Section 2: Gas exchange

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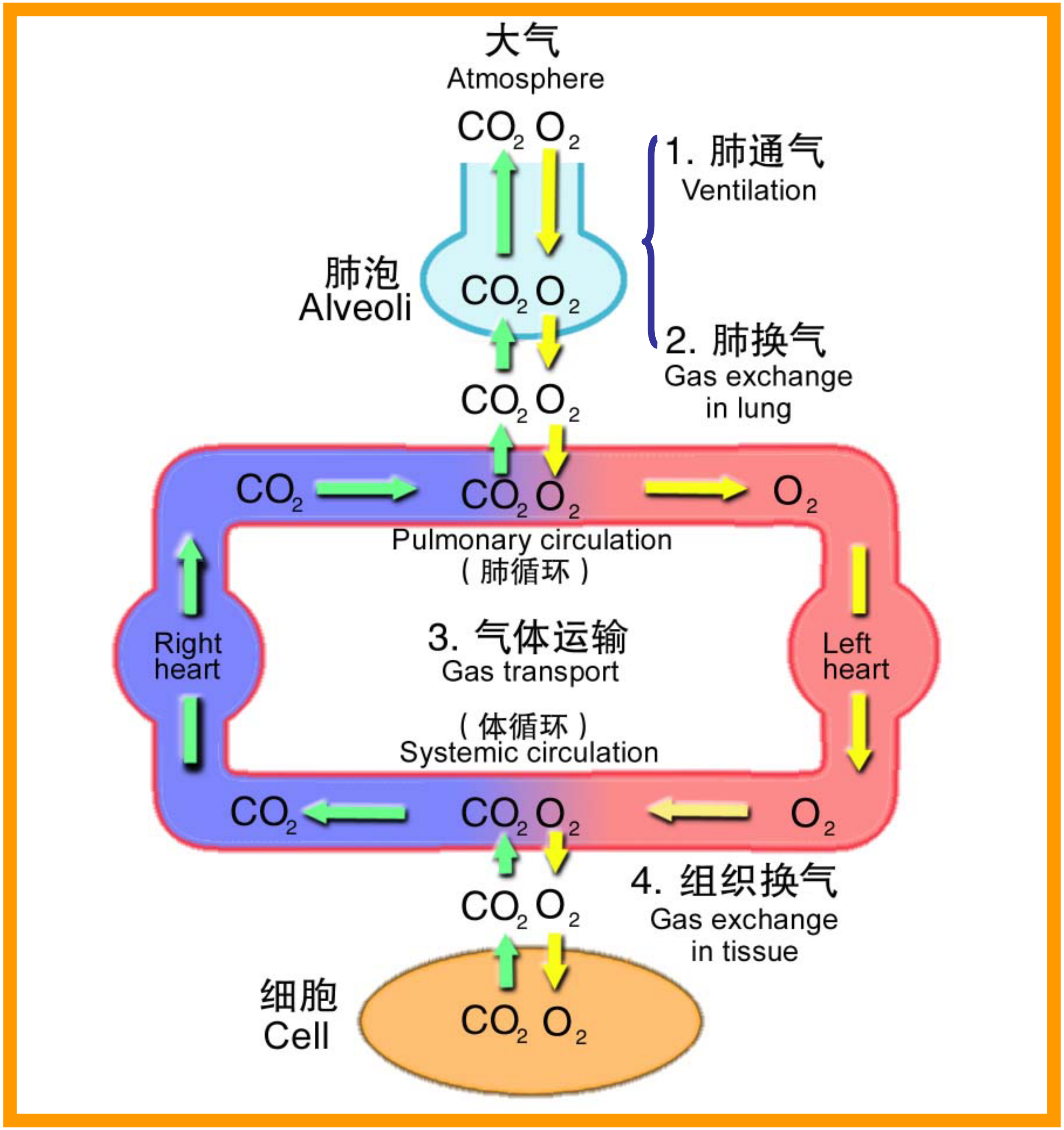
Diffusion:

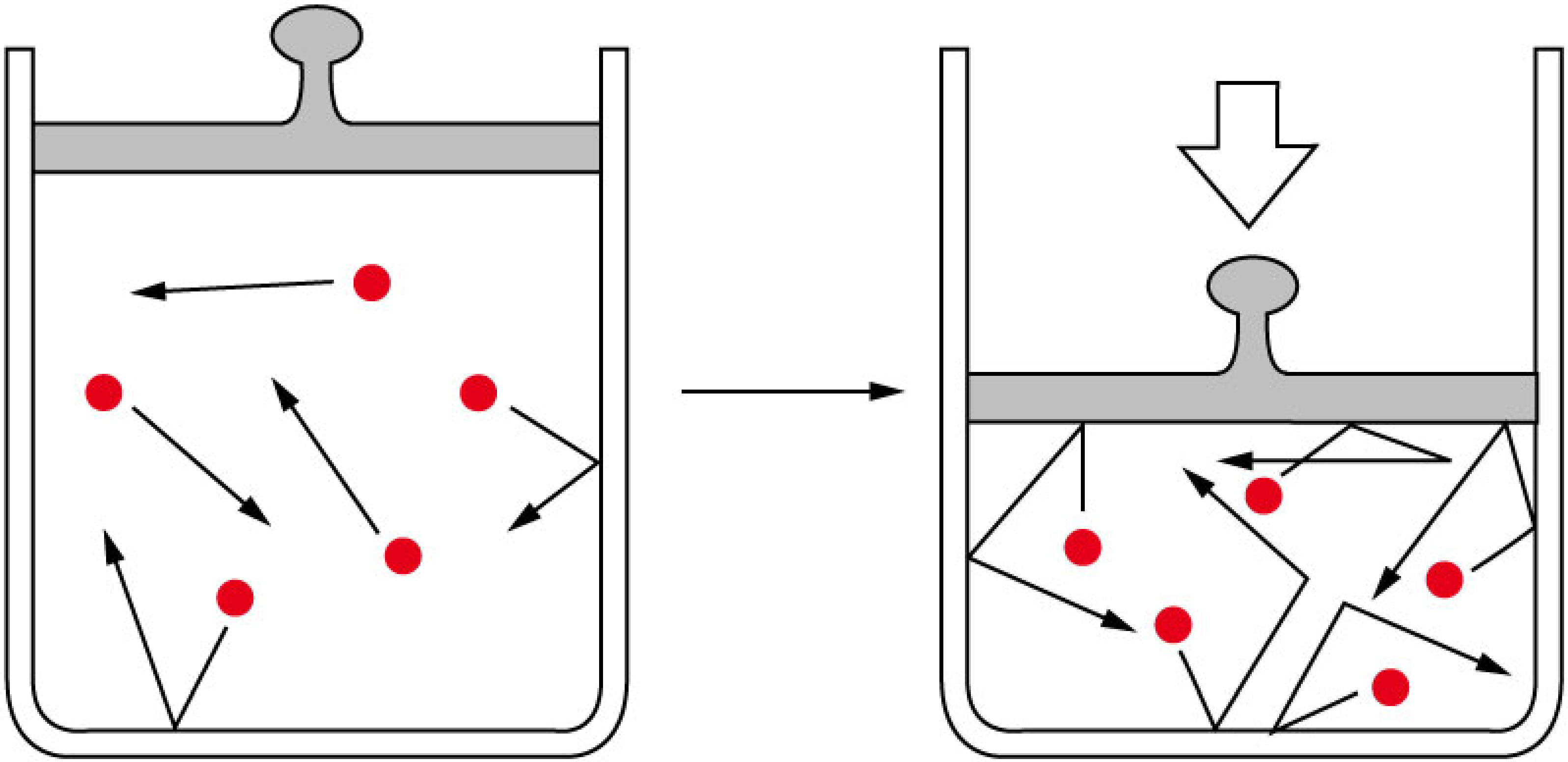
Diffusion rate (D):



Gas law

1. The total pressure of a mixture of gases is the sum of the pressure of the individual gases (Dalton's law)
2. Gases singly or in a mixture, move from areas of higher pressure to areas of lower pressure
3. If the volume of a container of gas changes, the pressure of the gas will change in an inverse manner (Boyle's law)

Boyle's Law: $P_1V_1 = P_2V_2$



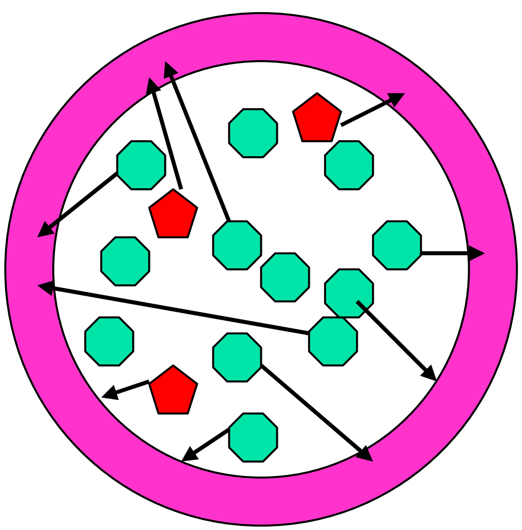
$V_1 = 1.0\ L$
$P_1 = 100\ mm\ Hg$

$V_2 = 0.5\ L$
$P_2 = 200\ mm\ Hg$

Partial pressure

- **In a gas mixture the pressure exerted by each individual gas is partial pressure (P)**

$$P_{gas} = \% \text{ of total gases} \times P_{total}$$



= oxygen ~21%

= nitrogen ~79%

Air pressure = 760 mm Hg

P_{O2} = 160 mm Hg

P_{N2} = 600 mm Hg

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.

