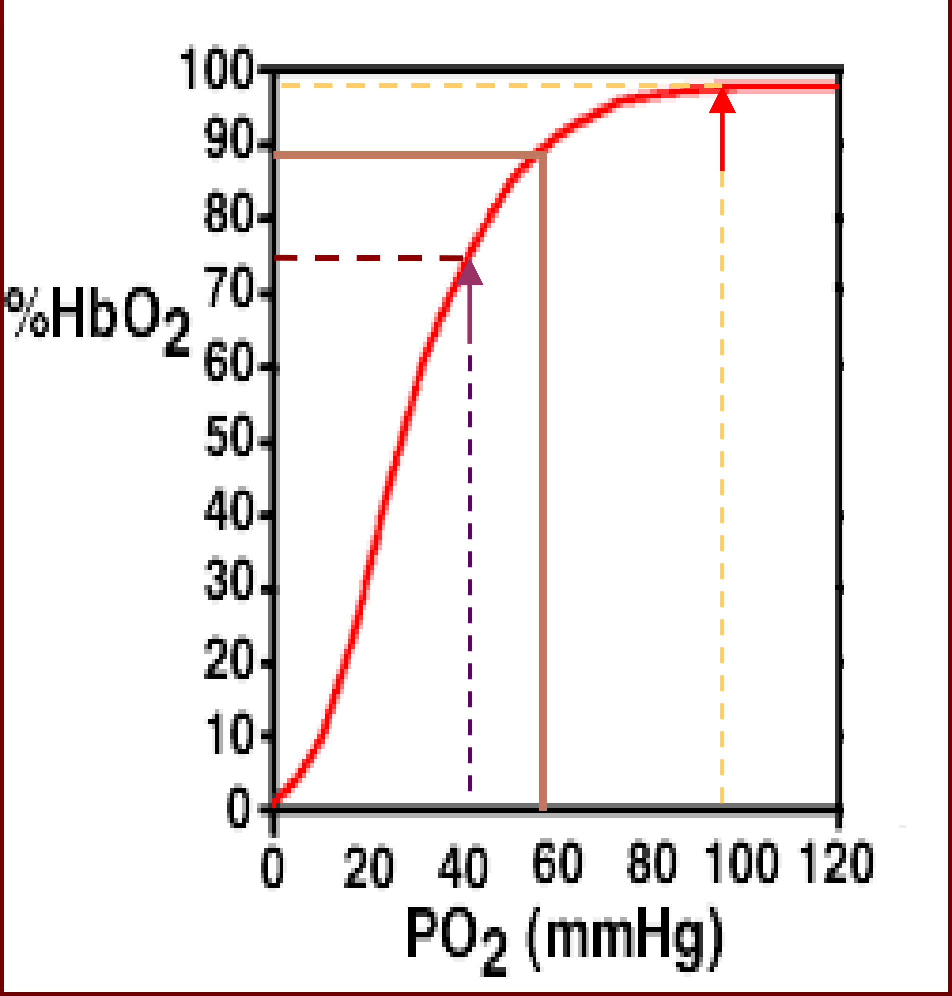
Oxygen dissociation curve

- PO_2 : 100～60mmHg
- The upper of the curve at higher PO_2 values suggests a moderate reduction in alveolar and therefore arterial PO_2, as in case of pulmonary disease or high altitude.



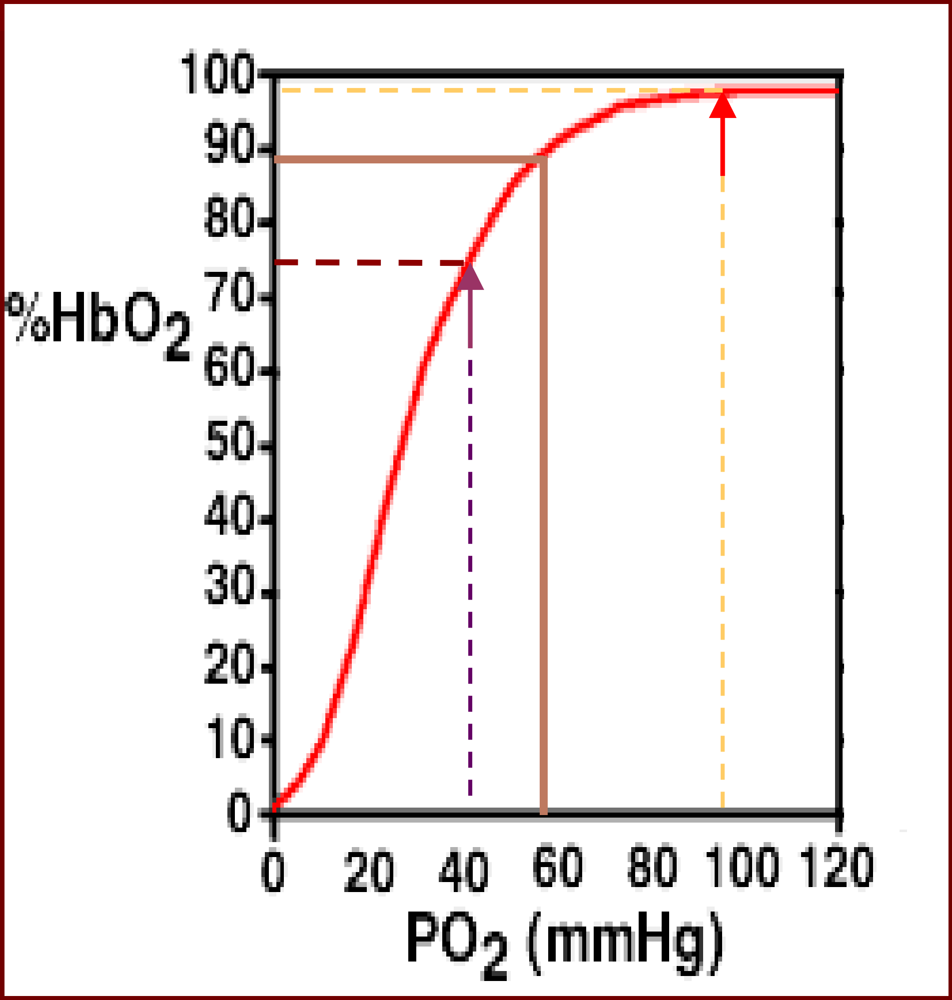
Oxygen dissociation curve

- PO_2 : 60～40mmHg
- The middle portion of the curve is ideal for unloading oxygen in the tissues, because any further decrease in PO_2 can result in a large amount of oxygen unloaded in the capillaries of the peripheral tissue.



Oxygen dissociation curve

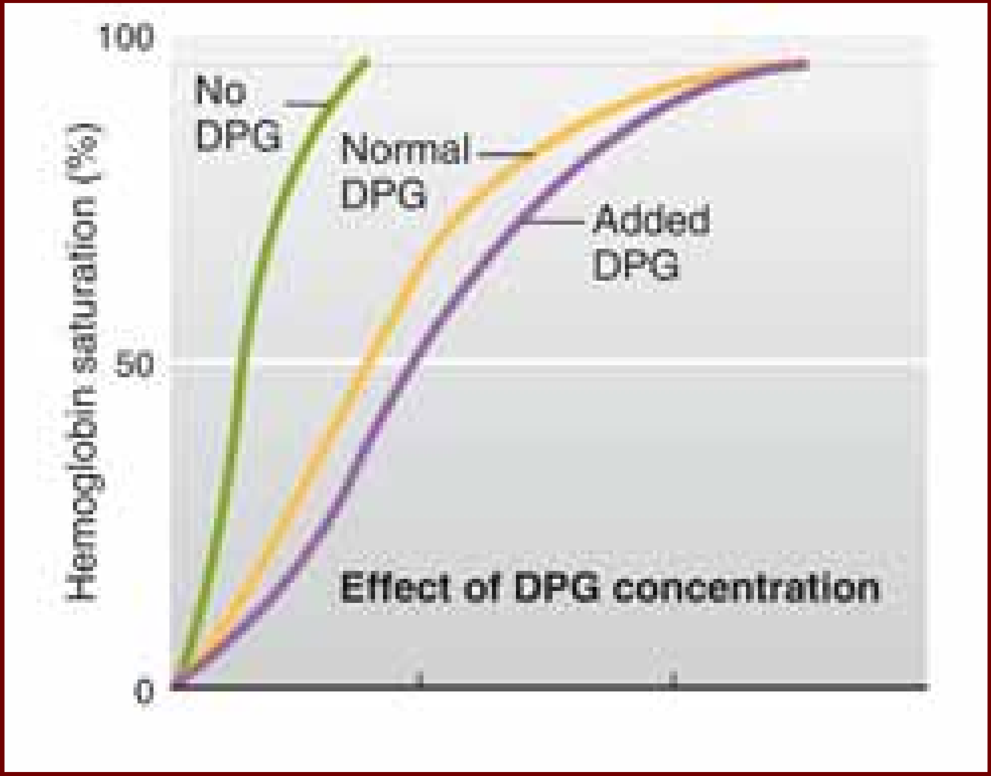
- PO_2：40～15mmHg
- The lower portion of the curve reflects the reserve of oxygen in the blood.



