SEMESTER – IV

ZOO CC409 : Animal Physiology: Life Sustaining Systems, Unit 2

Diffusion and Transport of Respiratory Gases

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Learning objectives

The students will learn:

- Structure of respiratory membrane
- Characteristics of respiratory membrane
- Diffusion and transport of oxygen
- Diffusion and transport of carbon-di-oxide
- Chloride shift mechanism
- Haldane effect

- Diffusion of respiratory gases occurs through the respiratory membrane.
- This “air-blood barrier” (the respiratory membrane) is where gas exchange occurs via passive diffusion
  - oxyygen diffuses from air in alveolus (singular of alveoli) to blood in capillary

– Carbon dioxide diffuses from the blood in

the capillary into the air in

the alveolus

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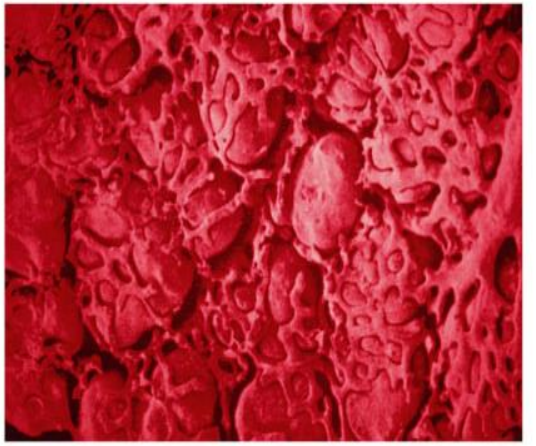


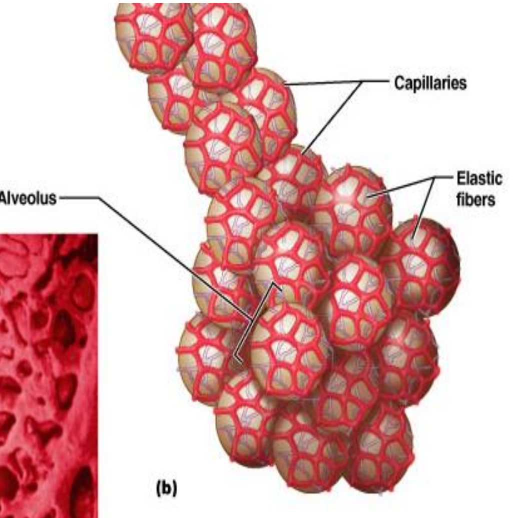
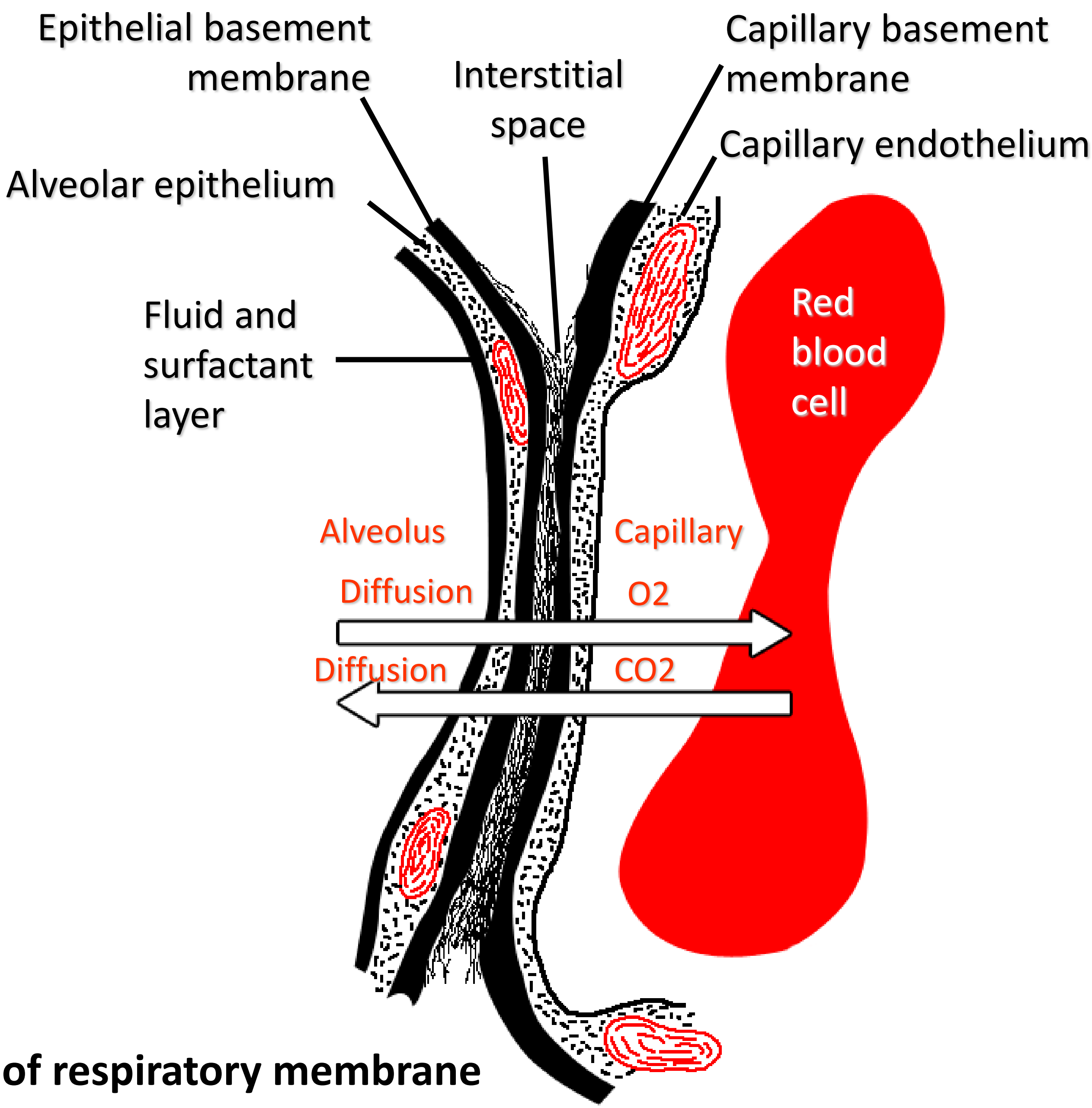


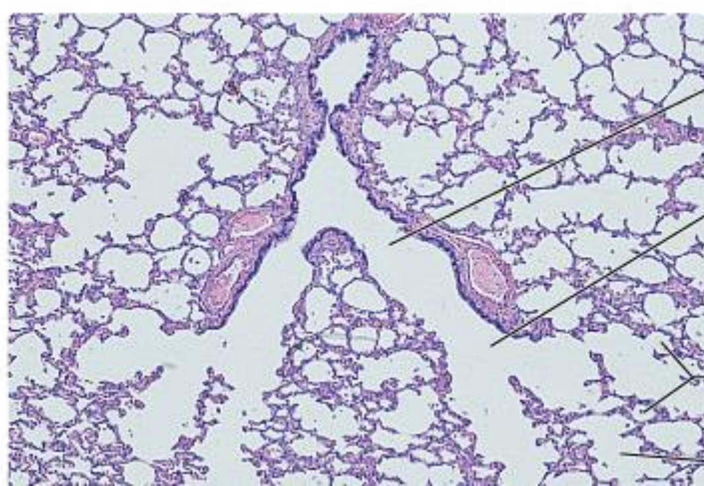
Fig: Respiratory Gas exchange area



Structure of respiratory membrane

Features of Respiratory membrane

- Thickness = 0.6um (15 X thinner than tissue paper)
- Air filled alveoli account for most of the lung volume
- Very great area for gas exchange =50-100 sqm
- Quantity of blood in the lung capillaries=60-140ml