Fick's law

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

Factors affecting gas exchange

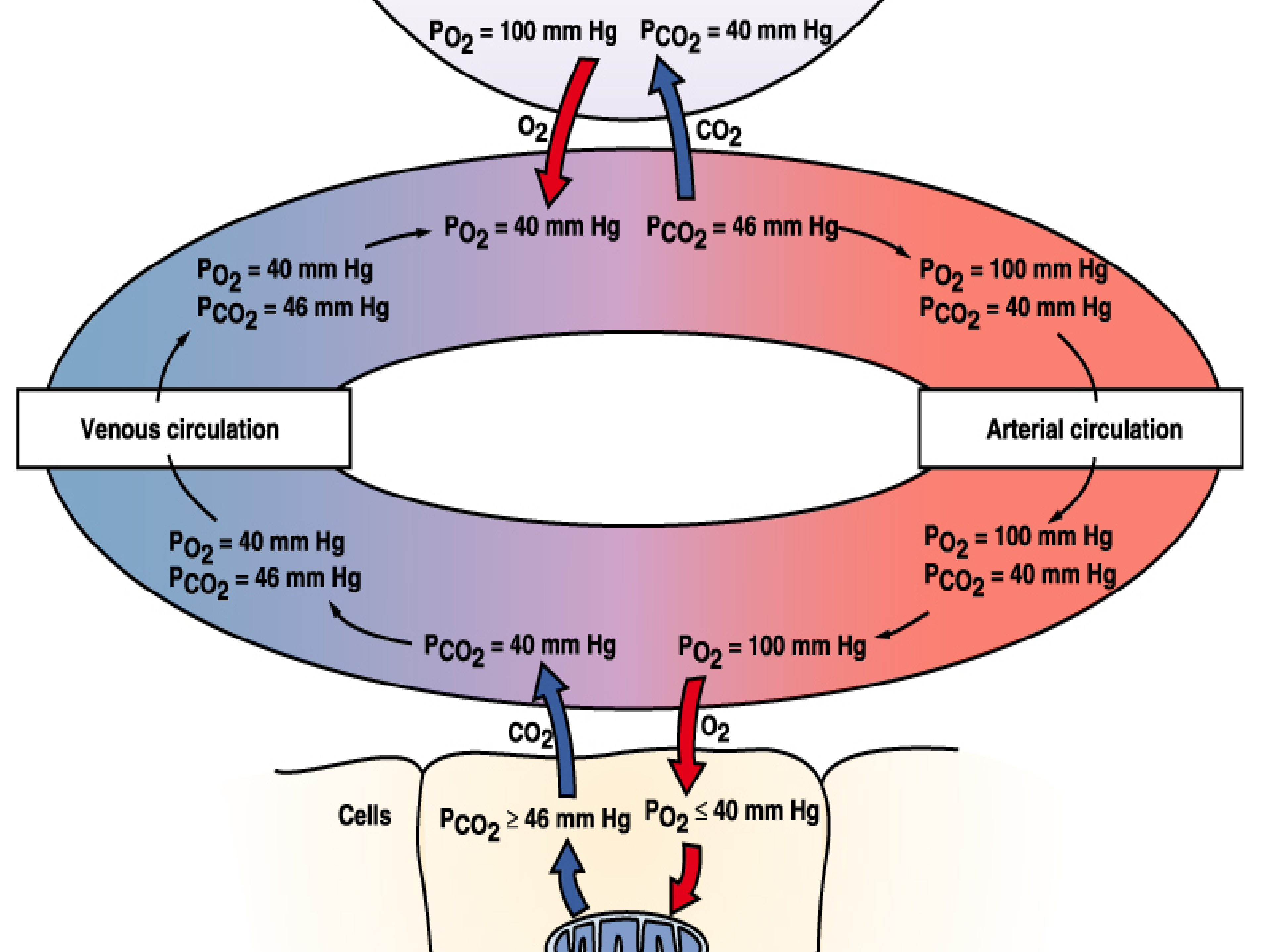
$$D \propto \frac{\Delta P \cdot T \cdot A \cdot S}{d\sqrt{MW}}$$

Diffusion coefficient

D:	Diffusion rate
T:	Absolute temperature
A:	Area of diffusion
S:	Solubility of the gas
ΔP:	Partial pressure
d:	Distance of diffusion
MW:	Molecular weight

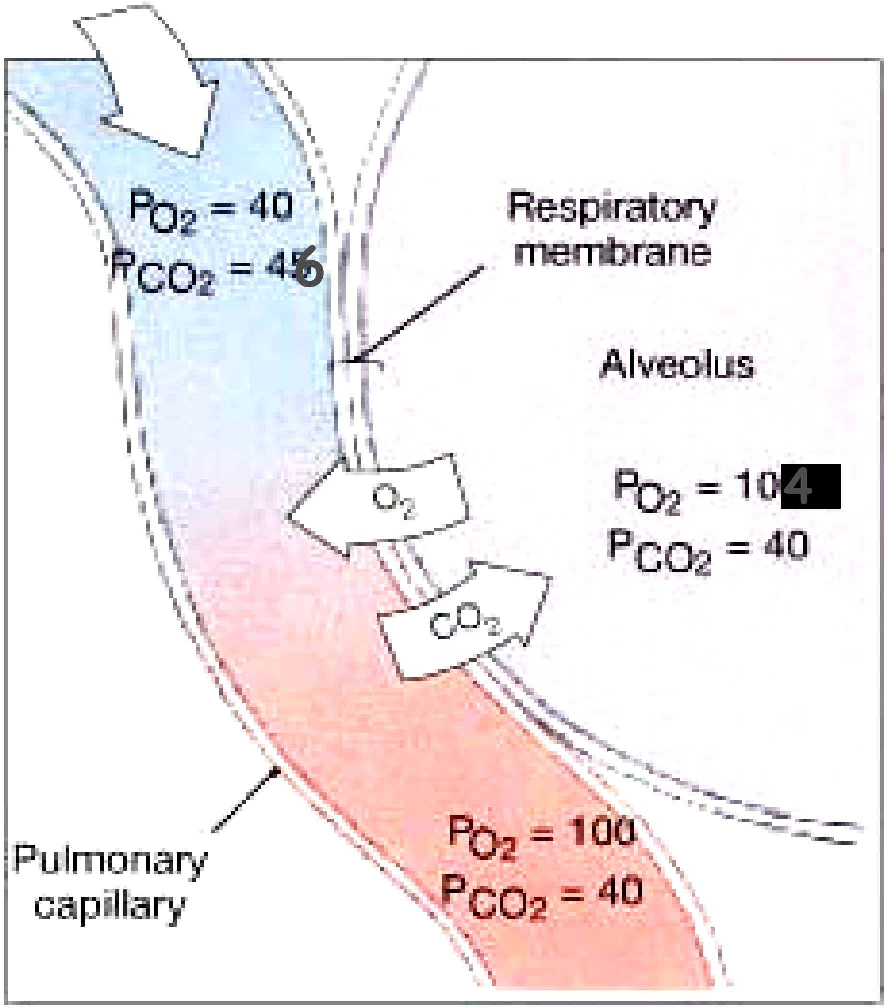
Gas partial pressrue (mmHg)

	Alveoli	Arterial	Venous	Tissue
PO_2	104	100	40	30
PCO_2	40	40	46	50



P_{O_2} = 100 mm Hg
P_{CO_2} = 40 mm Hg
O_2
CO_2
P_{O_2} = 40 mm Hg
P_{CO_2} = 46 mm Hg
P_{O_2} = 40 mm Hg
P_{CO_2} = 46 mm Hg
P_{O_2} = 100 mm Hg
P_{CO_2} = 40 mm Hg
Venous circulation
Arterial circulation
P_{O_2} = 40 mm Hg
P_{CO_2} = 46 mm Hg
P_{O_2} = 100 mm Hg
P_{CO_2} = 40 mm Hg
P_{CO_2} = 40 mm Hg
P_{O_2} = 100 mm Hg
CO_2
O_2
Cells
$P_{CO_2} \geq$ 46 mm Hg
$P_{O_2} \leq$ 40 mm Hg