Factors that shift oxygen dissociation curve

- PCO_2 and $[H^+]$
- Temperature
- 2,3-diphosphoglycerate (DPG)

Chemical and thermal factors that alter hemoglobin's affinity to bind oxygen alter the ease of "loading" and "unloading" this gas in the lungs and near the active cells.



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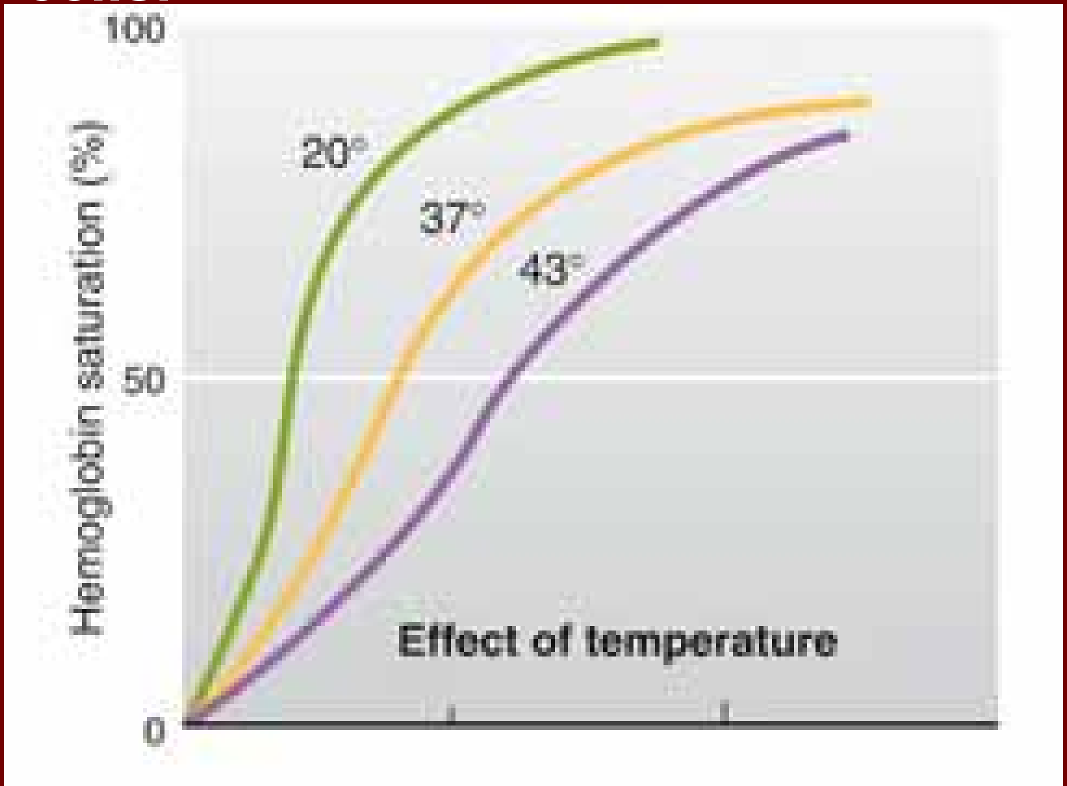
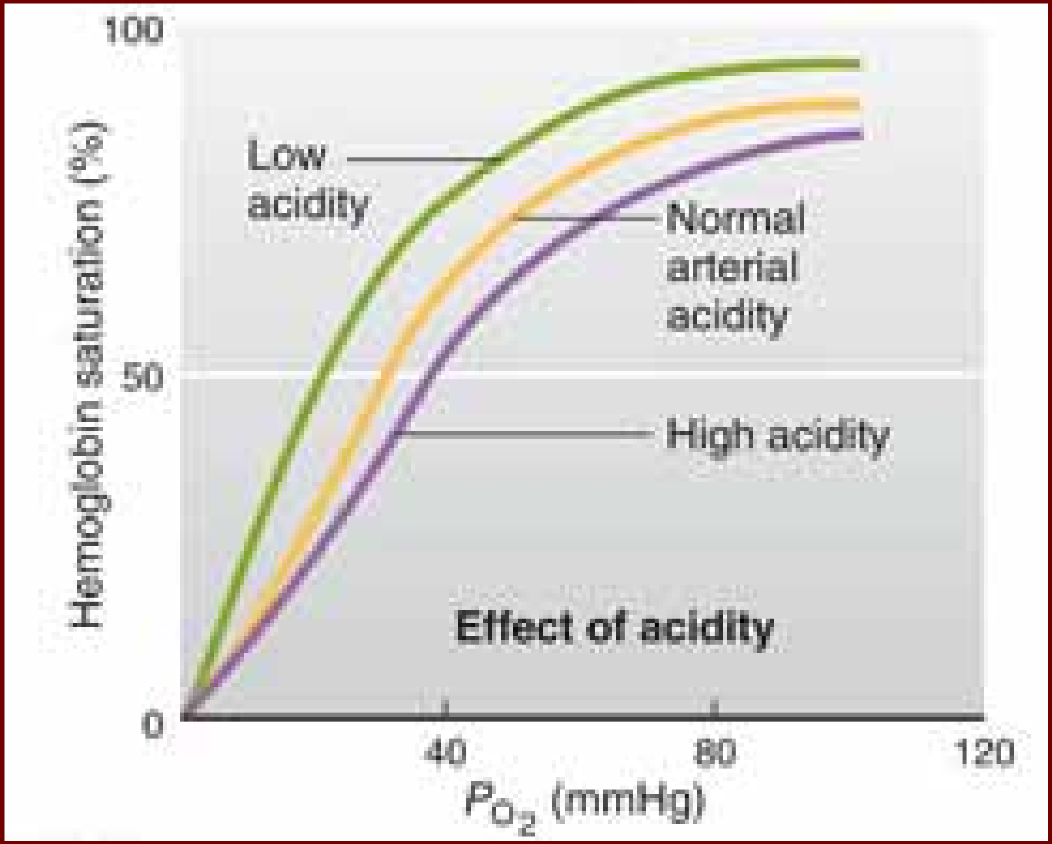




High acidity and low acidity can be caused by high PCO_2 and low PCO_2, respectively.