Features of Respiratory membrane

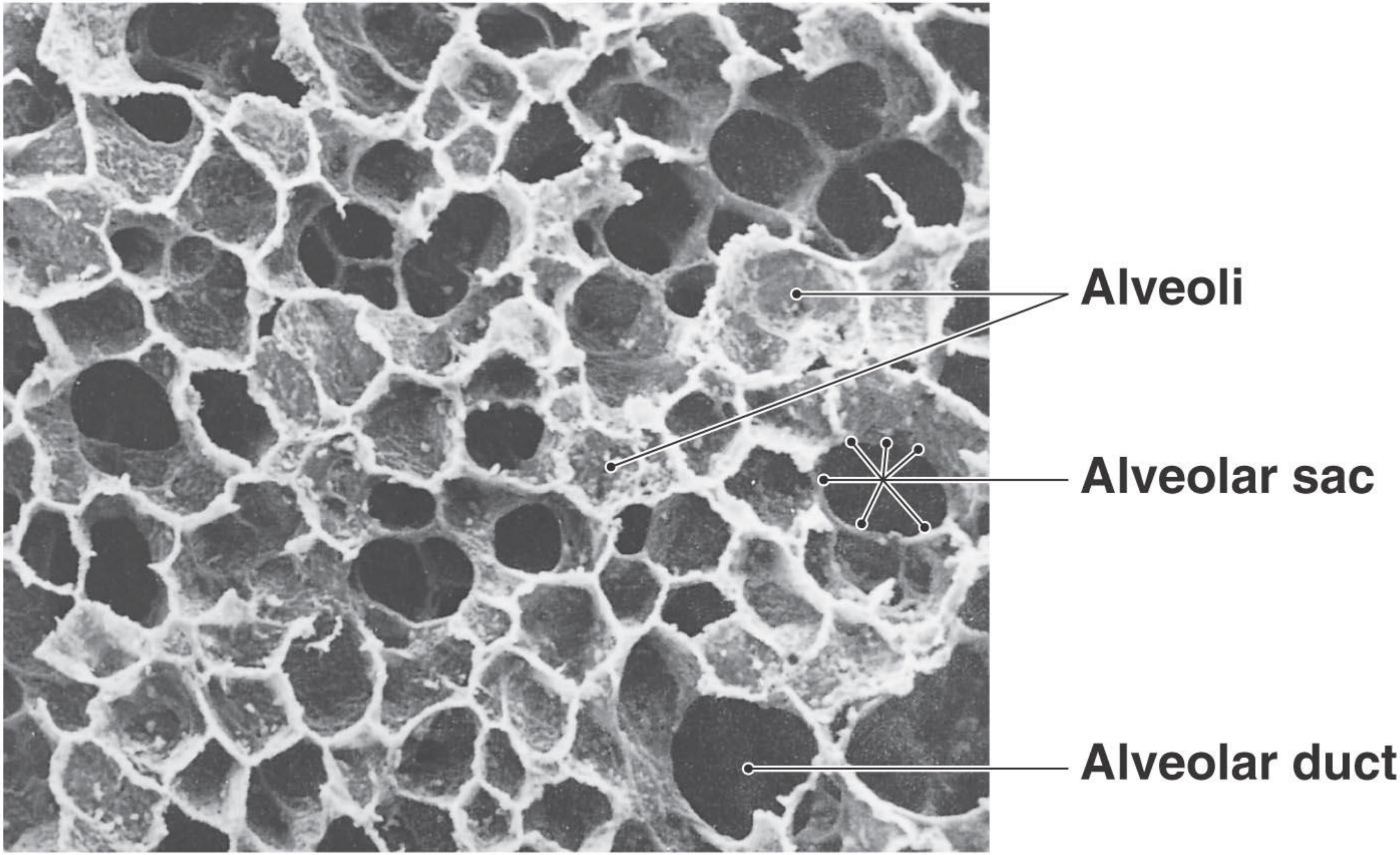
- Average diameter of pulmonary capillary=5um
- RBC size=7.5um (can squeeze through pulmonary capillary)
- Respiratory gases are highly soluble in lipids and thus in cell membrane and thus can easily pass through respiratory membrane
- All the above mentioned features facilitate rapid gaseous exchange across the respiratory membrane

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

1. **The thickness of the respiratory membrane 0.6 µm. The thickness of the respiratory membrane is inversely proportional to the rate of diffusion through the membrane. Lung fibrosis**
2. **Surface area of the membrane 50-100 sq m. Removal of an entire lung decreases the surface area to half normal. In emphysema with dissolution of the alveolar wall → ↓ S.A. to 5-folds because of loss of the alveolar walls.**

3. **The diffusion rate of the specific gas. Diffusion coefficient for the transfer of each gas through the respiratory membrane depends on its solubility in the membrane and inversely on the square root of its molecular weight. CO_2 diffuses 20 times as rapidly as O_2.**

4. **The pressure difference between the two sides of the membrane (between the alveoli and in the blood). The alveolar pressure represents a measure of the total number of molecules of a particular gas striking a unit area of the alveolar surface of the membrane in unit time. 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, but 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**

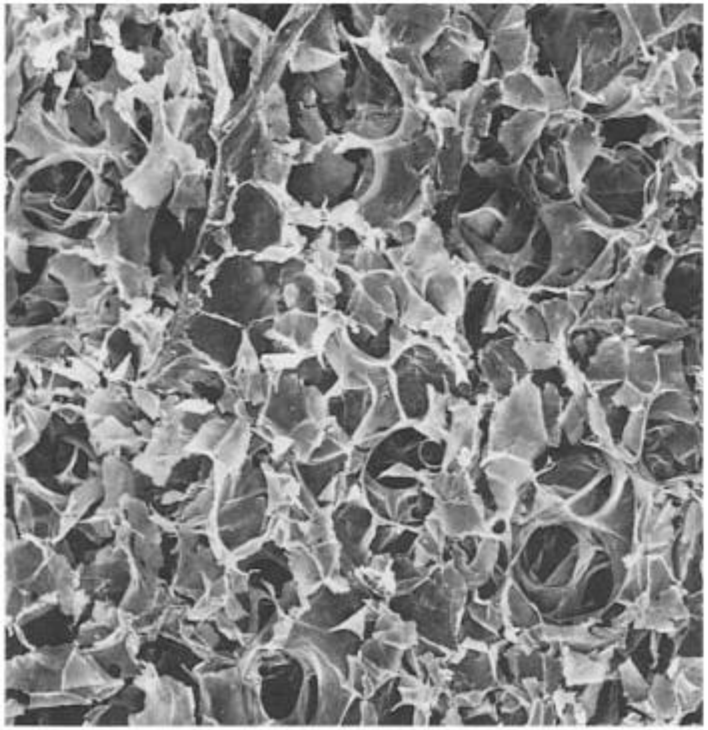


(b) SEM of lung alveoli

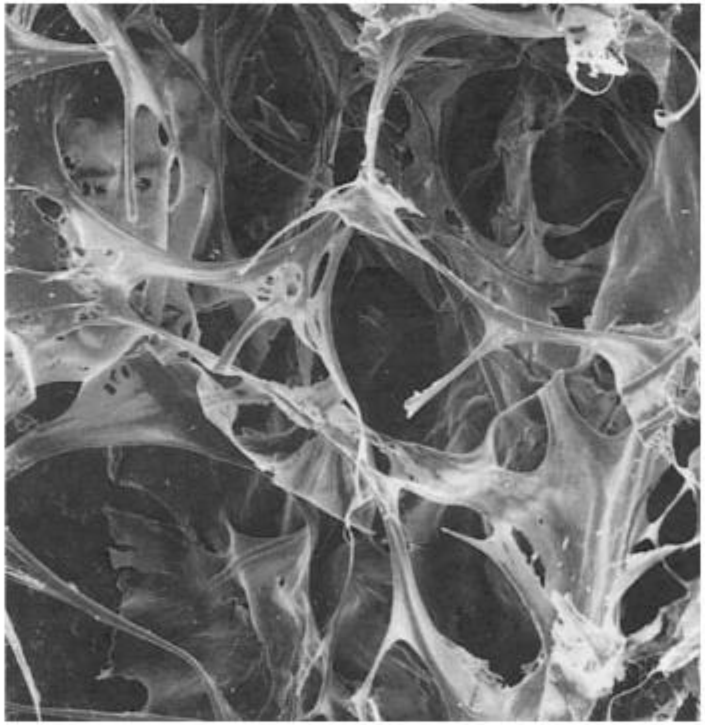
- There are many diseases of the respiratory system, including asthma, cystic fibrosis, COPD (chronic obstructive pulmonary disease – with chronic bronchitis and/or emphysema) and epiglottitis

example:

normal



emphysema



Relative Diffusion Coefficients

- These coefficients represent how readily a particular gas will diffuse across the respiratory membrane & is $\propto$ to its solubility and $1/\propto$ to sq. rt of MW.
  - O_2 1.0
  - CO_2 20.3
  - CO 0.81
  - N_2 0.53
  - He 0.95

Transport of O_2 & CO_2

- Oxygen- 5 ml/dl carried from lungs to tissue
  - Dissolved-3%
  - Bound to hemoglobin-97%
    - Hb increases O_2 carrying capacity 30-100 fold
- Carbon Dioxide- 4 ml/dl from tissue to lungs
  - Dissolved-7%
  - Bound to hemoglobin (and other proteins)-23%
  - Bicarbonate ion-70%

Respiratory Physiology

- Dalton's Law
  - Law of Partial Pressures
    - "each gas in a mixture of gases will exert a pressure independent of other gases present"

      Or
    - The total pressure of a mixture of gases is equal to the sum of the individual gas pressures.
  - Therefore,
    - If we know the total atmospheric pressure (760 mm Hg) and the relative abundances of gases (% of gases)
      - We can calculate individual gas effects!
      - P_{atm} x % of gas in atmosphere = Partial pressure of any atmospheric gas
        - » P_{O_2} = 760mmHg x 21% (.21) = **159 mm Hg**
    - Now that we know the partial pressures we know the gradients that will drive diffusion!