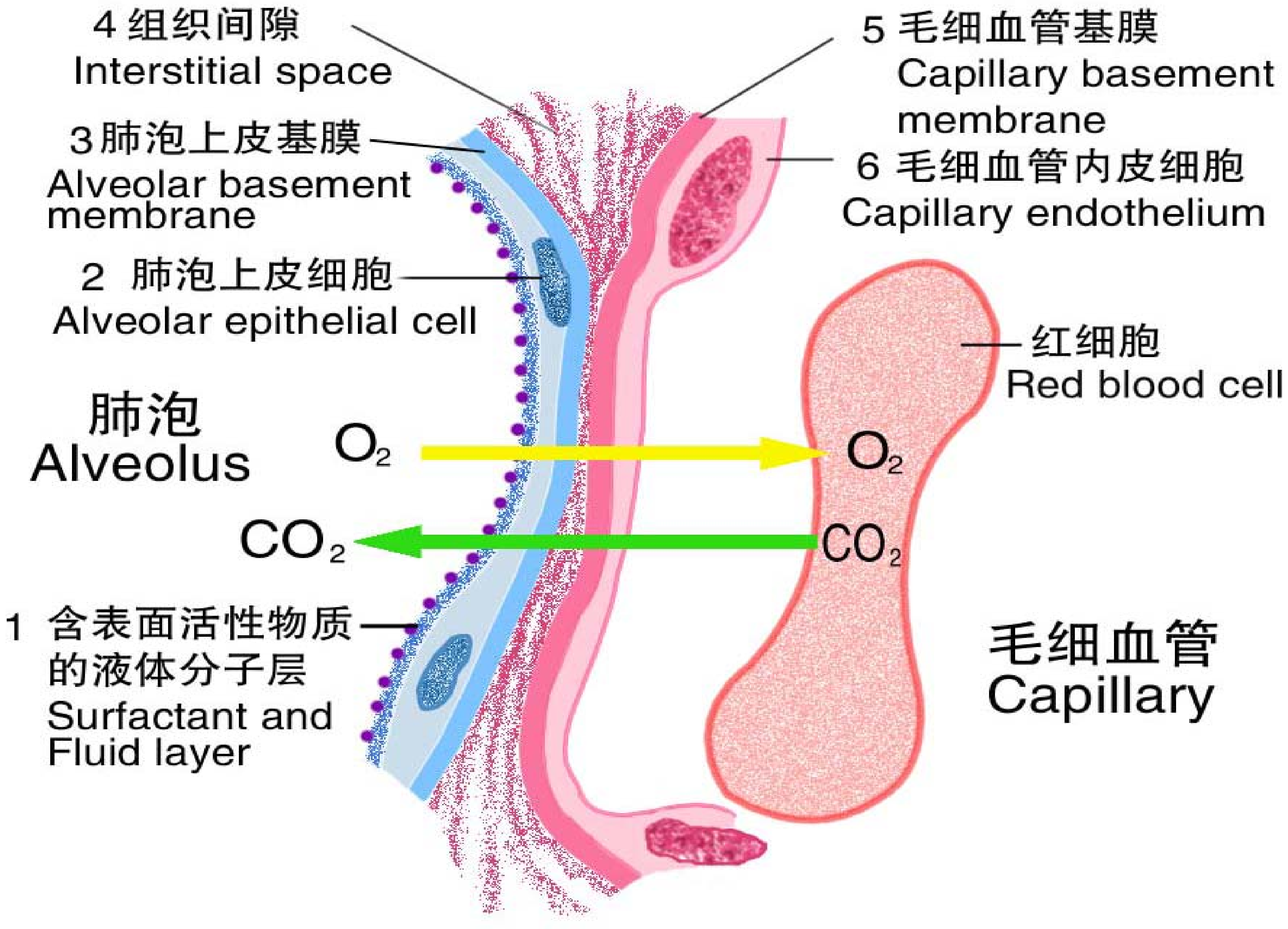
Process of pulmonary gas exchange

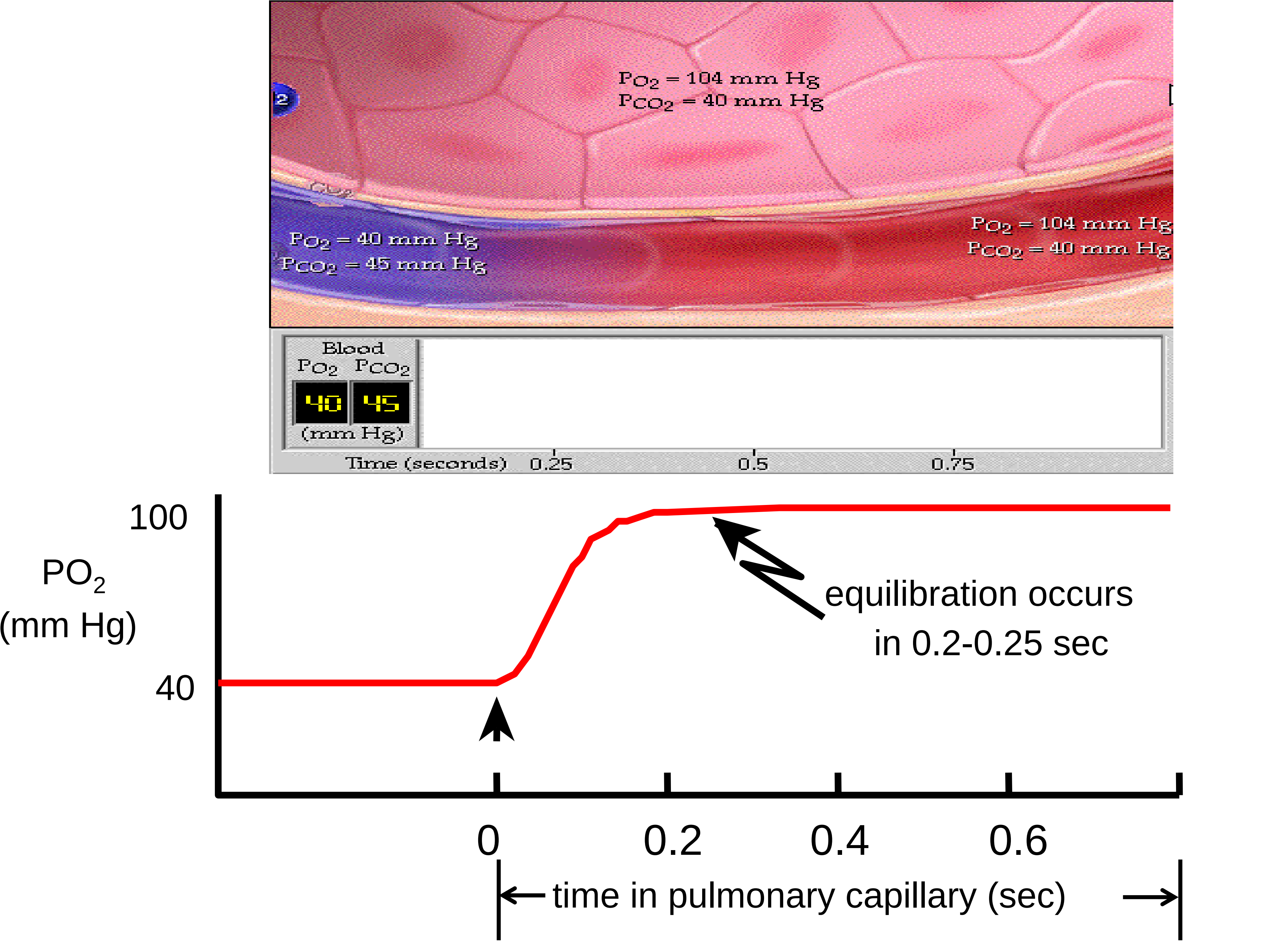


Thickness: 0.6 μm

Area: 70 m^2

Respiratory membrane





PO2 = 104 mm Hg
PCO2 = 40 mm Hg
PO2 = 40 mm Hg
PCO2 = 45 mm Hg
PO2 = 104 mm Hg
PCO2 = 40 mm Hg
Blood
PO2 PCO2
40 45
(mm Hg)
Time (seconds) 0.25 0.5 0.75
100
PO2 (mm Hg)
40
equilibration occurs in 0.2-0.25 sec
0 0.2 0.4 0.6
time in pulmonary capillary (sec)

Factors that affect pulmonary gas exchange

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

- Thickness of respiratory membrane
- Area of respiratory membrane
- Partial pressure differences and the gas diffusion coefficient