$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$

Oxygen Binding and Unloading

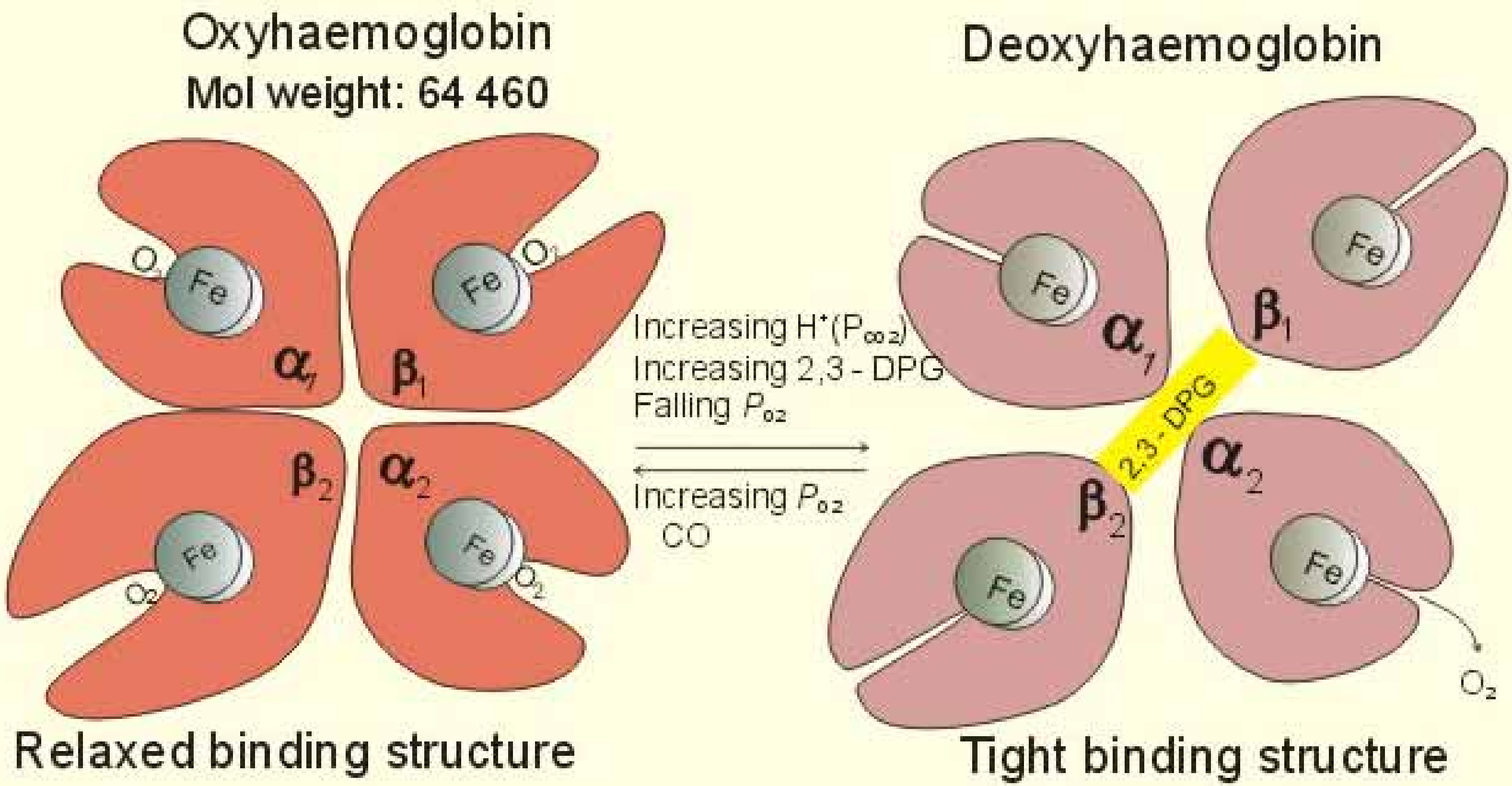


TABLE 13–9 *Effects of Various Factors on Hemoglobin*

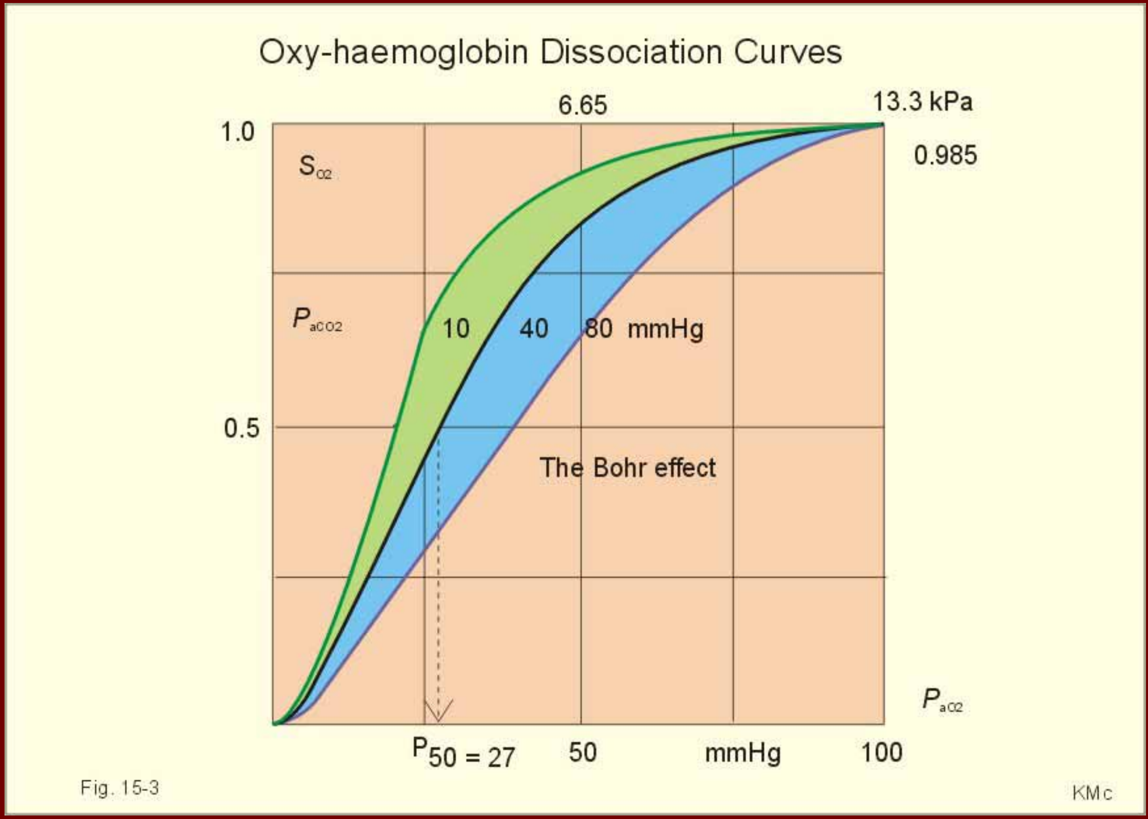
The affinity of hemoglobin for oxygen is decreased by:

1. Increased hydrogen ion concentration
2. Increased P_{CO_2}
3. Increased temperature
4. Increased DPG concentration

The affinity of hemoglobin for both hydrogen ions and carbon dioxide is decreased by increased P_{O_2}; that is, deoxyhemoglobin has a greater affinity for hydrogen ions and carbon dioxide than does oxyhemoglobin.

Bohr Effect

- Increased delivery of oxygen to the tissue when carbon dioxide and hydrogen ions shift the oxygen dissociation curve



Transport of carbon dioxide

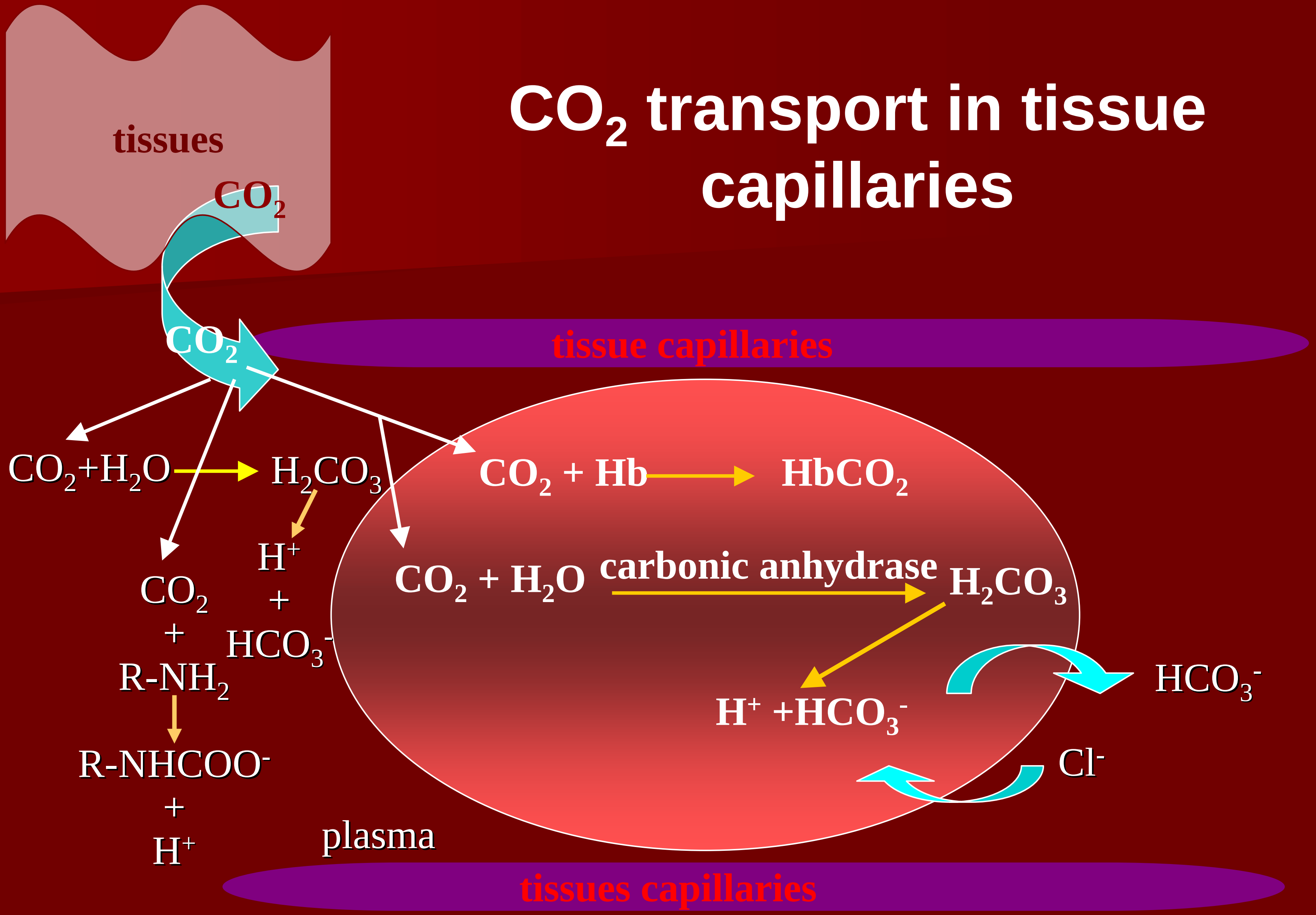
- Forms of carbon dioxide transported
  - Chemical combination: 93%
    - Bicarbonate ion: 70%
    - Carbamino hemoglobin: 23%
  - Physical dissolve: 7%