Partial pressure of O_2 and CO_2

- Atmosphere: PO_2=159 mmHg
  PCO_2=0.3 mmHg
- Alveolar air : PO_2=104 mmHg
  PCO_2=40 mmHg
- Arterial blood: PO_2=95mmHg
  PCO_2=40 mmHg
- Venous blood: PO_2= 40 mmHg
  PCO_2= 45 mmHg
- Tissues/cells: PO_2= 40 mmHg
  PCO_2= 45 mmHg

Vapor Pressure of H_2O

- The pressure that is exerted by the H_2O molecules to escape from the liquid to air
- Due to molecular motion
- Proportional to temperature
- At body temperature (37^{o}C) the vapor Pressure of H_2O is 47 mmHg. This vapor pressure dilutes all the gases in the inspired air.
- Humidification of the air reduces the PO_2 from 159 mmHg in atm air to 149 mmHg in the humidified air (i.e. in the respiratory tract).

Alveolar gas concentrations

Because of continuous diffusion of O_2 in the gas exchange area from the alveoli to the pulmonary blood

PO_2 reduces to 104 mmHg

- PO_2 in the alveoli averages 104 mmHg
- PCO_2 in the alveoli averages 40 mmHg

Uptake of O_2 by pulmonary blood

- Atmospheric PO_2 = 159 mmHg
- PO_2 in Respiratory tract = 149 mm Hg
- Alveolar PO_2 =104 mmHg

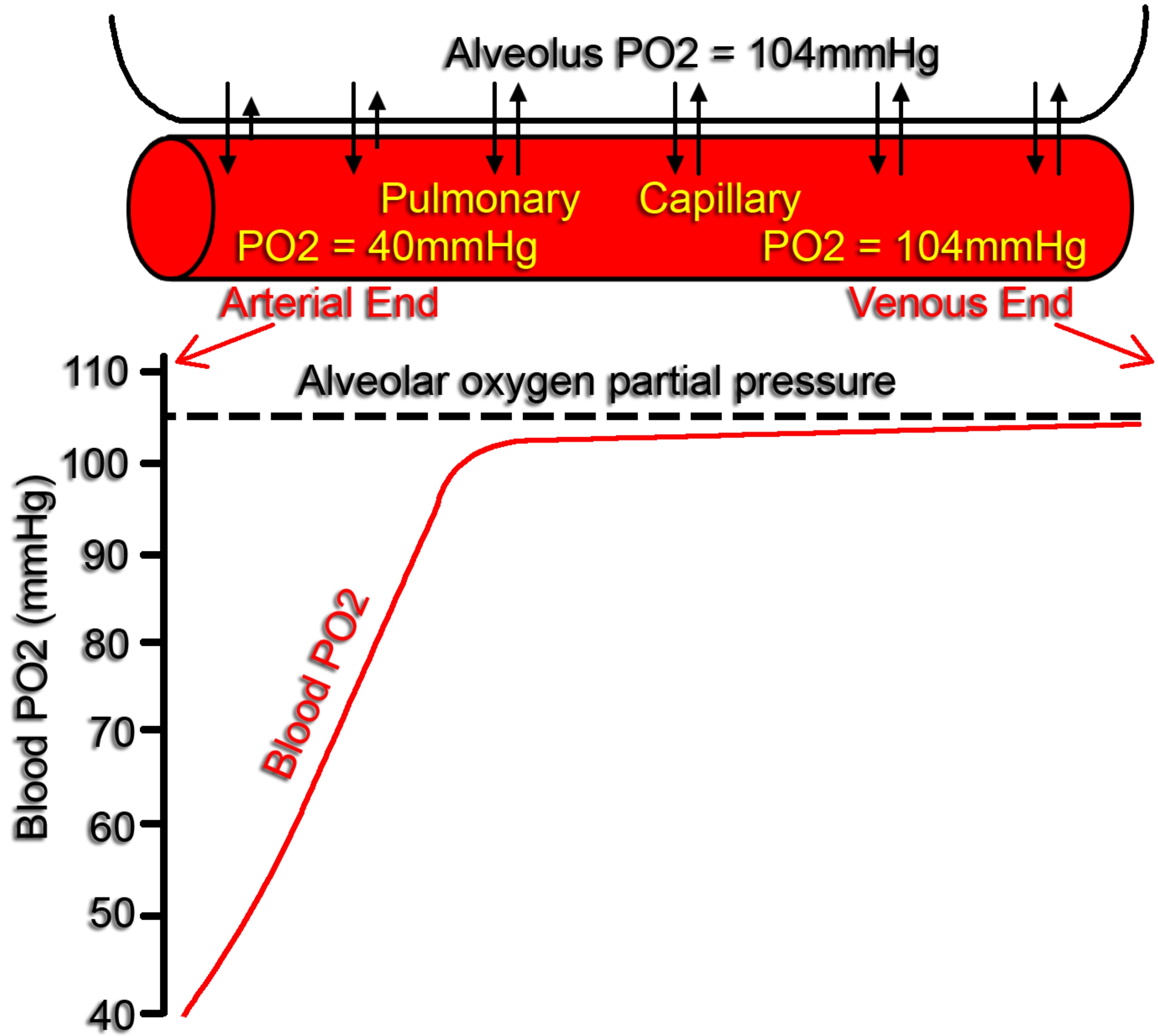
PO_2 in pulmonary venous blood = 40 mmHg

A press difference of = 64 mmHg

allows O_2 to diffuse from alveoli to pulmonary blood. PO_2 of pulmonary blood rises progressively to 104 mmHg

- 98% of blood coming to LA is fully oxygenated but 2% of blood has passed through dead space area and is not oxygenated. This blood has PO_2=40 mmHg.
- This venous admixture of blood has PO_2=95 mmHg and is pumped by LV into systemic aorta.