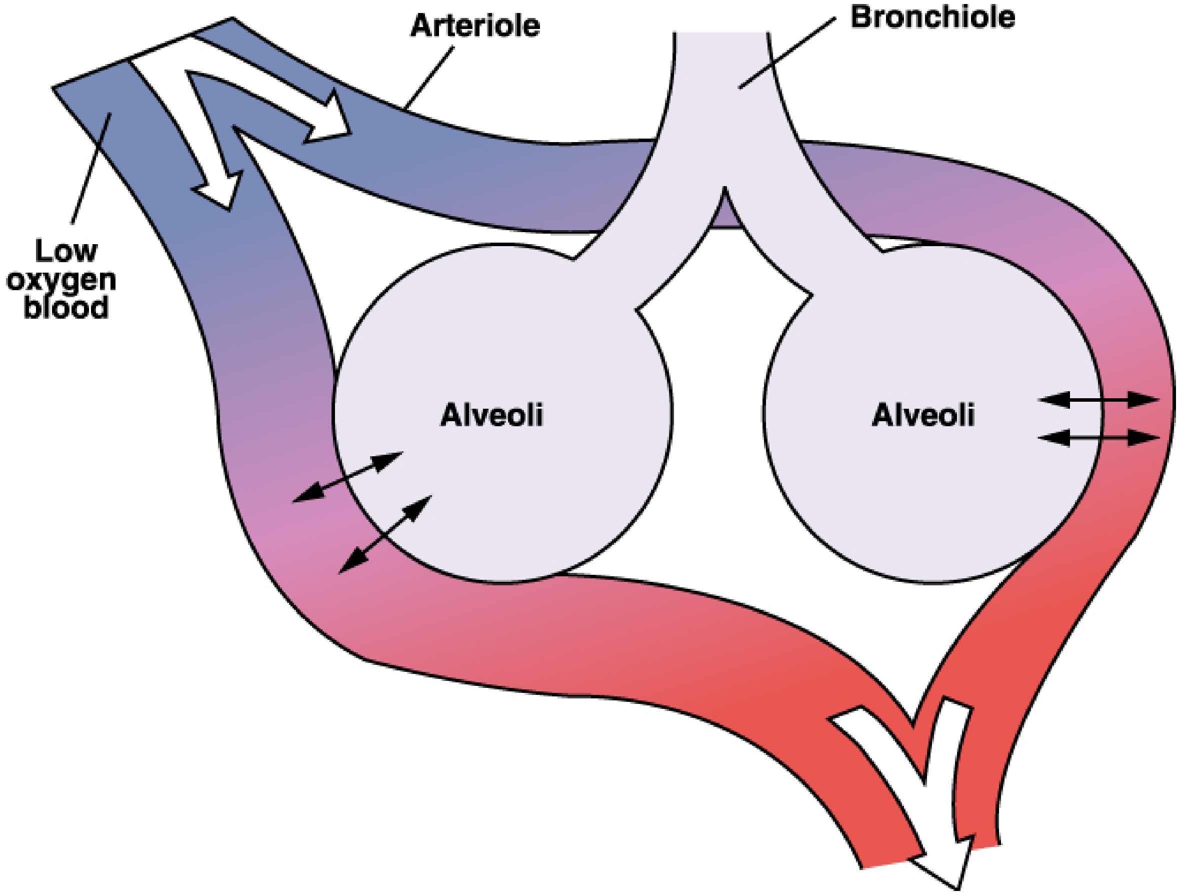
✓ alveolar ventilation

✓ pulmonary blood flow

✓ speed of chemical reaction

Ventilation/perfusion ratio

Ventilation in alveoli is matched to perfusion through pulmonary capillaries



通气/血流比值

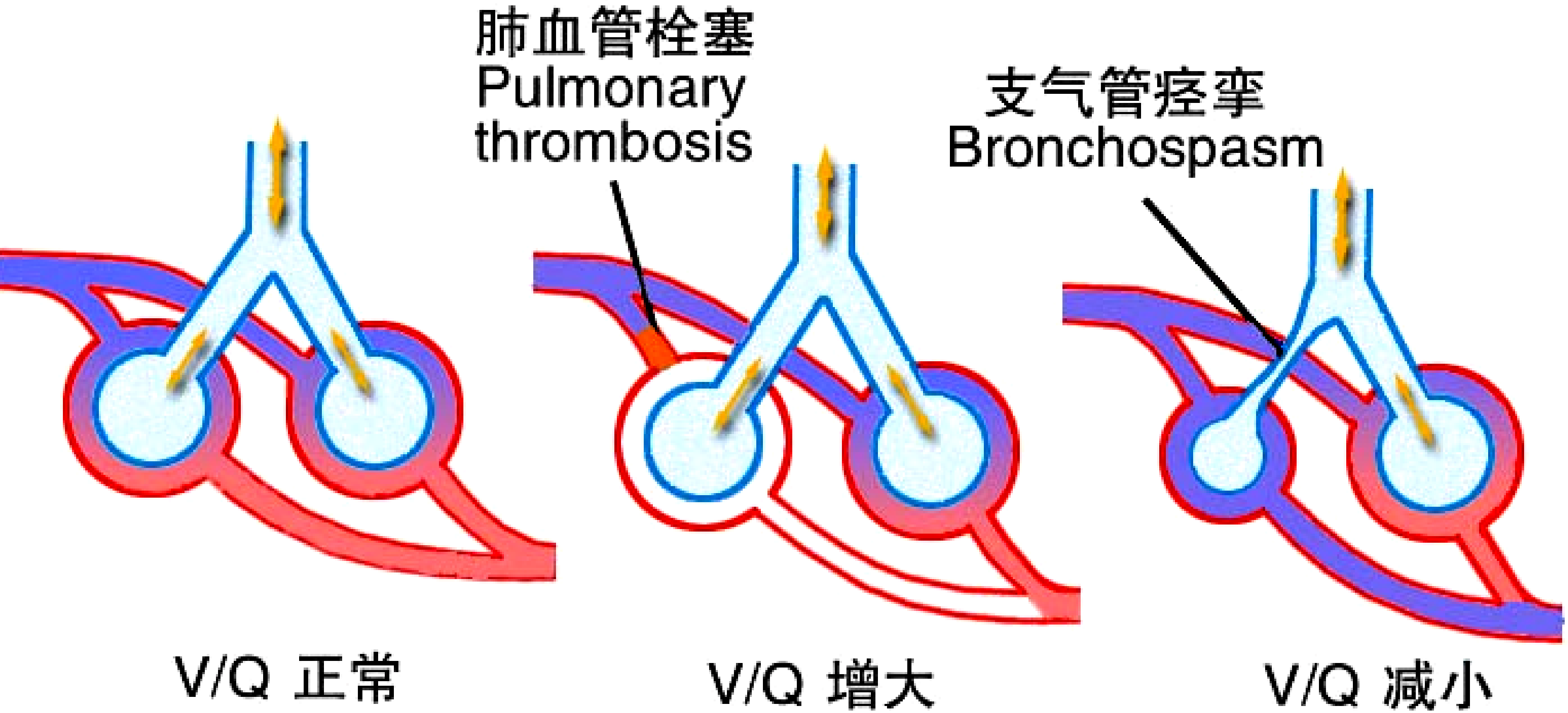
- 概念

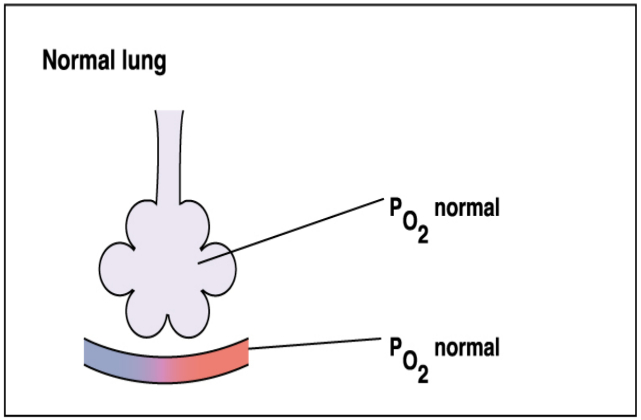
  肺泡通气量（4.2L）/ 肺血流量（5L） 0.84

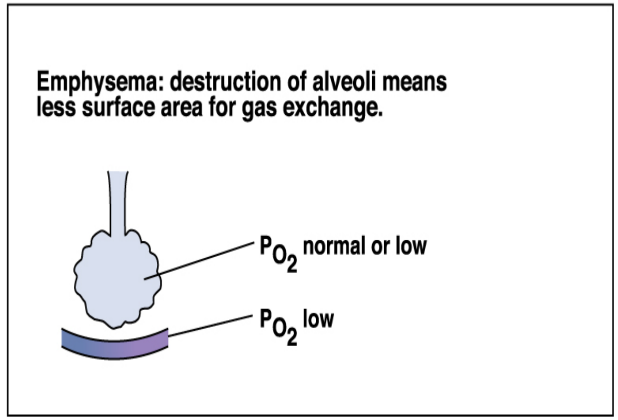
- $\dot{V}_A/\dot{Q}$

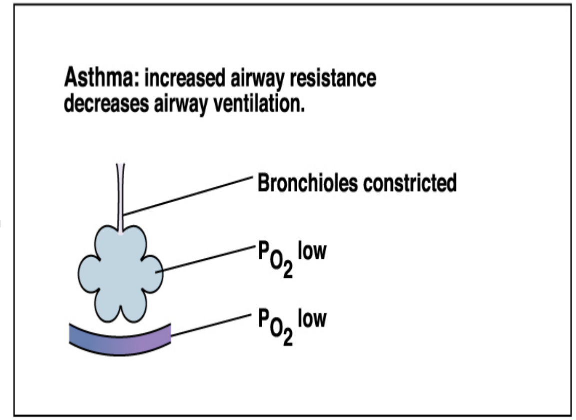
  >0.84 → dead space 肺泡无效腔 ↑

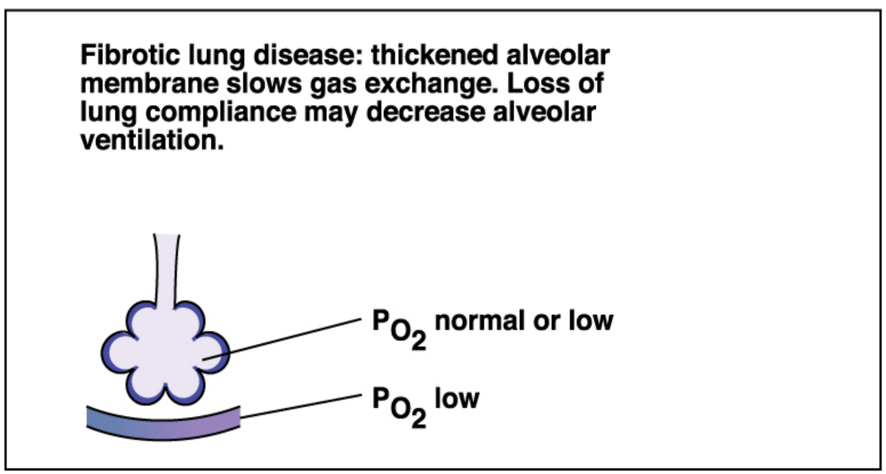
  <0.84 → functional shunt 功能性短路

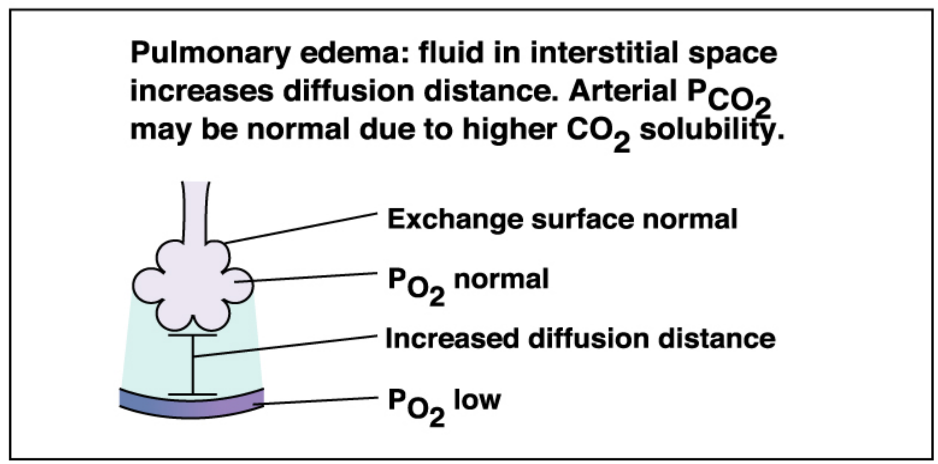

肺血管栓塞
Pulmonary thrombosis
支气管痉挛
Bronchospasm
V/Q 正常
V/Q 增大
V/Q 减小


Normal lung
P_{O_2} normal
P_{O_2} normal


Emphysema: destruction of alveoli means less surface area for gas exchange.
P_{O_2} normal or low
P_{O_2} low


Asthma: increased airway resistance decreases airway ventilation.
Bronchioles constricted
P_{O_2} low
P_{O_2} low