Total blood carbon dioxide

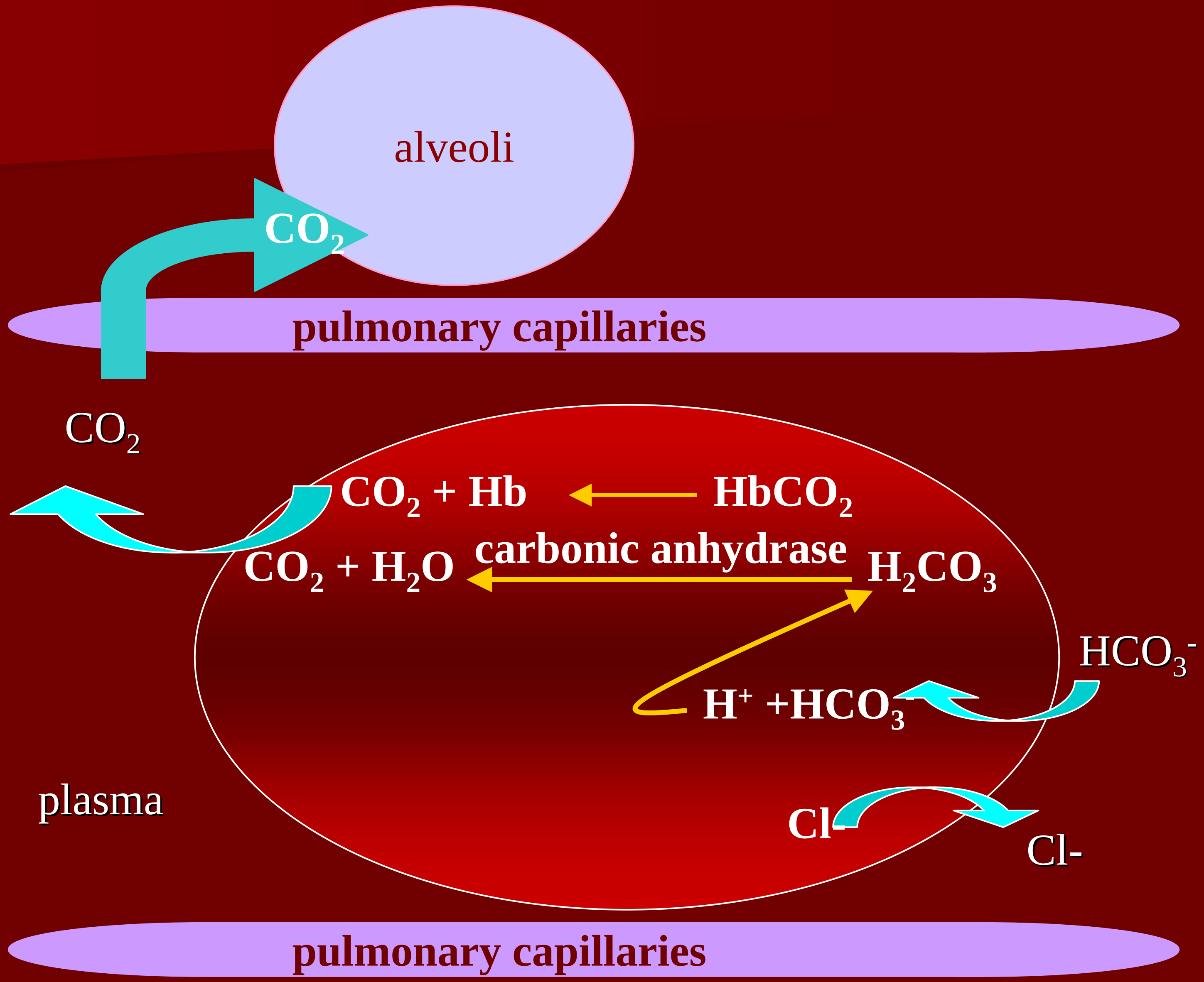
Sum of

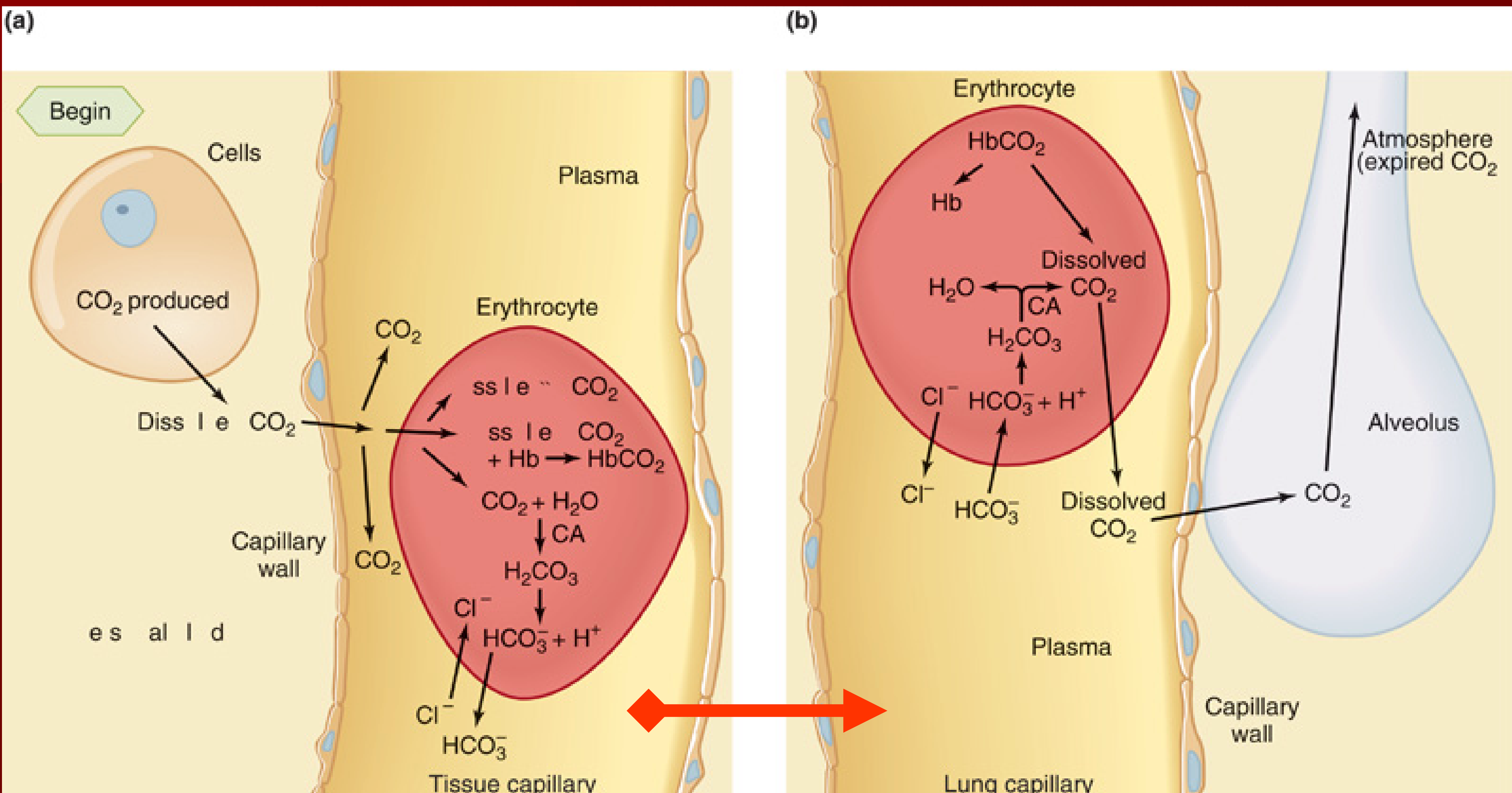
- Dissolved carbon dioxide
- Bicarbonate
- carbon dioxide in carbamino hemoglobin