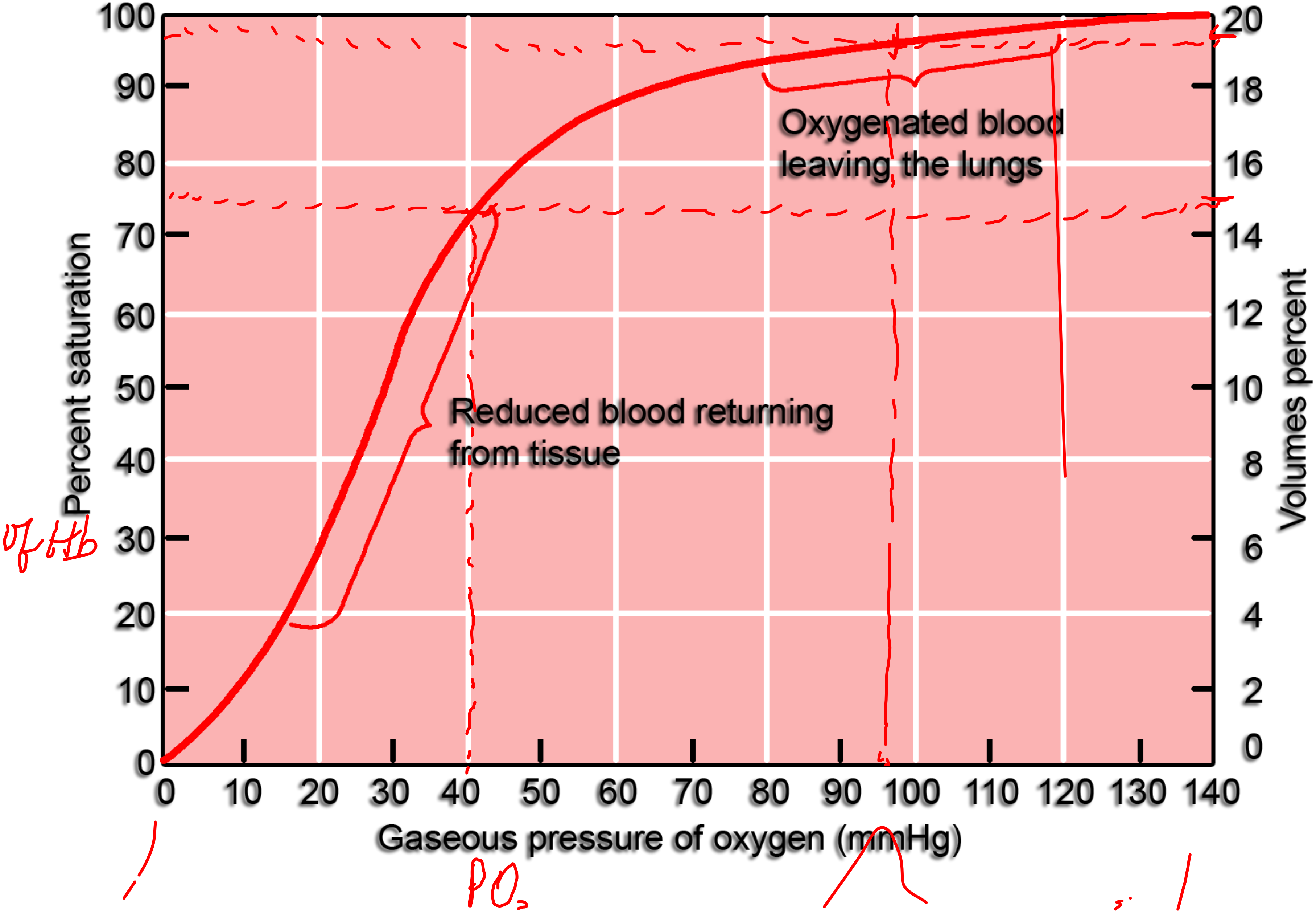
Uptake of O_2 by pulmonary blood



Maximum amount of O_2 than can combine with the Hb of the blood

In a normal person, 15gm of Hb is present in each 100ml of blood, each gram of Hb binds with a maximum of about 1.34ml of O_2. At 100% saturation, the Hb in 100ml of blood can combine with 20ml of O_2.

Oxy-Hb dissociation curve



Factors affecting the affinity of Hb for O_2

3 important conditions

1) The ↓ pH or ↑(H+ conc),
2) the ↑ temperature,
3) and the ↑ concentration of 2,3 diphosphoglycerate (2,3-DPG).
4) ↑ PCO_2 concentration (Bohr effect) → all shift the curve to the right.

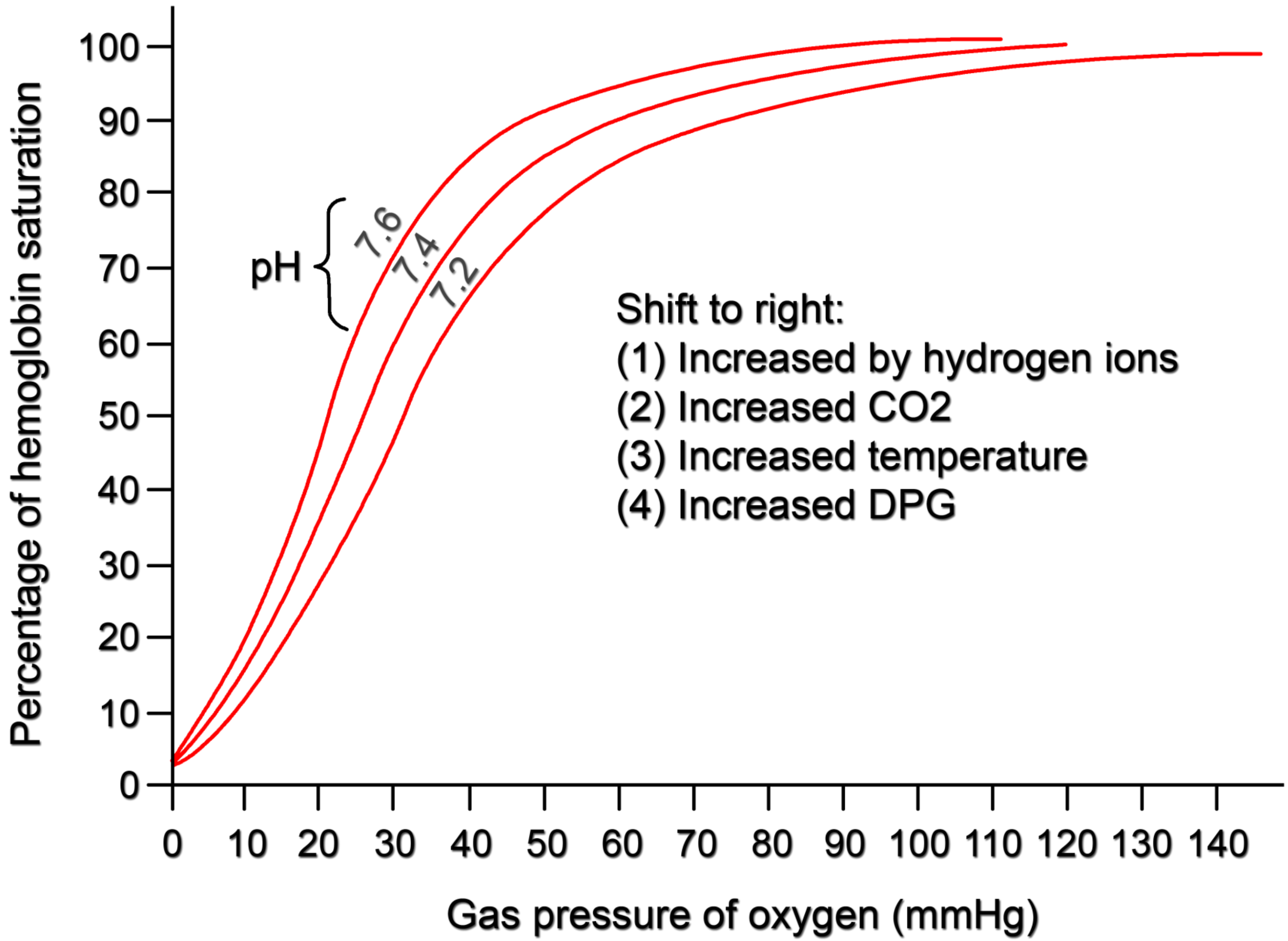
P50: it is the partial pressure of O_2 at which 50% of Hb is saturated with O_2.
↑ P50 means right shift → lower affinity for O_2.
↓ P50 means left shift → higher affinity for O_2.

The amount of O_2 released from the Hb in the tissues

- In the arterial blood 97/100 x 1.34 x 15gm of Hb = 19.4ml of O_2 is bound with Hb.
- In the venous blood 75/100 x 1.34 x 15gm = 14.4ml of O_2 is bound with Hb.
- So under normal conditions about 5ml of O_2 is transported to the tissues by each 100ml of blood.

Gas Transport

- **O_2 transport in blood**
- Hemoglobin – O_2 binds to the heme group on hemoglobin, with 4 oxygens/Hb
- PO_2 is the most important factor determining whether O_2 and Hb combine or dissociate
- O_2-Hb Dissociation curve