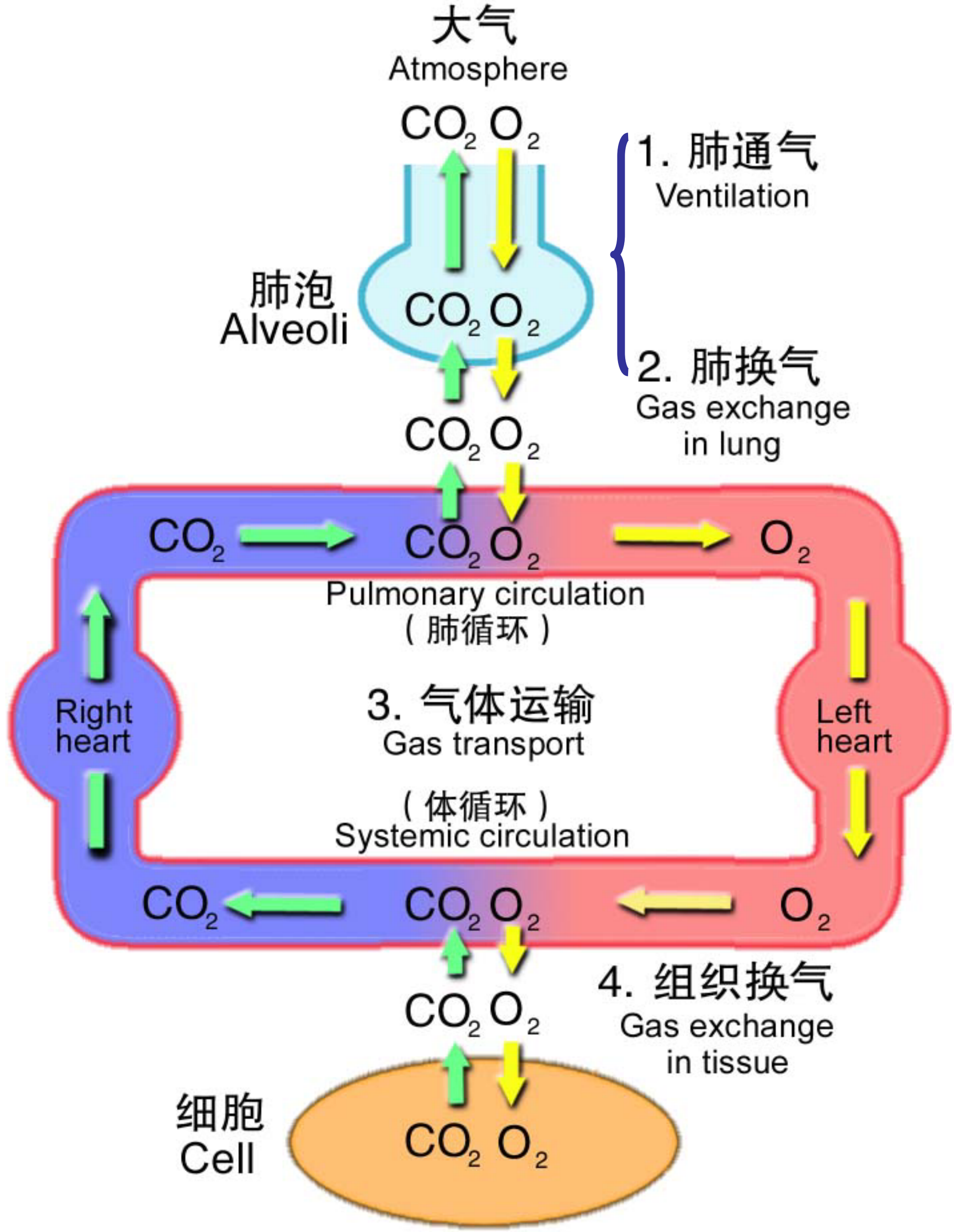

Fibrotic lung disease: thickened alveolar membrane slows gas exchange. Loss of lung compliance may decrease alveolar ventilation.
P_{O_2} normal or low
P_{O_2} low


Pulmonary edema: fluid in interstitial space increases diffusion distance. Arterial P_{CO_2} may be normal due to higher CO_2 solubility.
Exchange surface normal
P_{O_2} normal
Increased diffusion distance
P_{O_2} low

- Gas exchange in tissue affected by:
  - Distance
  - Blood flow in tissue
  - Metabolic rate in tissue

Section 3

Gas Transport in the Blood


大气
Atmosphere
CO2 O2
1. 肺通气
Ventilation
肺泡
Alveoli
CO2 O2
2. 肺换气
Gas exchange
in lung
CO2 O2
CO2
CO2 O2
O2
Pulmonary circulation
（肺循环）
Right
heart
3. 气体运输
Gas transport
Left
heart
（体循环）
Systemic circulation
CO2
CO2 O2
O2
4. 组织换气
Gas exchange
in tissue
CO2 O2
细胞
Cell
CO2 O2

Forms of Gas Transported

- **Physical dissolve**
- **Chemical combination**

Alveoli		Blood		Tissue
O_2 →	dissolve →	combine →	dissolve	→ O_2
CO_2 ←	dissolve ←	combine ←	dissolve	← CO_2

Transport of oxygen

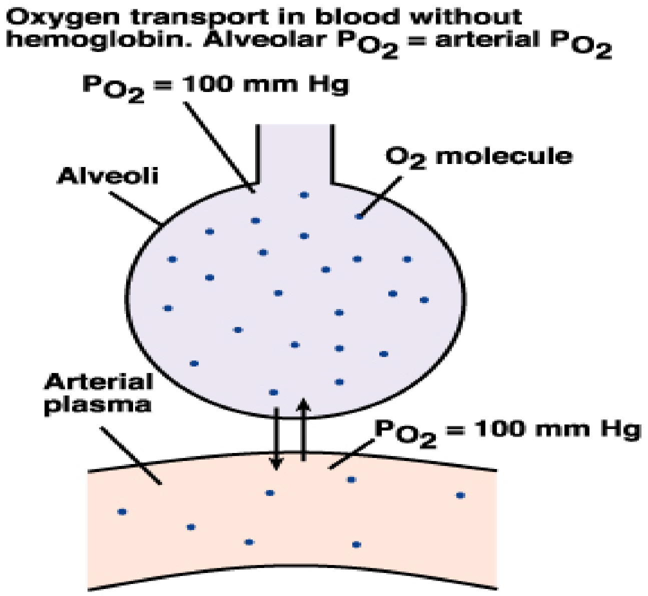
- Forms of oxygen transport
- Combination of oxygen with hemoglobin
- Oxygen-Hb dissociation curve
- Factors affecting oxygen-Hb dissociation curve

Transport of Oxygen

O_2 is carried in blood

in two forms:

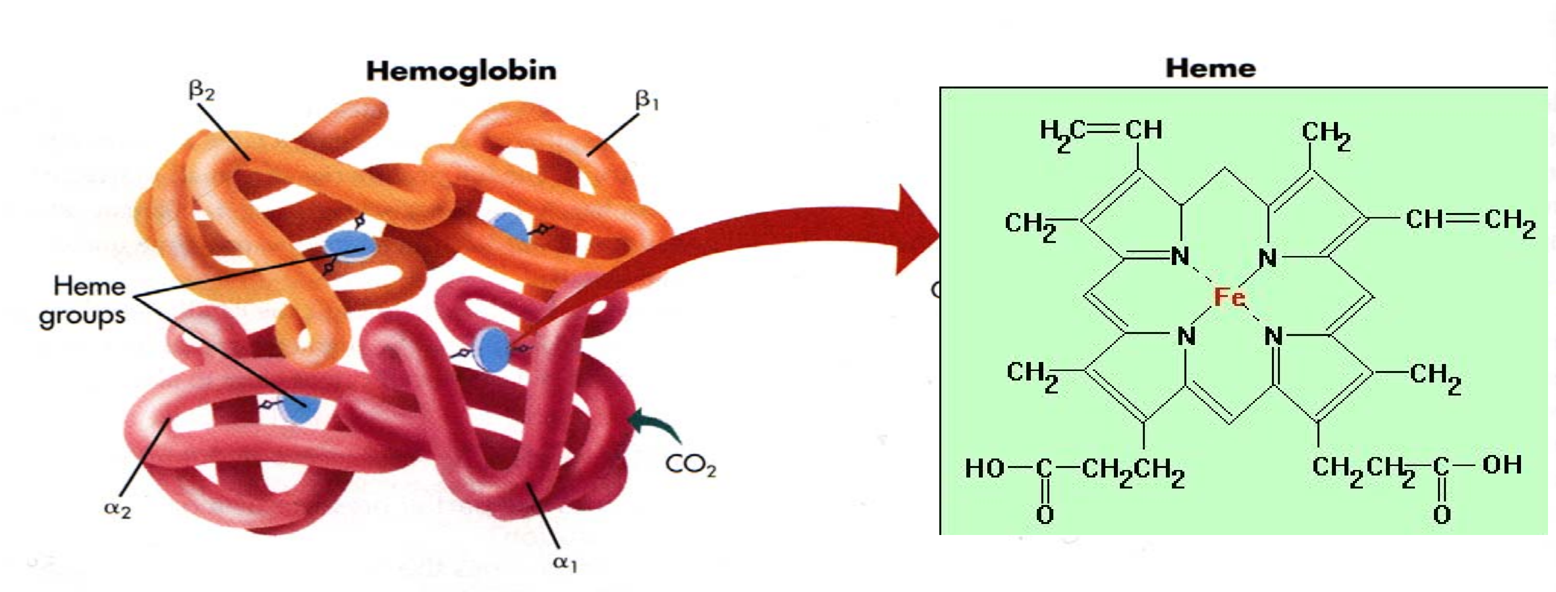
- dissolved in solution 1.5%
- bound to hemoglobin 98.5%



In a situation: blood has no Hb, only 3 ml of O_2 will dissolve in plasma, O_2 consumption at rest: 250 ml/min

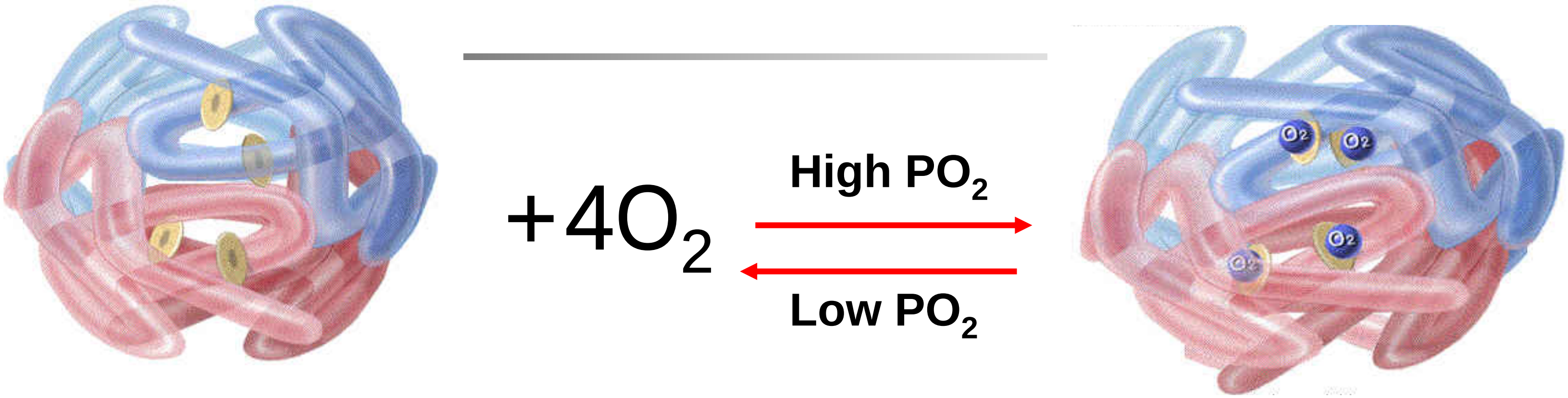
O_2 content of plasma	= 3 mL O_2/L blood
O_2 content of red blood cells	= 0
Total O_2 carrying capacity	3 mL O_2/L blood

Hemoglobin



Each Hb molecule is a protein made up of four subunits bound together. Each subunit consists of a molecule group termed heme and a polypeptide attached to the heme.