CO_2 transport in tissue capillaries



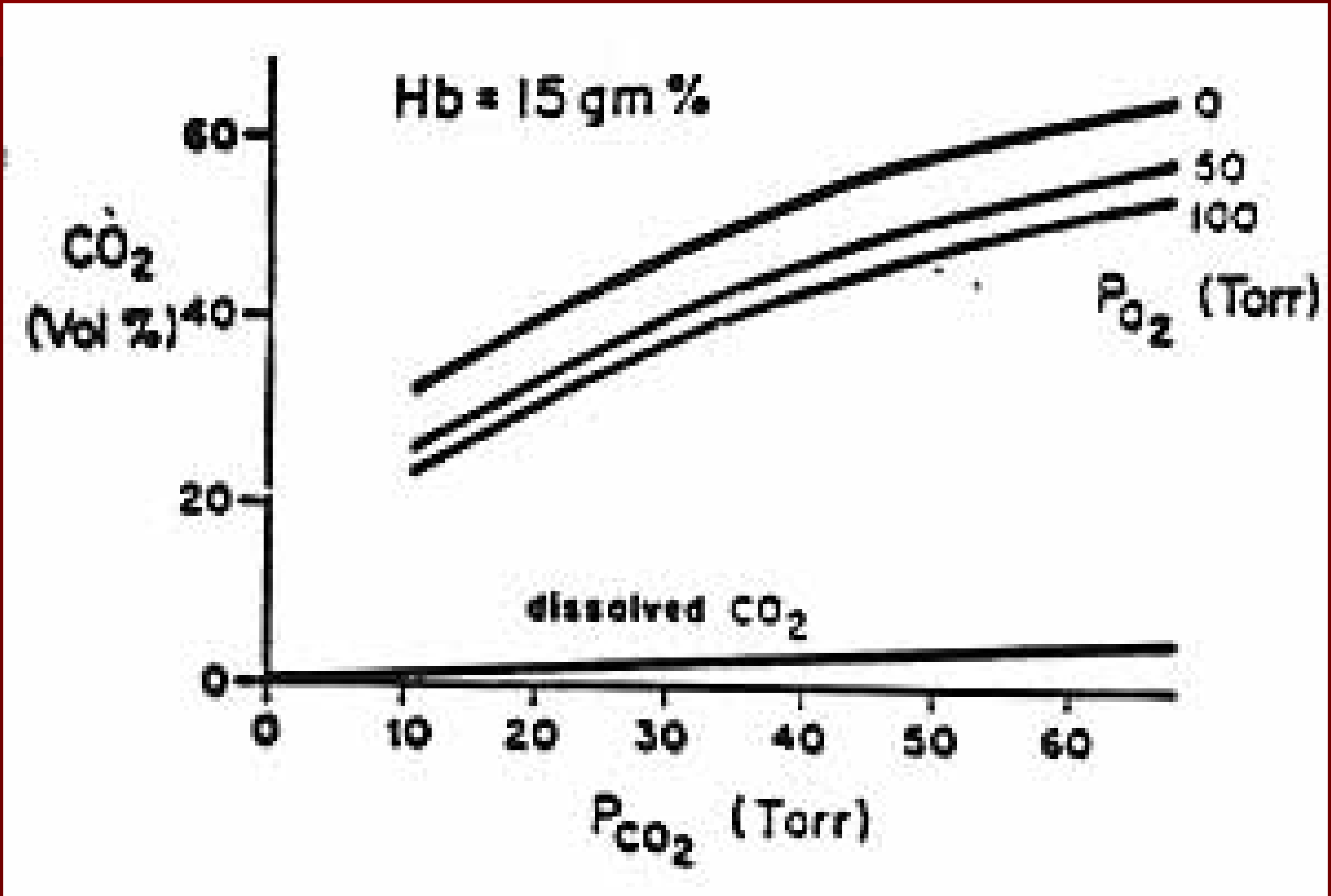
CO_2 transport in pulmonary capillaries





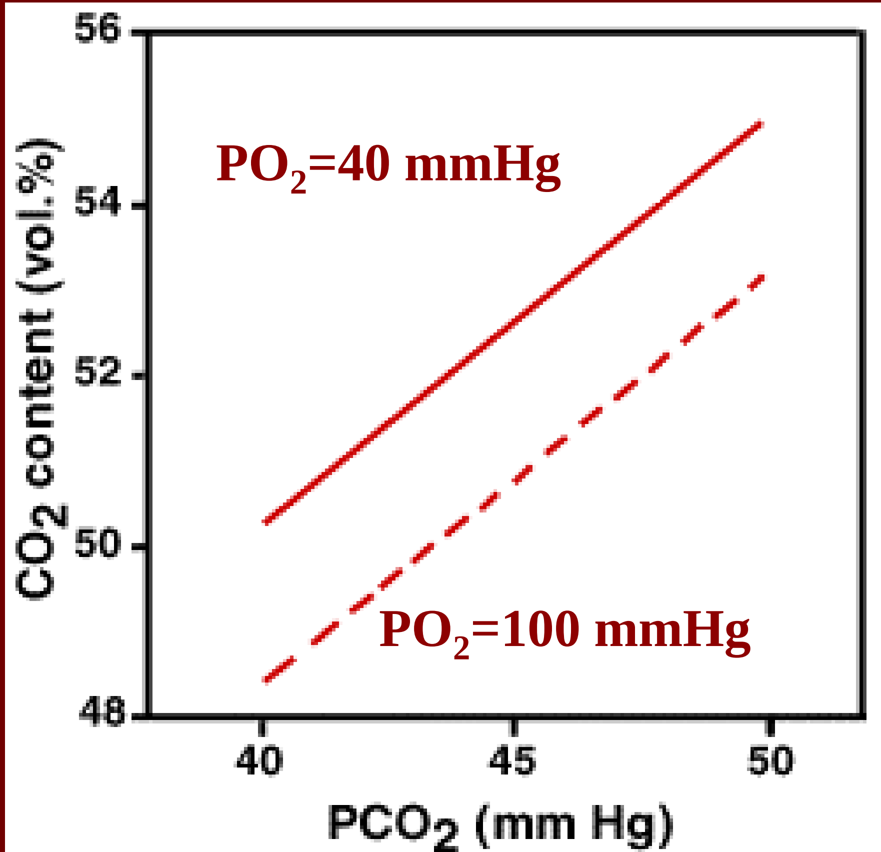
Summary of CO_2 movement

Carbon Dioxide Dissociation Curve



Haldane Effect

- When oxygen binds with hemoglobin, carbon dioxide is released



Bohr effect and Haldane effect

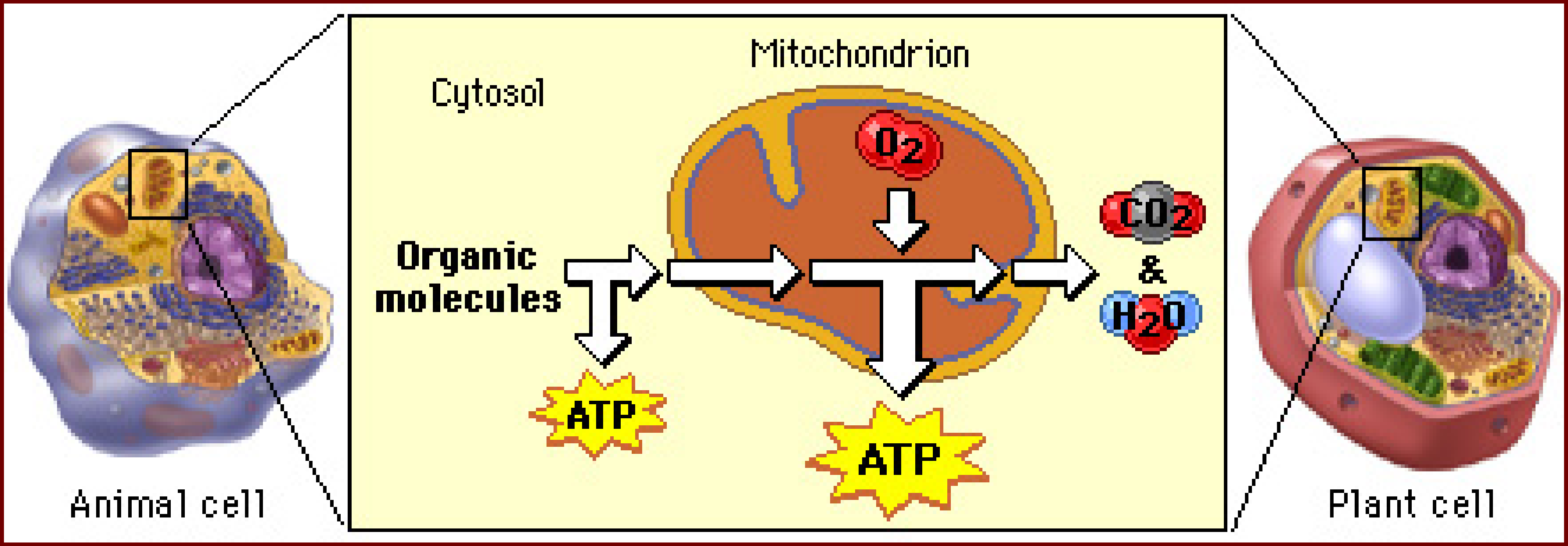
Bohr effect (tissue cells)