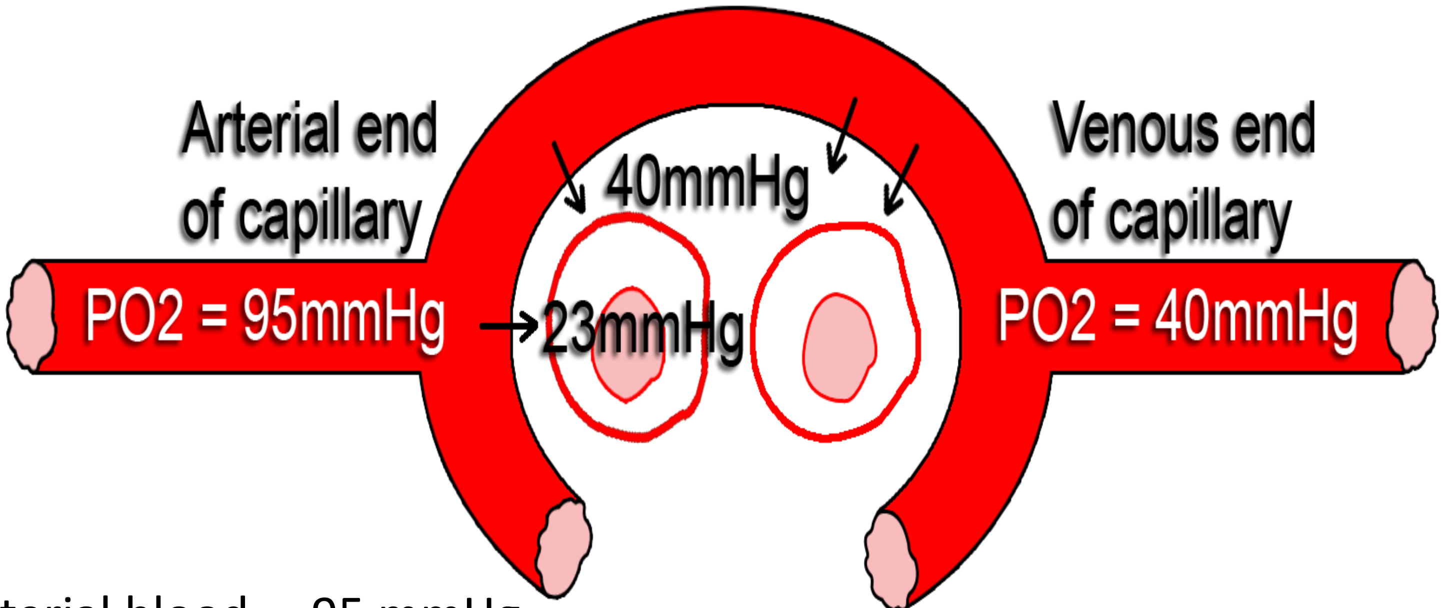


Percentage of hemoglobin saturation
100
90
80
70
60
50
40
30
20
10
0
pH
7.6
7.4
7.2
Shift to right:
(1) Increased by hydrogen ions
(2) Increased CO2
(3) Increased temperature
(4) Increased DPG
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
Gas pressure of oxygen (mmHg)

Oxy-Hemoglobin Dissociation curve

- As $PO_2 \Downarrow$, hemoglobin releases more oxygen
  - PO_2 = 95 mmHg $\Rightarrow$ 97% Hb saturation (arterial)
  - PO_2 = 40 mmHg $\Rightarrow$ 75% Hb saturation (venous)
- It is Sigmoid shaped curve with steep portion below a PO_2 of 40 mmHg
  - slight $\Downarrow$ in $PO_2 \Rightarrow$ large release in O_2 from Hgb
- Shift to the right (promote dissociation)
  - increase temperature
  - increase CO_2 (Bohr effect) decrease pH
  - increase 2,3 diphosphoglycerate (2,3 DPG)

Diffusion of O_2 from tissue capillary to cells

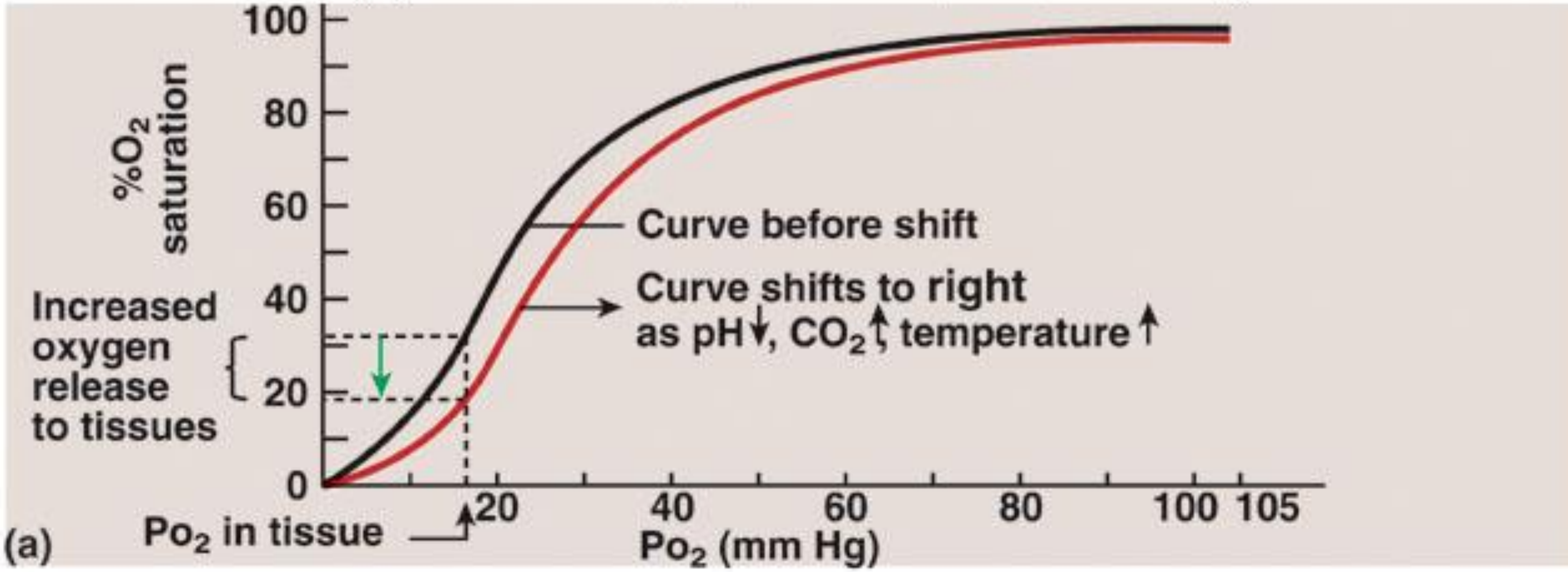


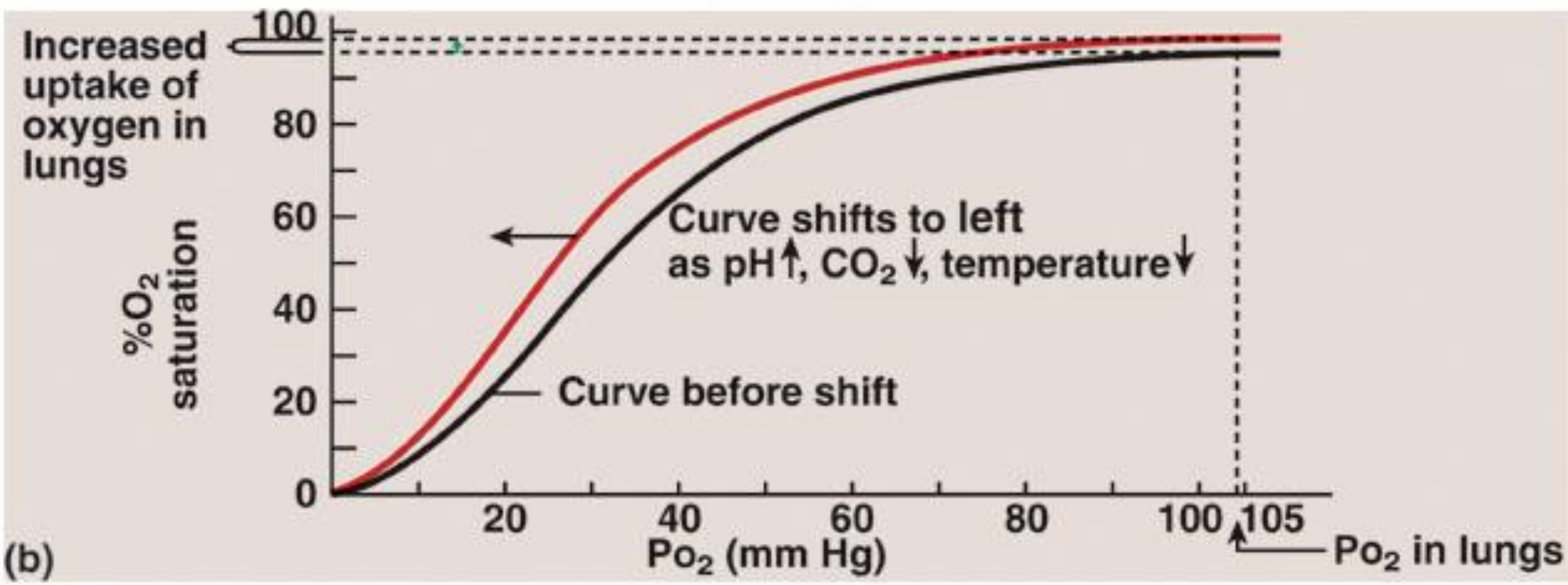
PO_2 In Arterial blood = 95 mmHg
PO_2 in ECF = 40 mmHg
Difference = 55 mm Hg allows O_2 In Arterial blood to diffuse into cells

PO_2 In ECF = 40 mmHg
PO_2 in cells = 23 mmHg
Difference = 17 mm Hg allows O_2 In ECF to diffuse into cells