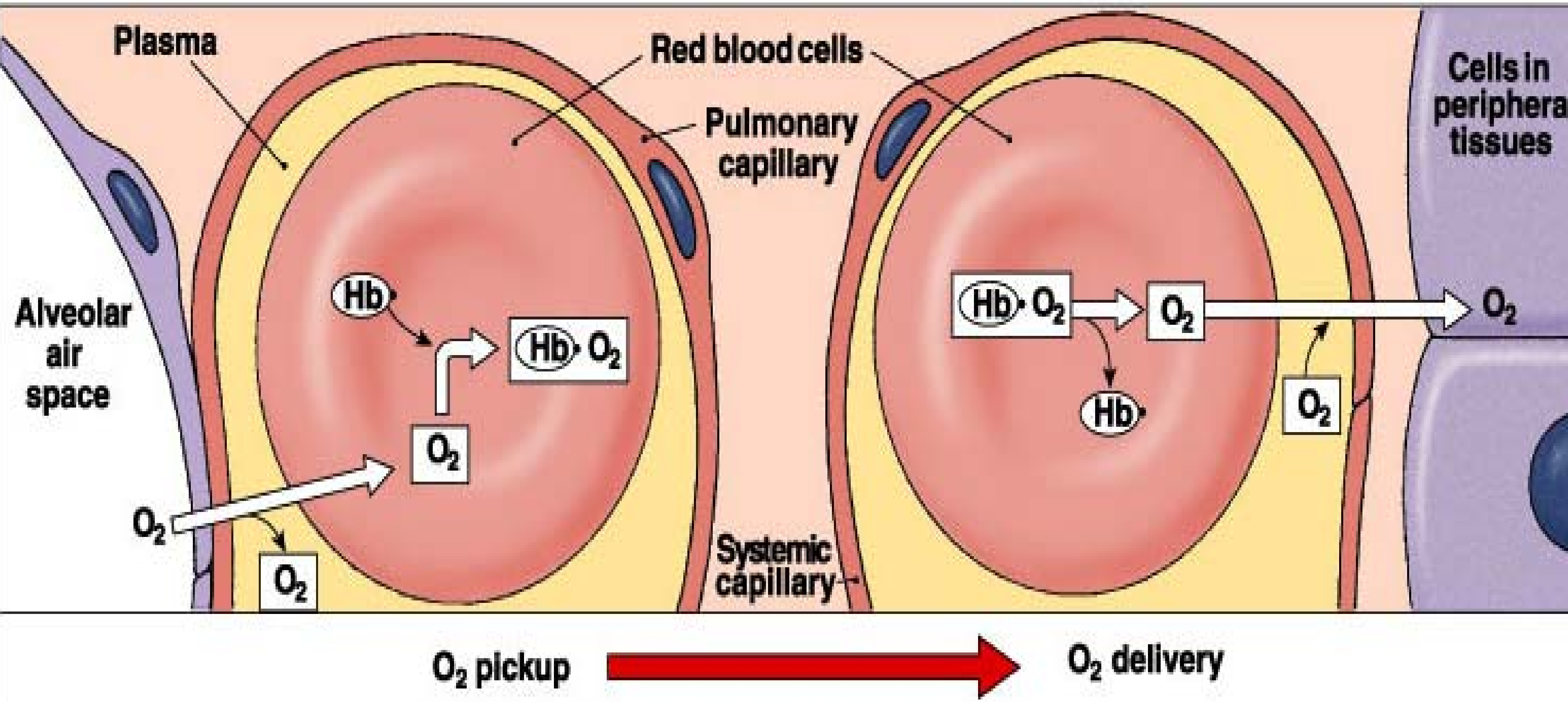
Each of the four heme groups contains one atom of iron, to which oxygen binds. Thus, a single hemoglobin molecule can bind four molecules of oxygen.



Oxygen combines loosely and reversibly with the heme portion of Hb. Oxygen binds with the Hb when PO2 is high, but when PO2 is low, oxygen is released from the Hb.

Fast and reversible, depend on the Po2

Oxygenation rather than oxidation



There are two forms of Hb: deoxyhemoglobin (deoxyHb) and oxyhemoglobin (HbO_2).

The HbO_2 looks in red and deoxyHb looks in blue.

If the deoxyHb concentration is higher than 50g/L, the mucosa of the body looks in lilac.

This condition is called cyanosis.

Cyanosis

- **deoxy Hb>50g/L**

A "blue baby" is an infant born with a congenital heart defect. The defect prevents oxygen-rich blood from circulating to the body, which gives the infant's skin a bluish tint.

- **Oxygen capacity** （氧容量）

the maximum amount of O_2 that can combine with Hb

100ml : 14 g×1.34ml/g= 18.8ml O_2

- **Oxygen content** （氧含量）

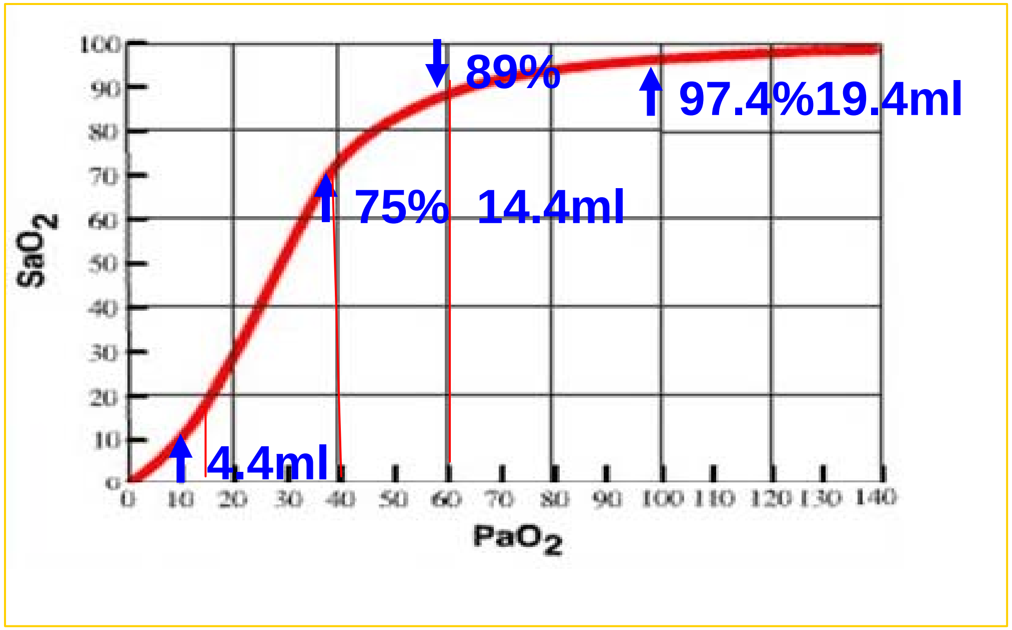
the amount of O_2 that combine with Hb. 15ml O_2

- **Oxygen saturation** 15ml / 18.8ml ×100% = 80%

(O_2 content / O_2 capacity)×100%

Hemoglobin-O_2 dissociation curve

The relationship between plasma PO_2 & oxygen saturation



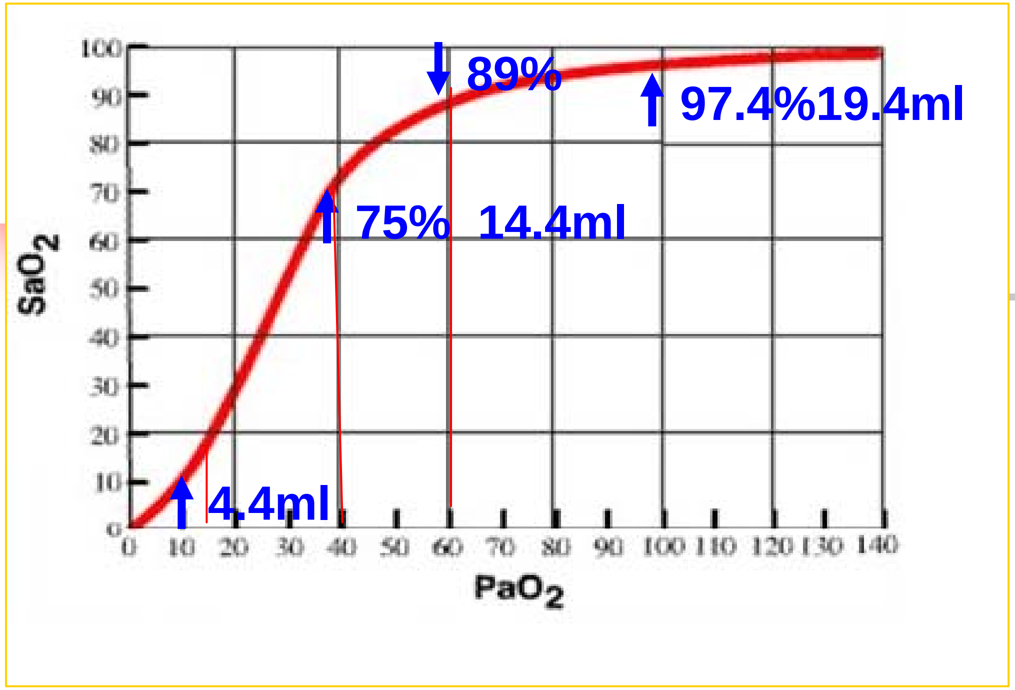
The curve is sigmoid shaped. Because the 4 subunits react sequentially, with each combination facilitating the next one.