CO_2 and H^+ shift the oxygen dissociation curve

Haldane effect (lung)

When O_2 binds with Hb, CO_2 is released

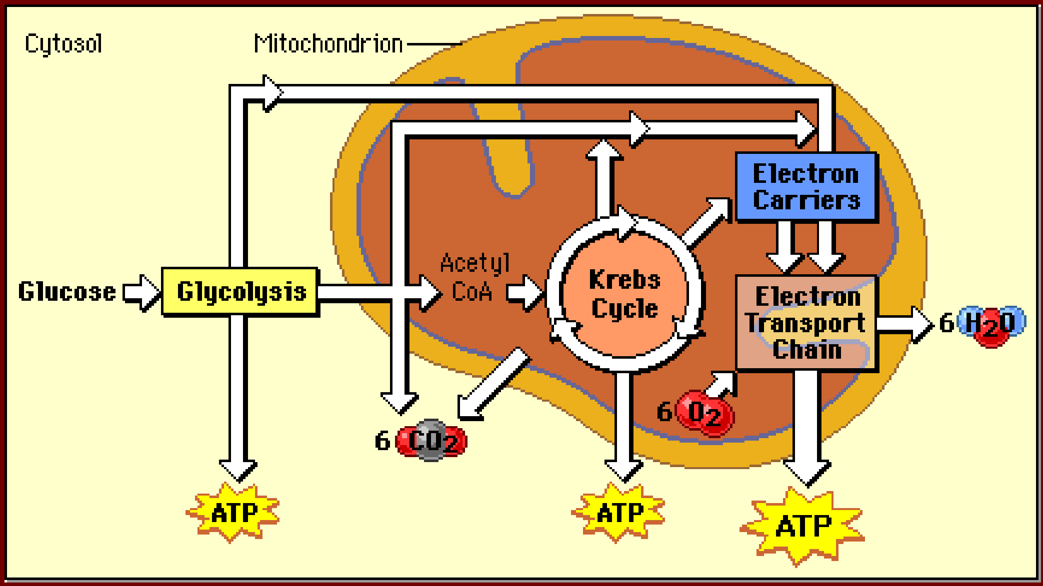
Cell Respiration



- Oxidation
- Glycolysis

Cell Respiration

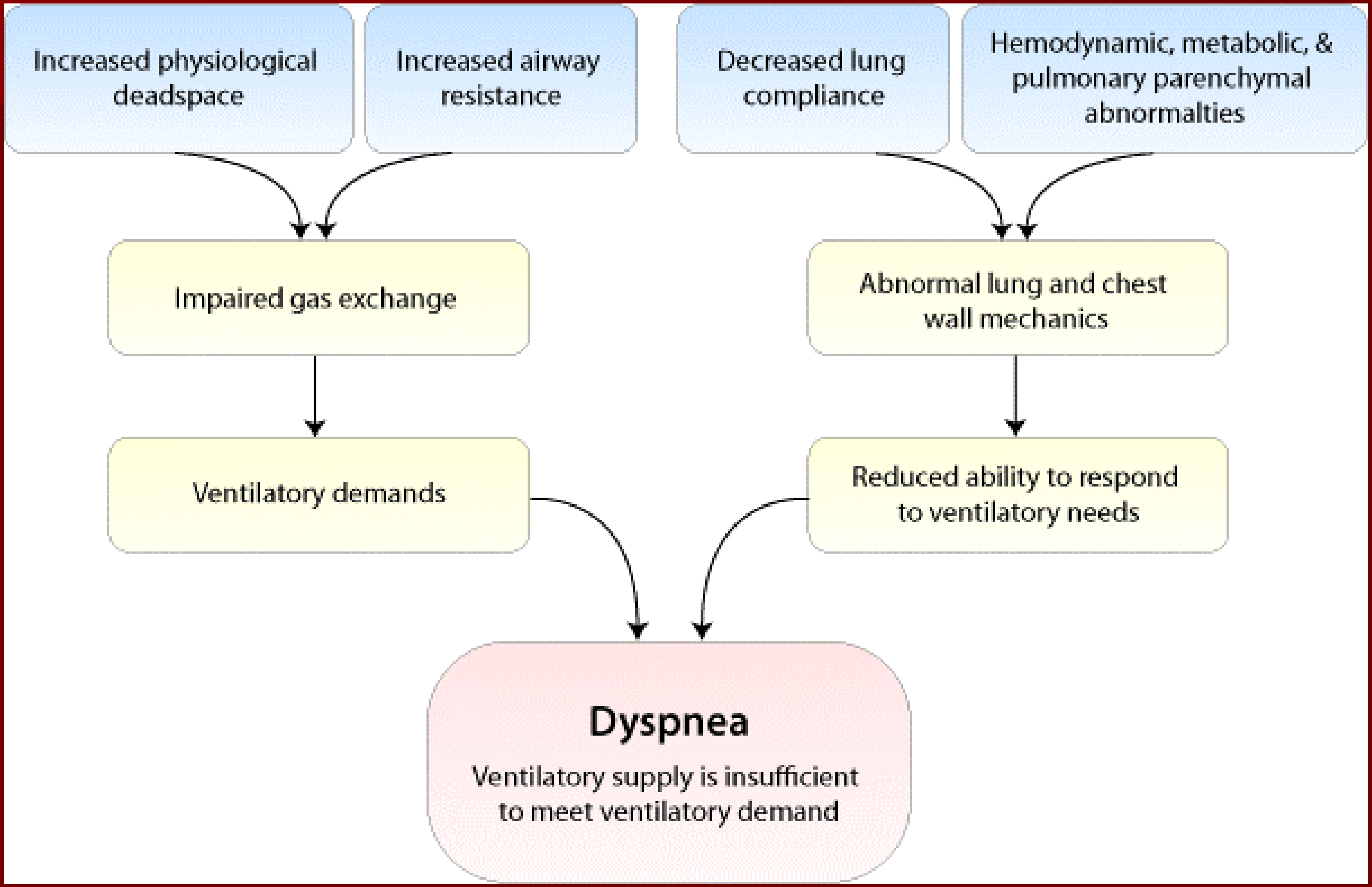
- Cellular respiration is the process by which the chemical energy of "food" molecules is released and partially captured in the form of ATP. Carbohydrates, fats, and proteins can all be used as fuels in cellular respiration, but glucose is most commonly used as an example to examine the reactions and pathways involved.