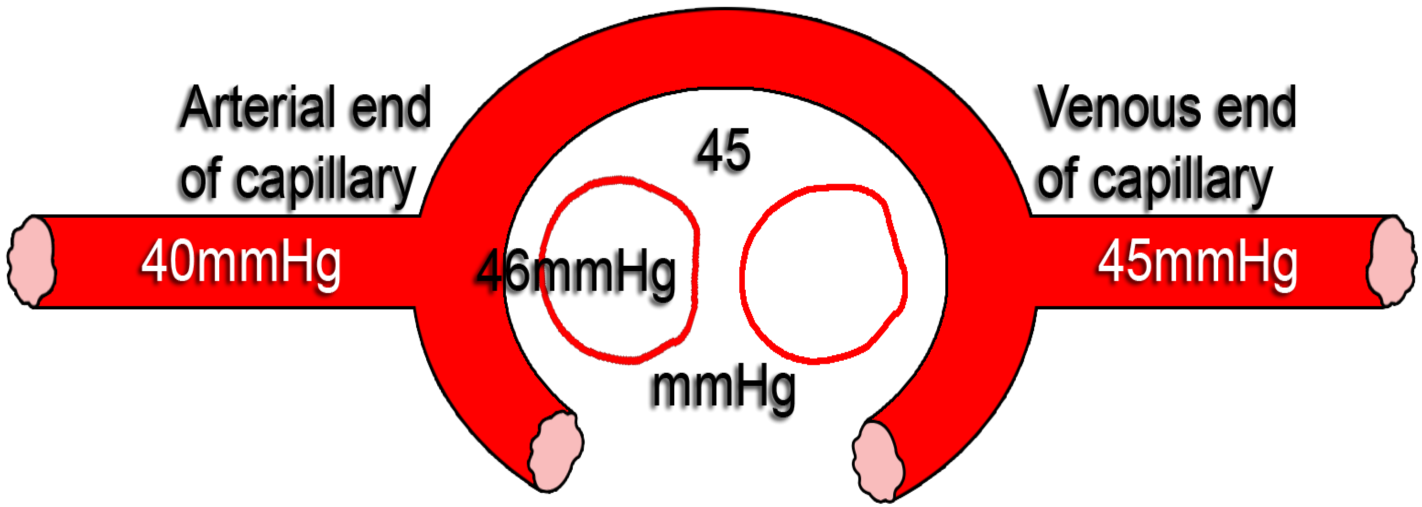
Factors affecting Oxy-Hb dissociation curve

- pH
- CO_2
- Temperature
- 2,3- DPG is present in RBC. It binds with greater affinity with deoxygenated Hb. It promotes release of oxygen from Hb. Thus it enhances release of oxygen by RBC near tissues that need it.


100
80
60
40
20
0
%O2 saturation
Curve before shift
Curve shifts to right
as pH↓, CO2↑, temperature↑
Increased oxygen release to tissues
20
40
60
80
100
105
(a)
Po2 in tissue
Po2 (mm Hg)


Increased uptake of oxygen in lungs
100
80
60
40
20
0
%O2 saturation
Curve shifts to left
as pH↑, CO2↓, temperature↓
Curve before shift
20
40
60
80
100
105
(b)
Po2 (mm Hg)
Po2 in lungs

Diffusion of CO_2 from cells to tissue capillary



PCO_2 in cells = 46 mmHg
PCO_2 In ECF = 45 mmHg
Difference = 1 mm Hg

Chemical forms in which CO_2 is transported

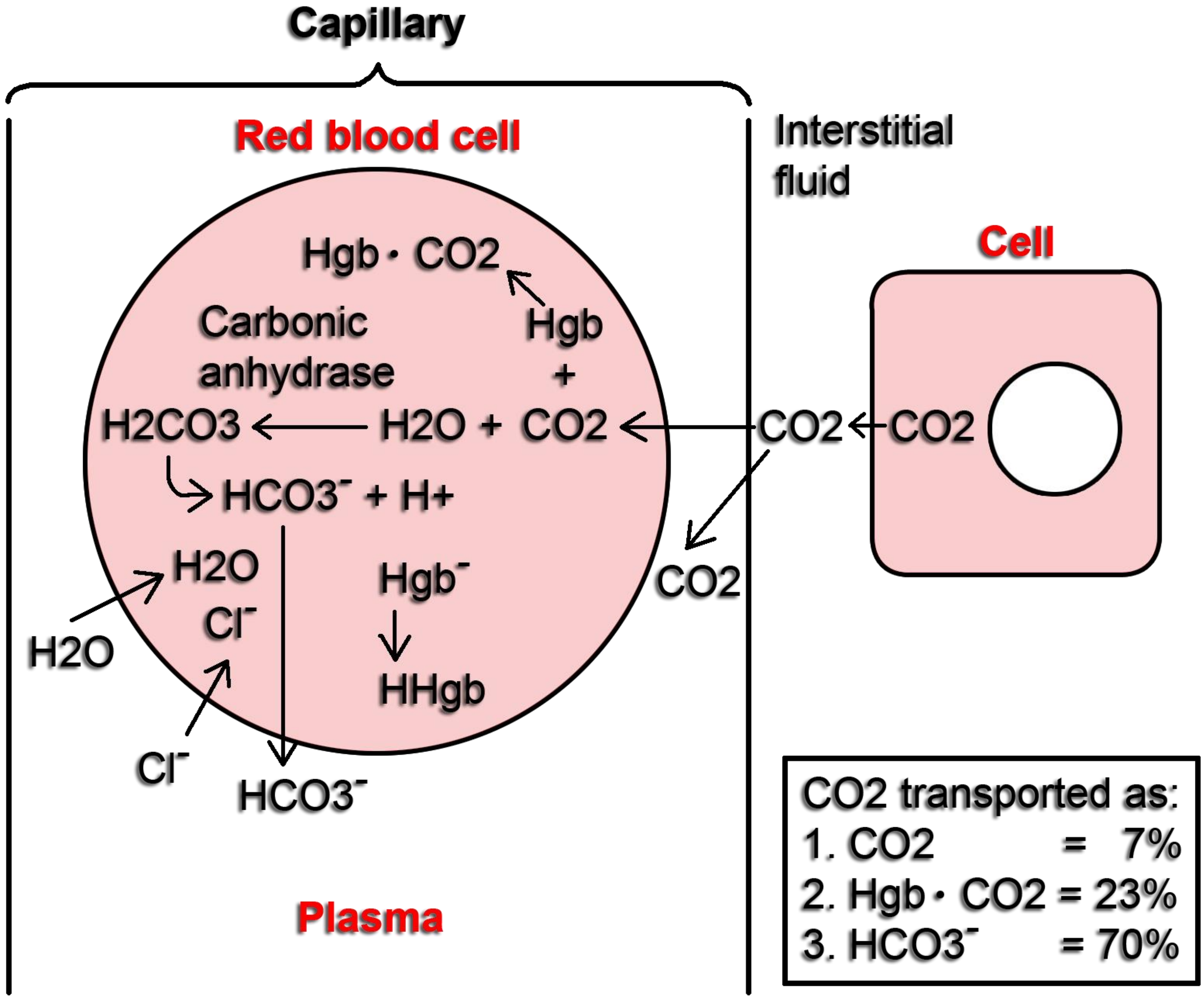
- 7% of CO_2 is transported in the dissolved state.

- 23% in carbamino compounds (bound to globin part of Hb). 23% of CO_2 is transported in combination with Hb and plasma proteins as carbamino-Hb: CO_2 reacts with the amino group of the Hb to form the carbamino-Hb (CO_2HHB). This reaction is reversible when CO_2 is released into the alveoli.

- 70% as Bicarbonate ion in the blood plasma.