The curve has a deep slope between 15 and 60 mmHg PO2

60mmHg: a further increase in PO2 produces only a small increase in SaO2

Upper part: (plateau) PO2 fell, only a few decrease of the total quantity of O2

(pulmonary disease or high altitude) The plateau provides an excellent safety factor such that a significant limitation of lung function can still allow almost normal oxygen saturation of Hb.



The middle portion of the curve is ideal for unloading O2 in the tissues, because any further decreases in PO2 can results in a large amount of oxygen unloaded in the capillaries of the peripheral tissue.

The lower portion of the curve reflexes the reserve of O2 in the blood.

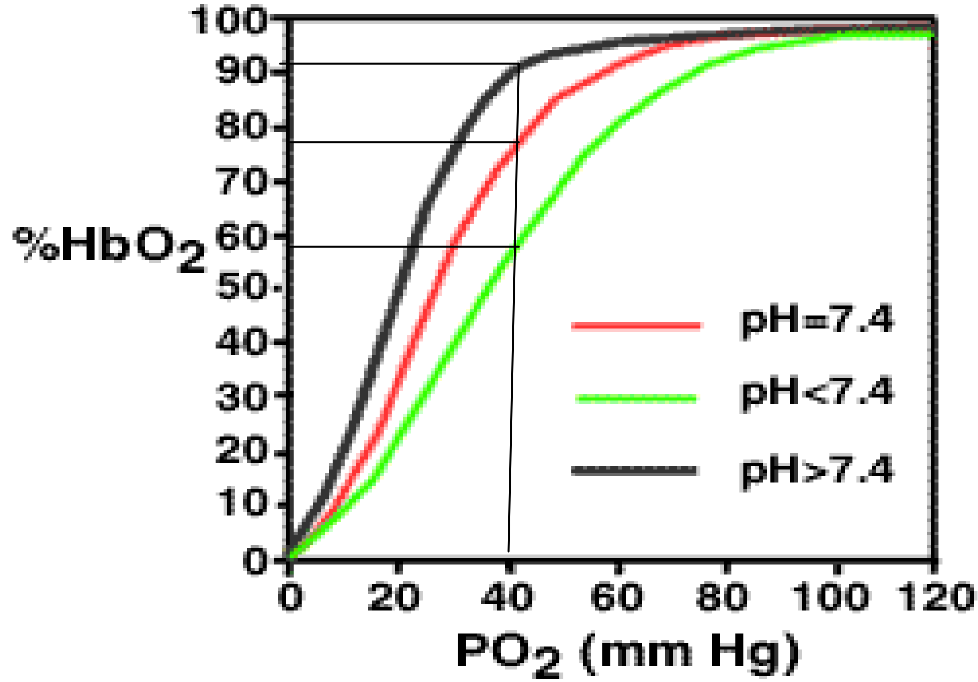
When the metabolism is enhanced, PO2 continues to fall , even down to 15.

Each 100 ml of blood unloads 15 more mL of oxygen.

Factors that shift O_2 dissociation curve

- P_{CO2} and $[H^+]$
- Temperature
- 2,3-DPG

Effects of PCO_2 & pH



Bohr effect

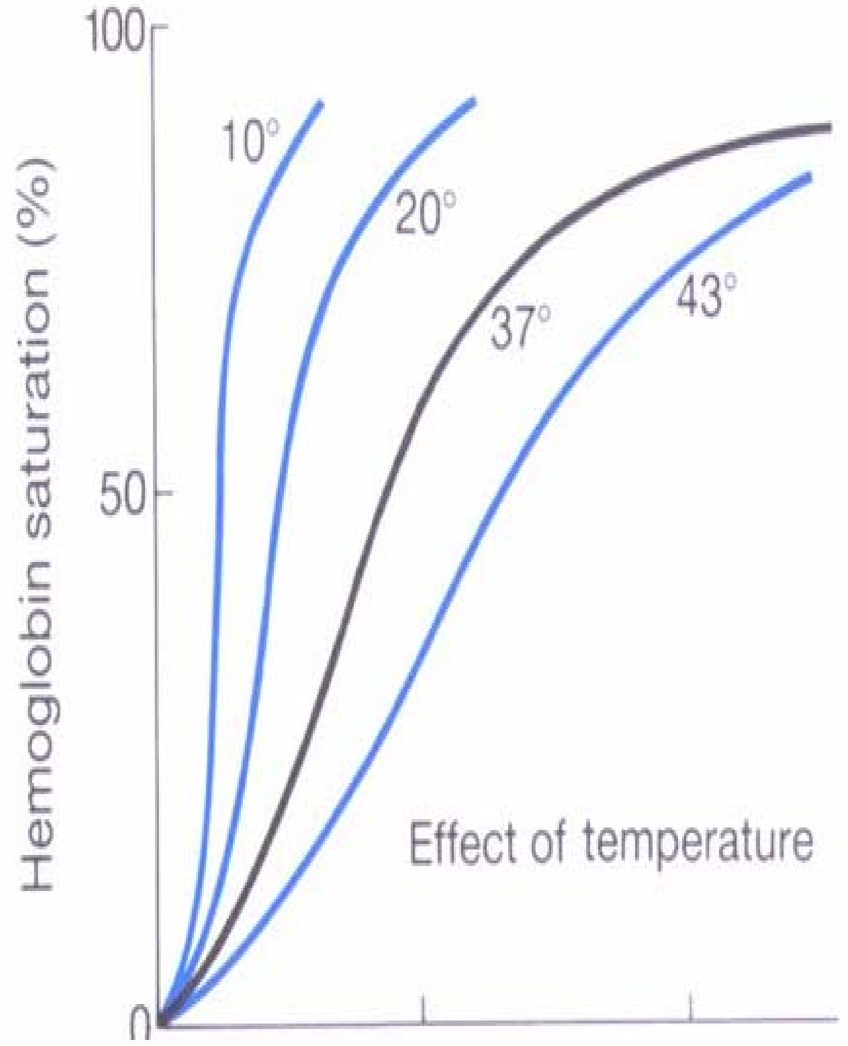
（波尔效应）

- **Mechanism:** [H^+] **affect the conformation of Hb**
- **Physiological significance:**
  - **- Lung: combination of oxygen & Hb**
  - **- Tissue: dissociation of oxygen & Hb**

Effect of temperature

- **Exercise, fever**
- **Anaesthesia**

Low temperature



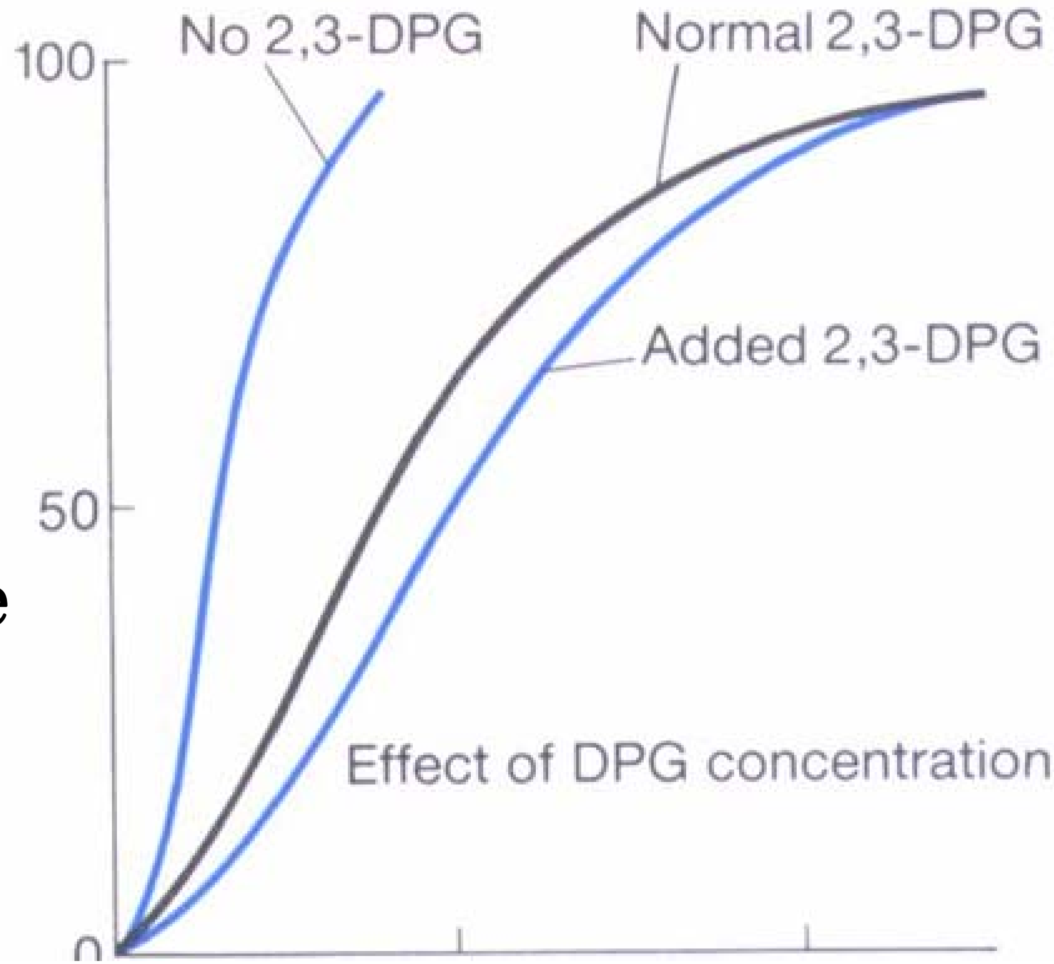
Effect of DPG (diphosphoglycerate)