Dyspnea

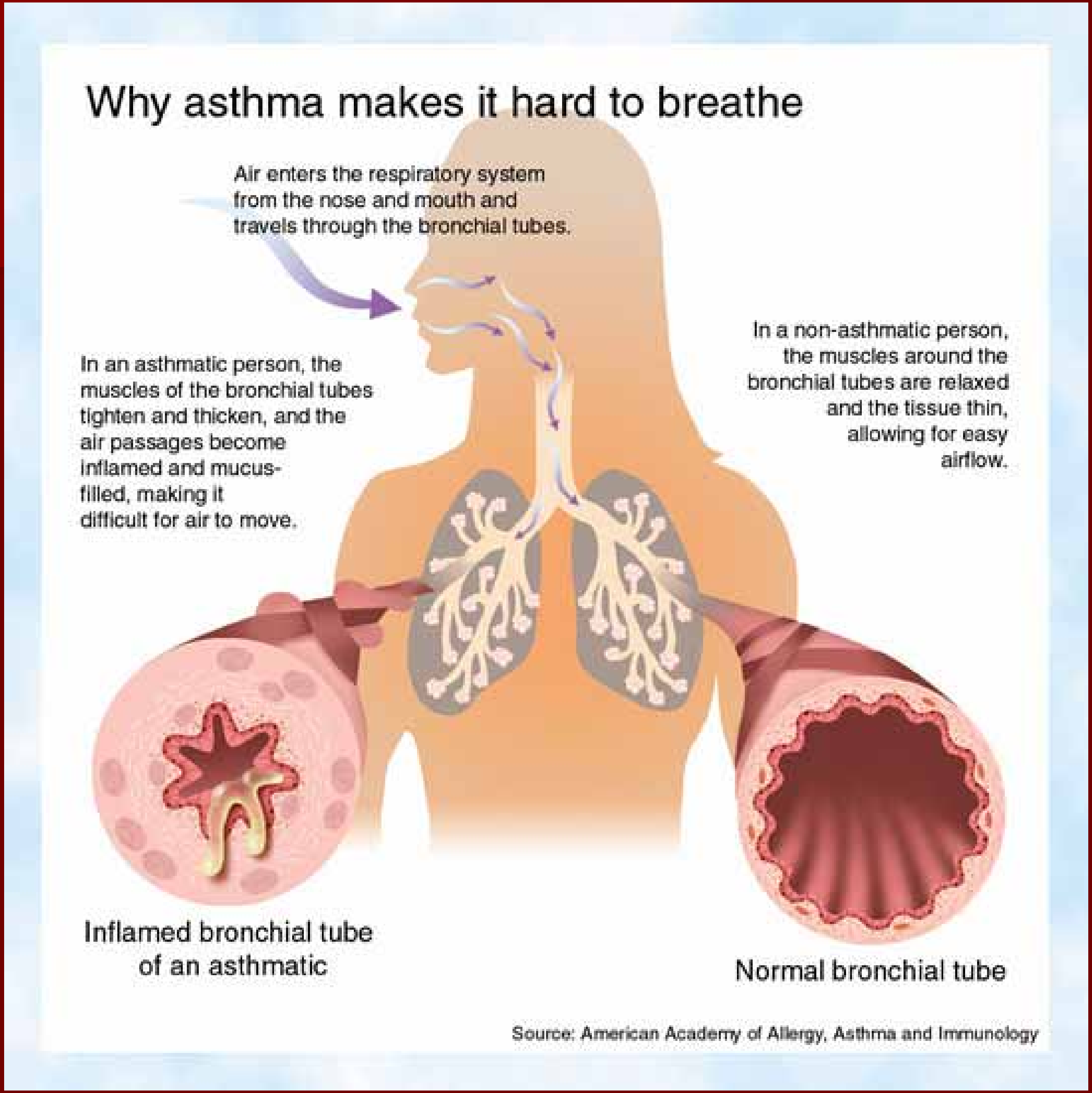
- Definition: Difficult or labored breathing; shortness of breath.
- Dyspnea is a sign of serious disease of the airway, lungs, or heart.

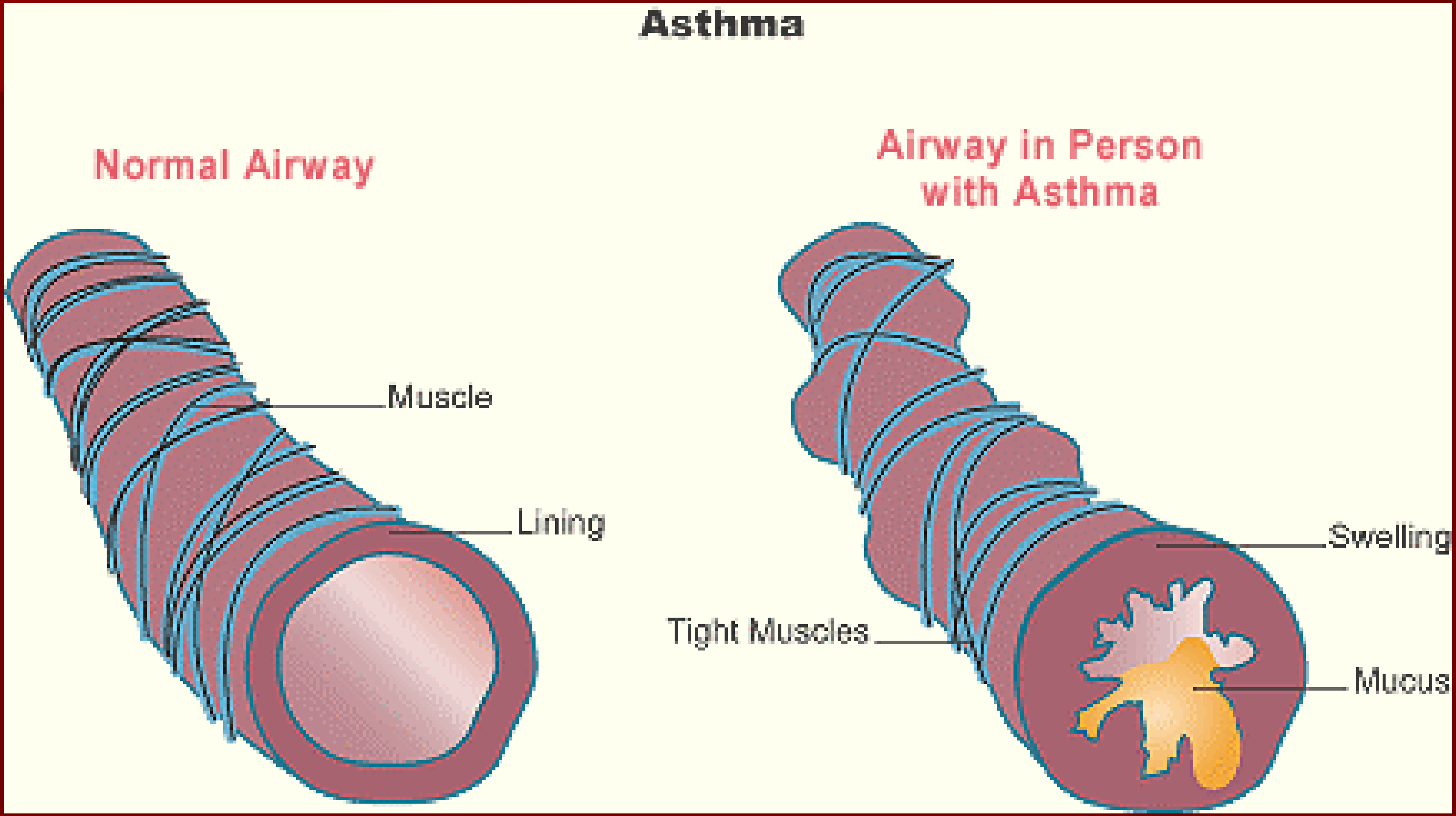
Mechanisms of Dyspnea



Asthma

- Asthma is a chronic disease that affects airways. If a person have asthma, the inside walls of airways are inflamed (swollen). The inflammation makes the airways very sensitive, and they tend to react strongly to things that the patient is allergic to or find irritating. When the airways react, they get narrower, and less air flows through to lung tissue.
- a whistling sound when one breathes
- coughing, chest tightness, and trouble breathing
- especially at night and in the early morning.

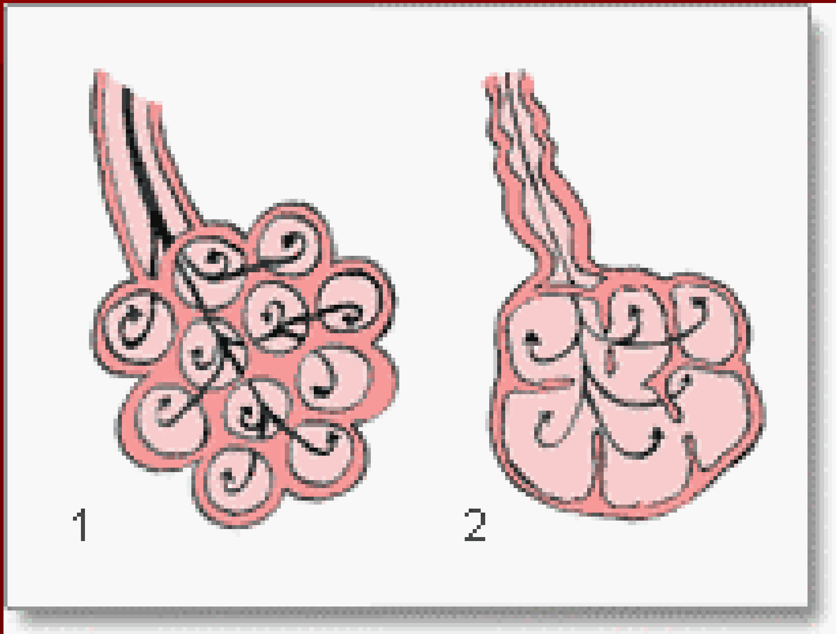

Why asthma makes it hard to breathe
Air enters the respiratory system from the nose and mouth and travels through the bronchial tubes.
In an asthmatic person, the muscles of the bronchial tubes tighten and thicken, and the air passages become inflamed and mucus-filled, making it difficult for air to move.
In a non-asthmatic person, the muscles around the bronchial tubes are relaxed and the tissue thin, allowing for easy airflow.
Inflamed bronchial tube of an asthmatic
Normal bronchial tube
Source: American Academy of Allergy, Asthma and Immunology