CO_2 transport

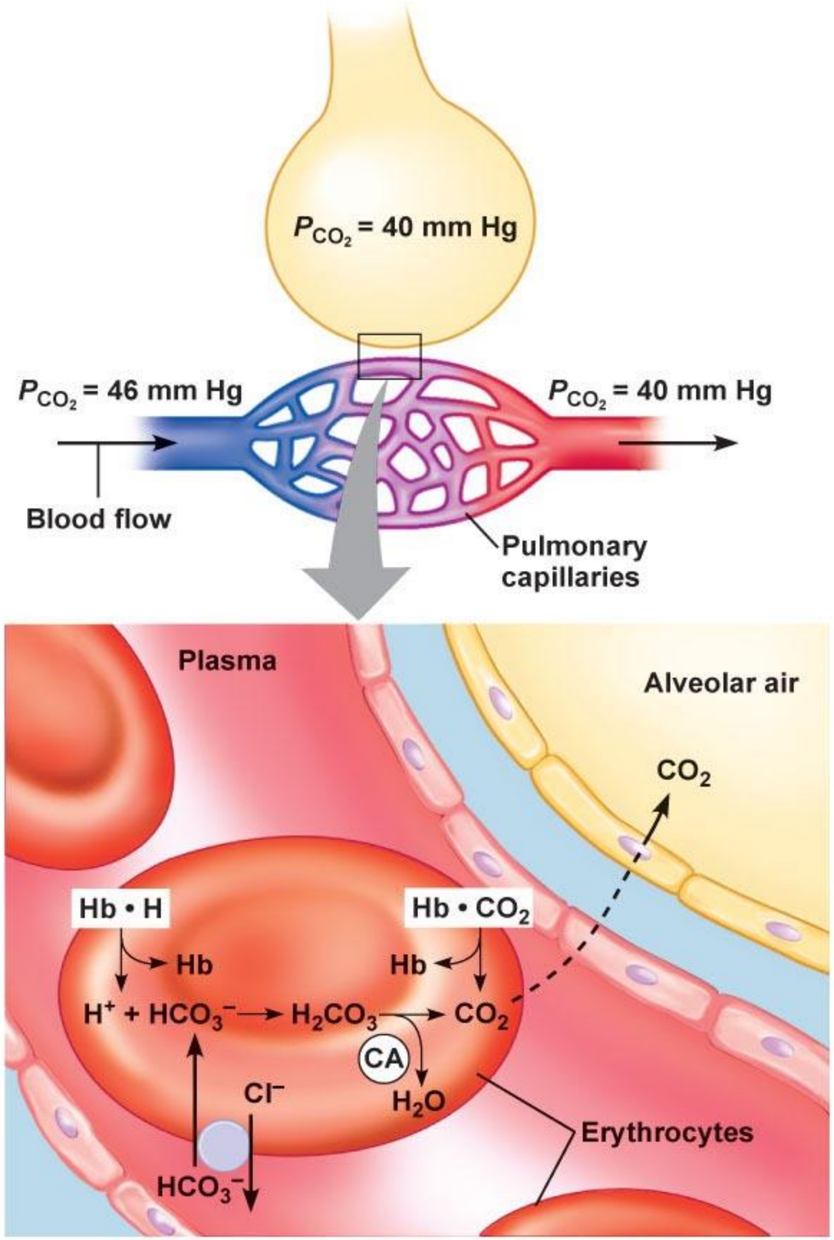
- 70% of CO_2 is transported in the form HCO_3^-. CO_2 reacts with the water of RBC in the presence of the enzyme CA to form H_2CO_3 which immediately dissociates into H^+ and HCO_3^-. HCO_3^- diffuses out of the RBC and Cl^- ions diffuse into the RBC (chloride shift). The H^+ cannot leave the cell for two good reasons.
- The first reason is that H^+ is bound to the Hb molecule. Hb acts as a buffer.
- The second reason is the H^+ cannot easily diffuse across the cell membrane because the cell membrane is practically impermeable to cations.
- If the H^+ was allowed to follow the bicarbonate out, it would eventually begin to lower the blood pH and cause acidosis, a very dangerous condition.


Capillary
Red blood cell
Interstitial fluid
Cell
Hgb · CO2
Carbonic anhydrase
Hgb
+
H2CO3
H2O + CO2
CO2
CO2
HCO3⁻ + H+
H2O
Cl⁻
Hgb⁻
HHgb
CO2
H2O
Cl⁻
HCO3⁻
Plasma
CO2 transported as:
1. CO2 = 7%
2. Hgb · CO2 = 23%
3. HCO3⁻ = 70%

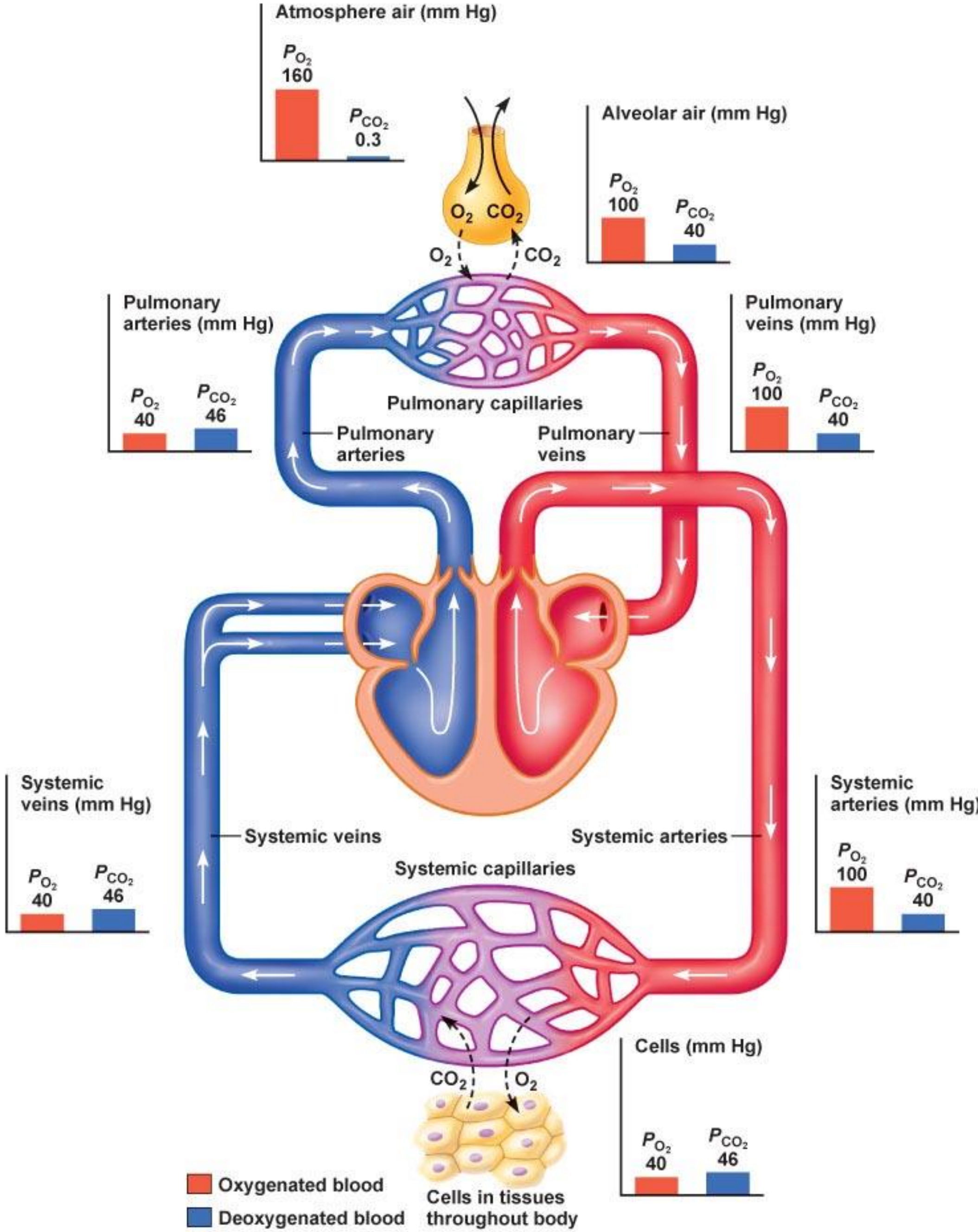
Chloride shift

- **Chloride shift** (also known as the **Hamburger shift** or **Hamburger phenomenon**, named after Hartog Jakob Hamburger, a Dutch physiologist.
- The Cl^- content of venous RBC is greater than that of arterial RBC. This phenomenon is called chloride shift.

PCO$_2$ in venous blood = 45mmHg
PCO$_2$ in lung alveoli = 40 mm Hg
Difference = 5 mm Hg

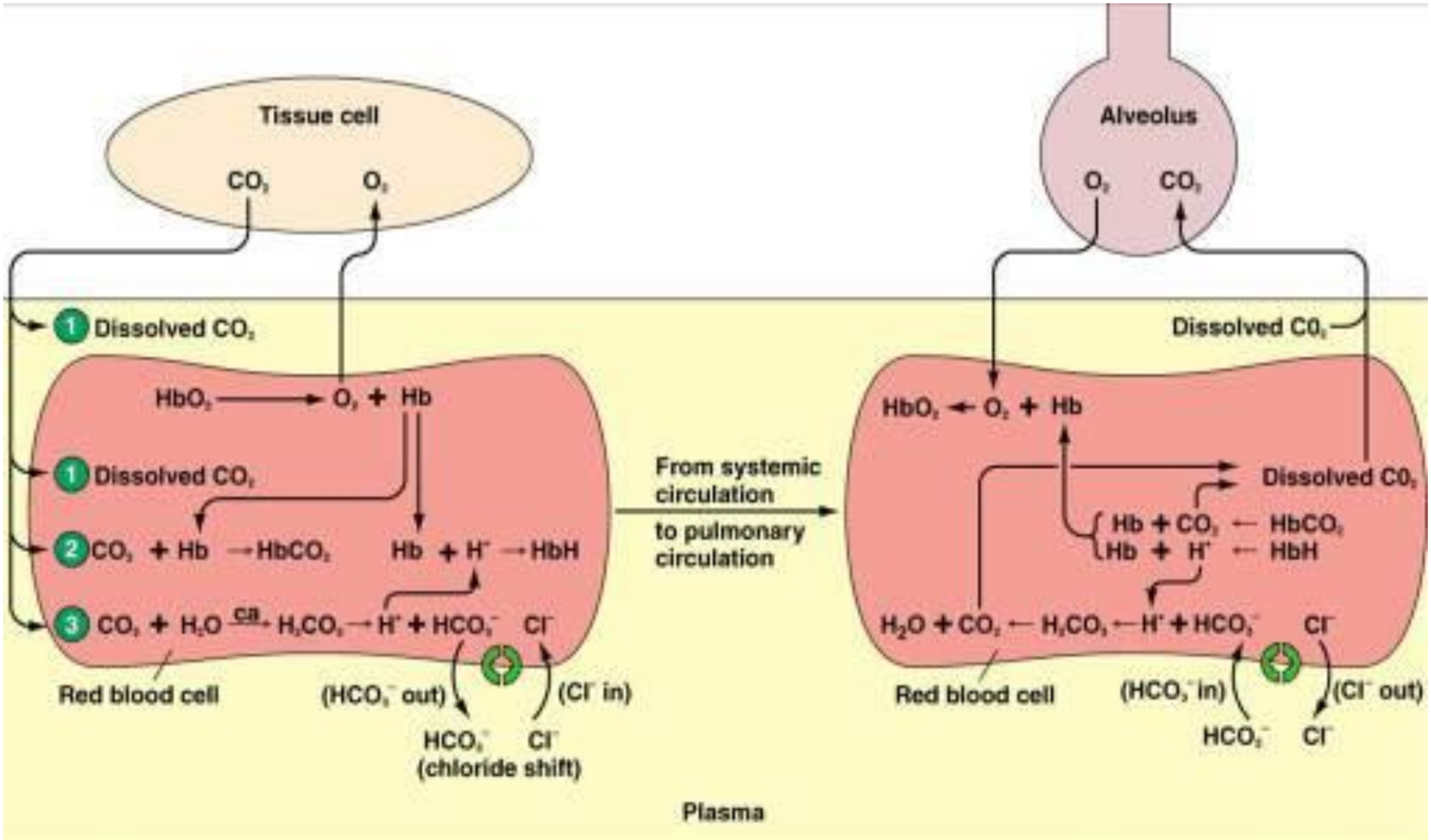


(b)



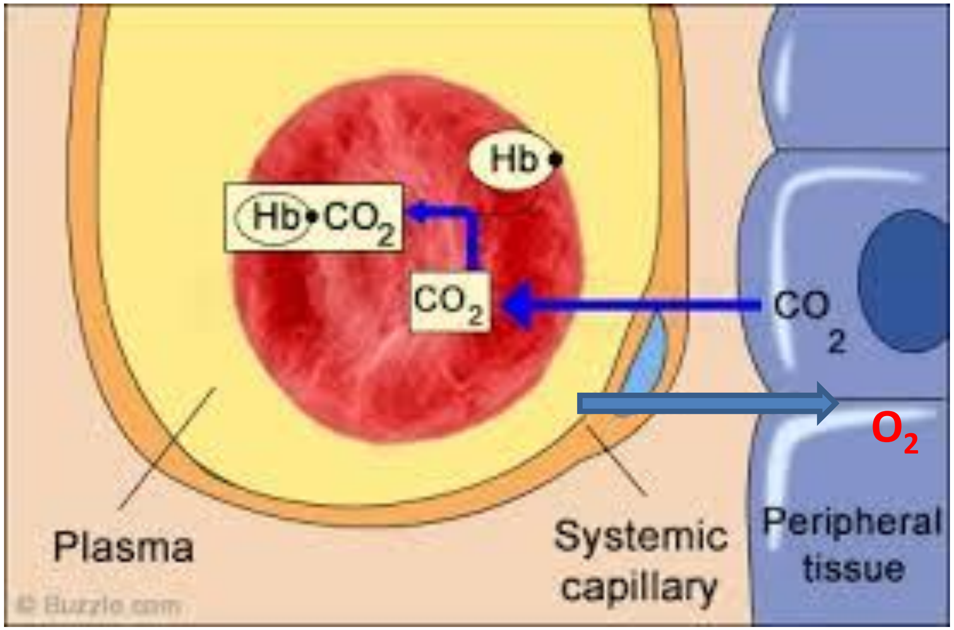
Atmosphere air (mm Hg)
P_{O_2} 160
P_{CO_2} 0.3
O_2 CO_2
Alveolar air (mm Hg)
P_{O_2} 100
P_{CO_2} 40
O_2
CO_2
Pulmonary arteries (mm Hg)
P_{O_2} 40
P_{CO_2} 46
Pulmonary capillaries
Pulmonary veins (mm Hg)
P_{O_2} 100
P_{CO_2} 40
Pulmonary arteries
Pulmonary veins
Systemic veins (mm Hg)
P_{O_2} 40
P_{CO_2} 46
Systemic veins
Systemic arteries
Systemic capillaries
Systemic arteries (mm Hg)
P_{O_2} 100
P_{CO_2} 40
CO_2
O_2
Cells (mm Hg)
P_{O_2} 40
P_{CO_2} 46
Oxygenated blood
Deoxygenated blood
Cells in tissues throughout body

Haldane effect

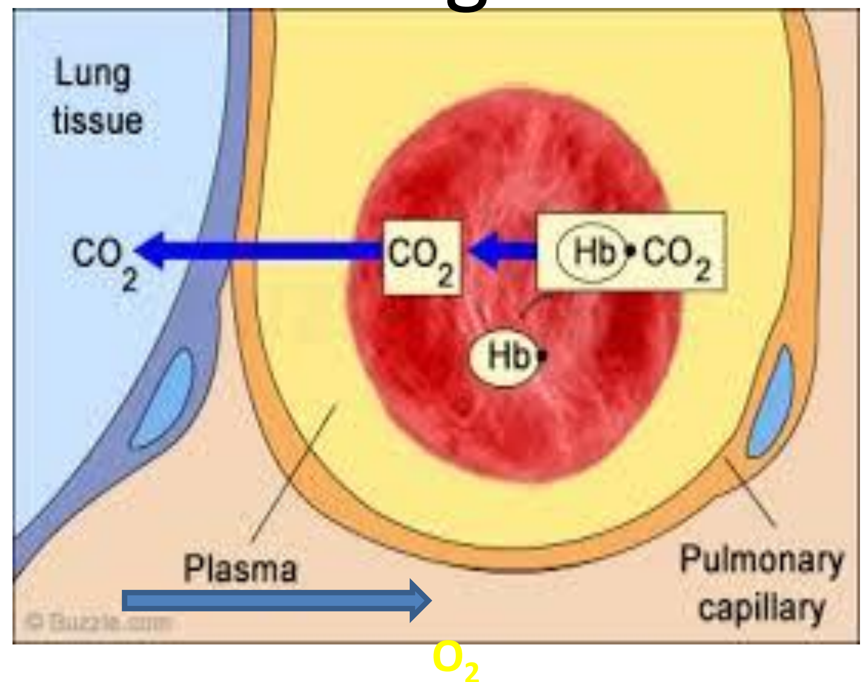


ca = Carbonic anhydrase

Tissues



Lung



The Haldane Effect describes the phenomenon by which binding of oxygen to hemoglobin promotes the release of carbon dioxide.

The **Haldane effect** is a property of hemoglobin first described by John Scott Haldane. Oxygenation of blood in the lungs displaces carbon dioxide from hemoglobin which increases the removal of carbon dioxide. This property is the Haldane effect. Conversely, oxygenated blood has a reduced affinity for carbon dioxide.

References

- Guyton, A.C. & Hall, J.E. (2006). Textbook of Medical Physiology. XI Edition. Hercourt Asia PTE Ltd. W.B. Saunders Company.
- Tortora, G.J. & Grabowski, S. (2006). Principles of Anatomy & Physiology. XI Edition John Wiley & sons,