Asthma
Normal Airway
Muscle
Lining
Airway in Person with Asthma
Swelling
Tight Muscles
Mucus

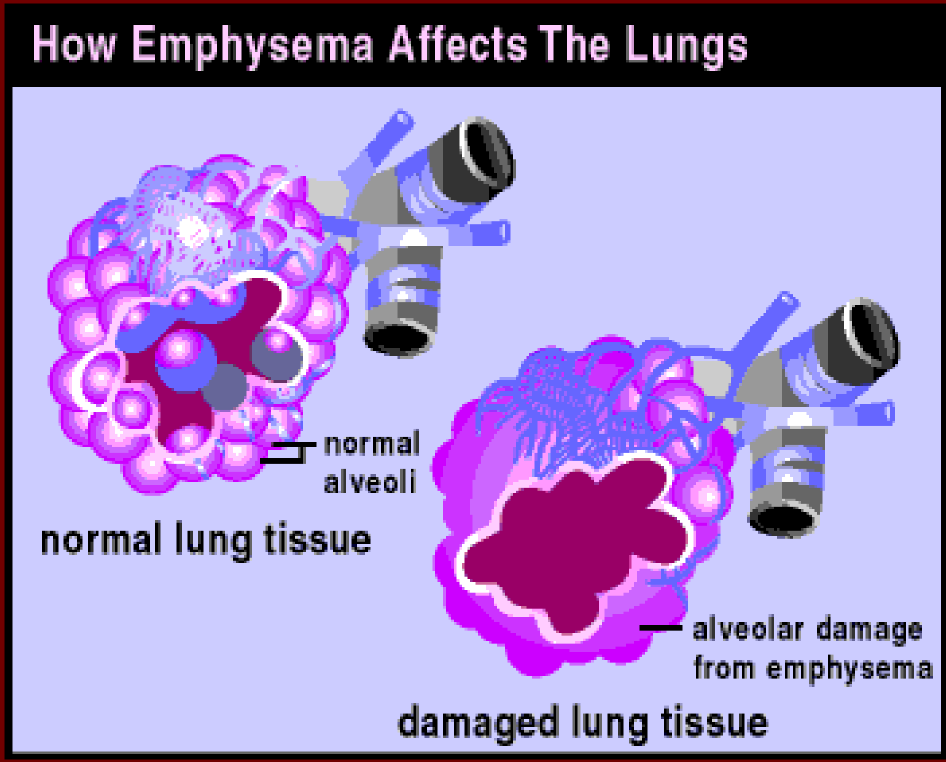
Emphysema

- Emphysema causes the walls of the alveoli to break down so that larger air spaces are formed.
- The effect is that the total surface area available for gas exchange is greatly reduced. This means that less oxygen gets into blood and there is a reduced supply of oxygenated blood to the muscles and vital organs. Also, the waste gas, carbon dioxide, is unable to pass from the blood back into the alveoli where it can be exhaled and, as a result, there is a rise in the amount of this gas in blood.

Emphysema

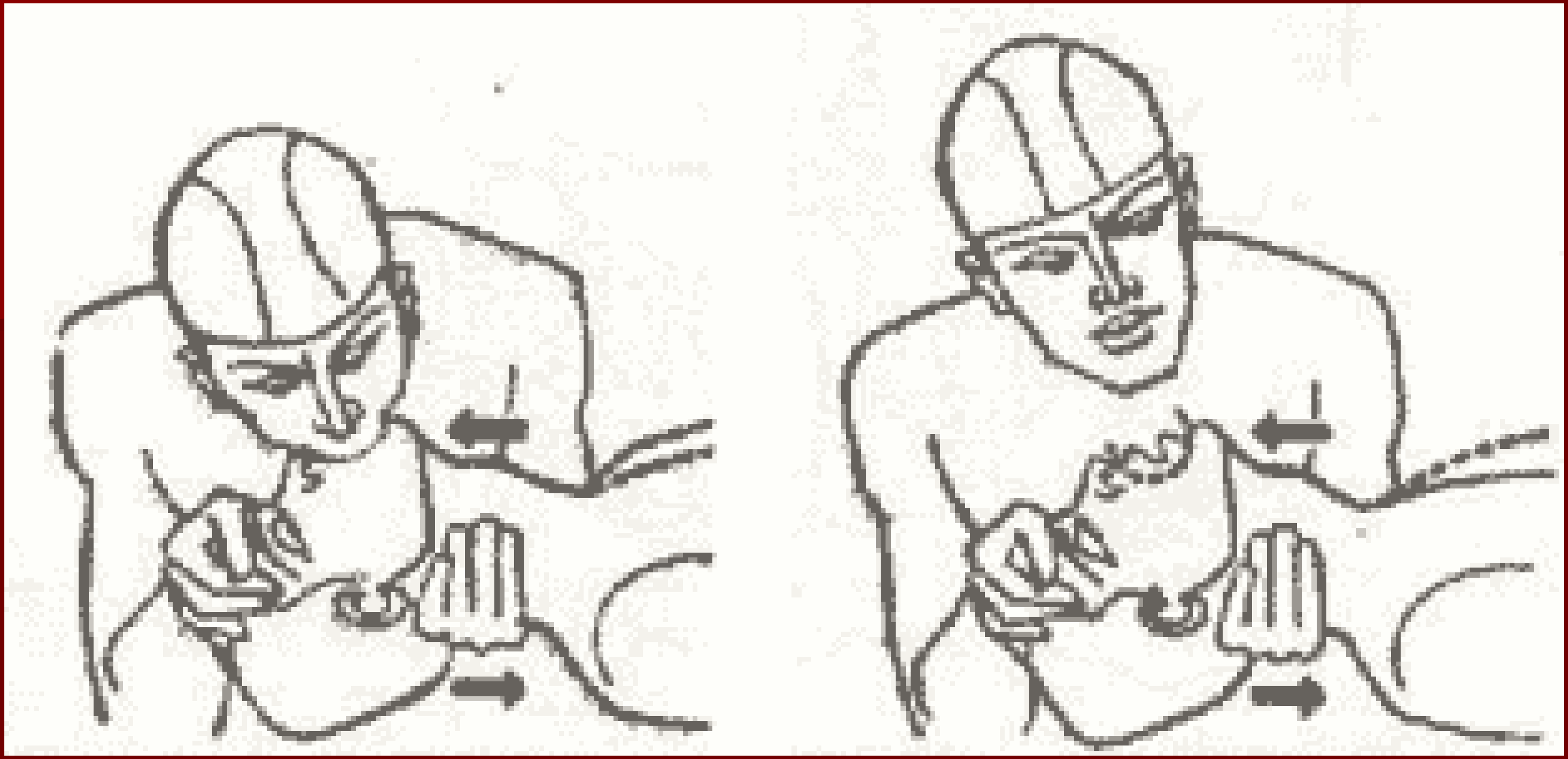


1. Healthy alveolus
2. Alveolus with emphysema



Artificial respiration

- A procedure used to restore or maintain respiration in a person who has stopped breathing. The method uses mechanical or manual means to force air into and out of the lungs in a rhythmic fashion.



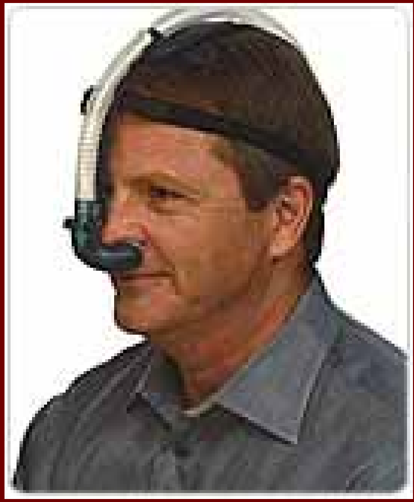
To perform rescue breathing, perform the following steps:

1. Check the mouth for obstructions, lift the neck and tilt the head back.
2. Pinch the nostrils and seal the mouth, and exhale directly into the victim's mouth.
3. Release the nostrils and the seal around the mouth.
4. Watch for the victim's chest to rise by itself.
5. Feel for a pulse on the victim's neck.
6. If the victim's chest does not start to rise on its own, repeat this process from number 1, until professional help arrives.

Therapeutic use of oxygen

- Supplemental or "extra" oxygen is one of the most widely used therapies for people admitted to the hospital. It is also frequently used for patients with chronic lung disease who live at home. In all cases oxygen is administered by inhalation. The importance of oxygen therapy for many patients with heart and lung diseases is now universally recognized.

O_2 therapy



Face mask

Mobile oxygen

Home oxygen concentrator