- **Product by glycolysis（糖酵解）in RBC**
- **Hypoxia**
- **Stored blood**

  （>3 weeks）

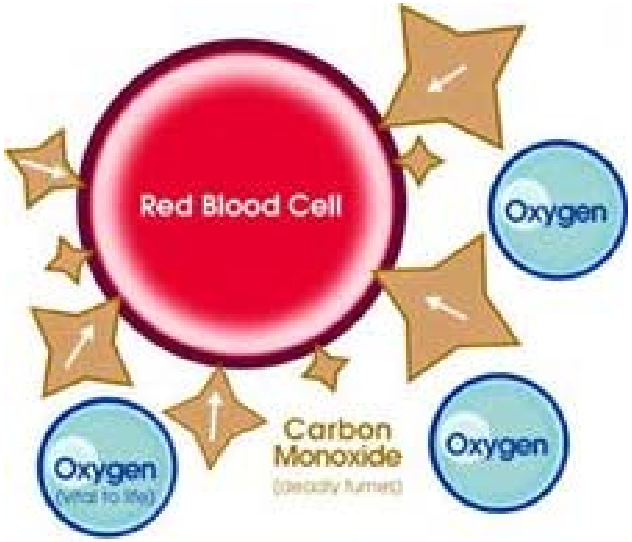
Glycolysis cease

DPG decrease



Carbon Monoxide Poisoning

- **CO competes for O_2 sides in Hb**
- **CO has extremely high affinity for Hb**



Transport of Carbon dioxide

- **Forms of CO_2 transport**
- **Carbon dioxide dissociation curve**
- **Factors affecting carbon dioxide dissociation curve**

Forms of CO_2 transport

- **Dissolved state: 7%**
- **Chemical combination: 93%**

（1）Carbaminohemoglobin（氨基甲酰血红蛋白）

$$HbNH_2O_2 + H^+ + CO_2 \underset{\text{Lung}}{\overset{\text{Tissue}}{\rightleftharpoons}} HHbNHCOOH + O_2$$

HbNH2

CO2 react reversibly with the amino groups of Hb form CH. This reaction goes rapidly without enzyme assistance.

Hb is more powerful to bind CO2 and form CH than HbO2.

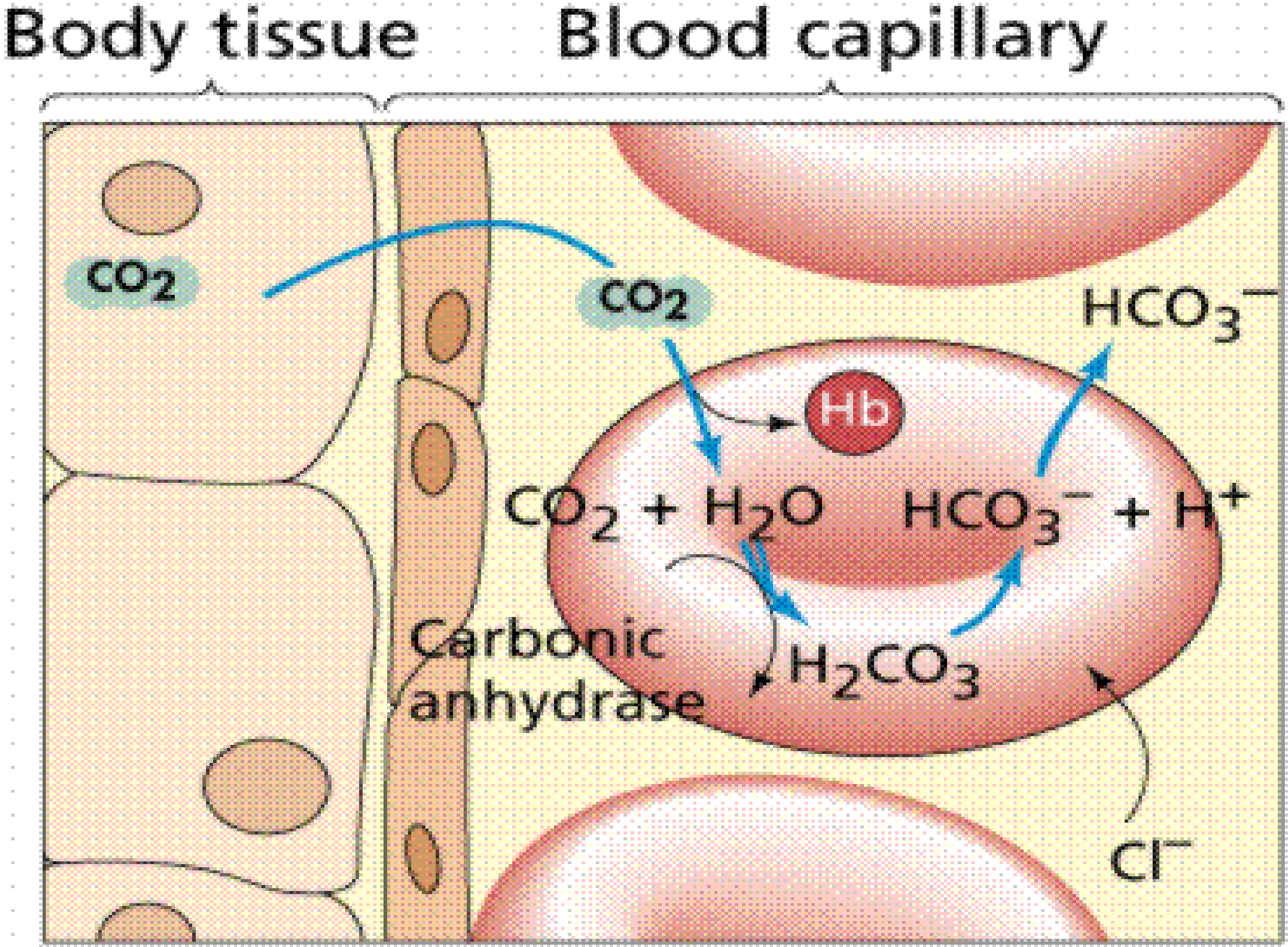
In the tissues, HbO2 releases O2 to from Hb, which binds CO2 to from CH.

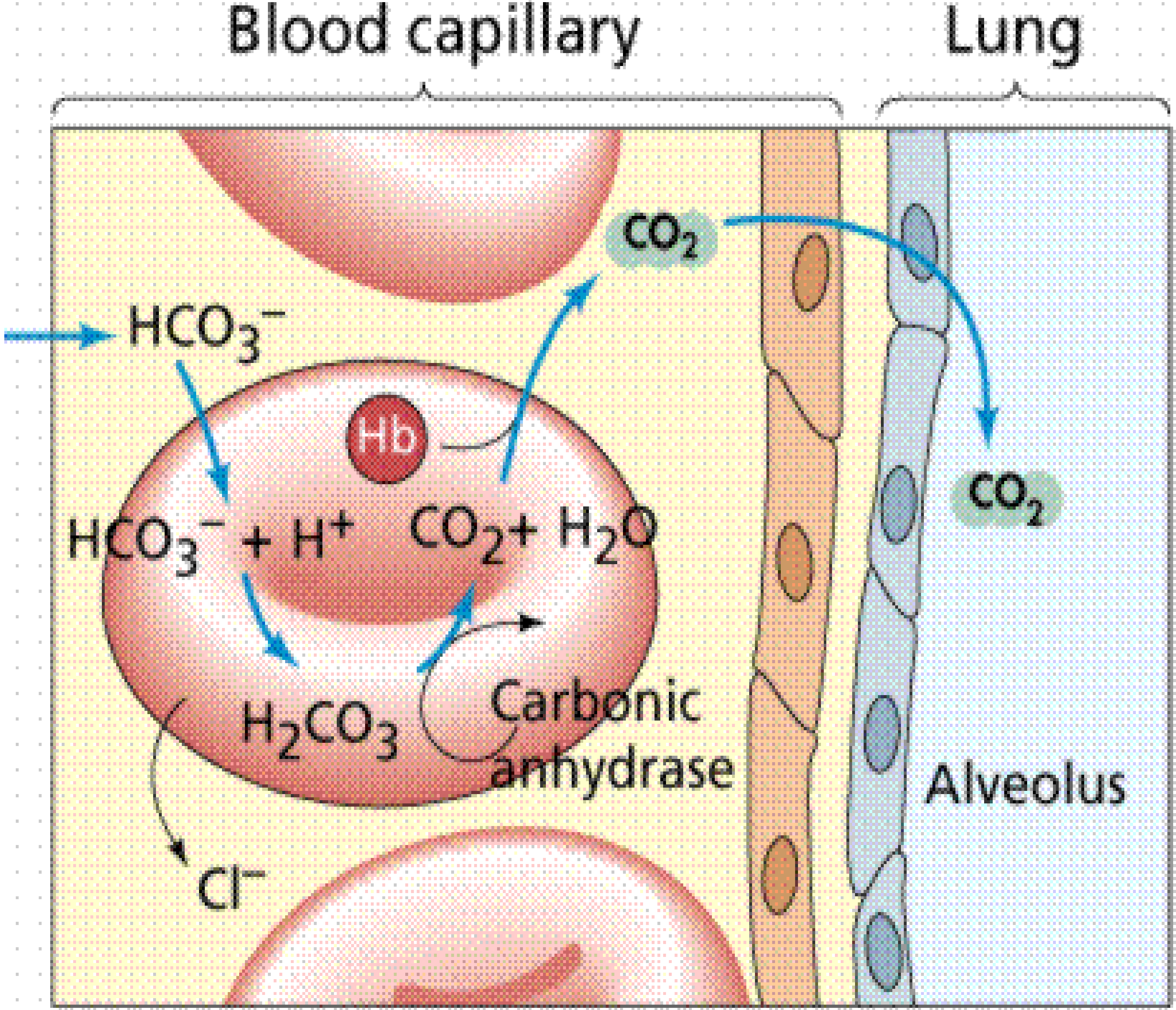
In the lungs, more HbO2 is produced, causing CH to release CO2 and H+.

$$HbNH_2O_2 + H^+ + CO_2 \underset{\text{Lung}}{\overset{\text{Tissue}}{\rightleftharpoons}} HHbNHCOOH + O_2$$

HbNH2

（2） Bicarbonate ion (HCO_3^-)





Blood capillary
Lung
CO_2
HCO_3^-
Hb
$HCO_3^- + H^+$
$CO_2 + H_2O$
CO_2
H_2CO_3
Carbonic anhydrase
Alveolus
Cl^-

Carbon dioxide dissociation curve

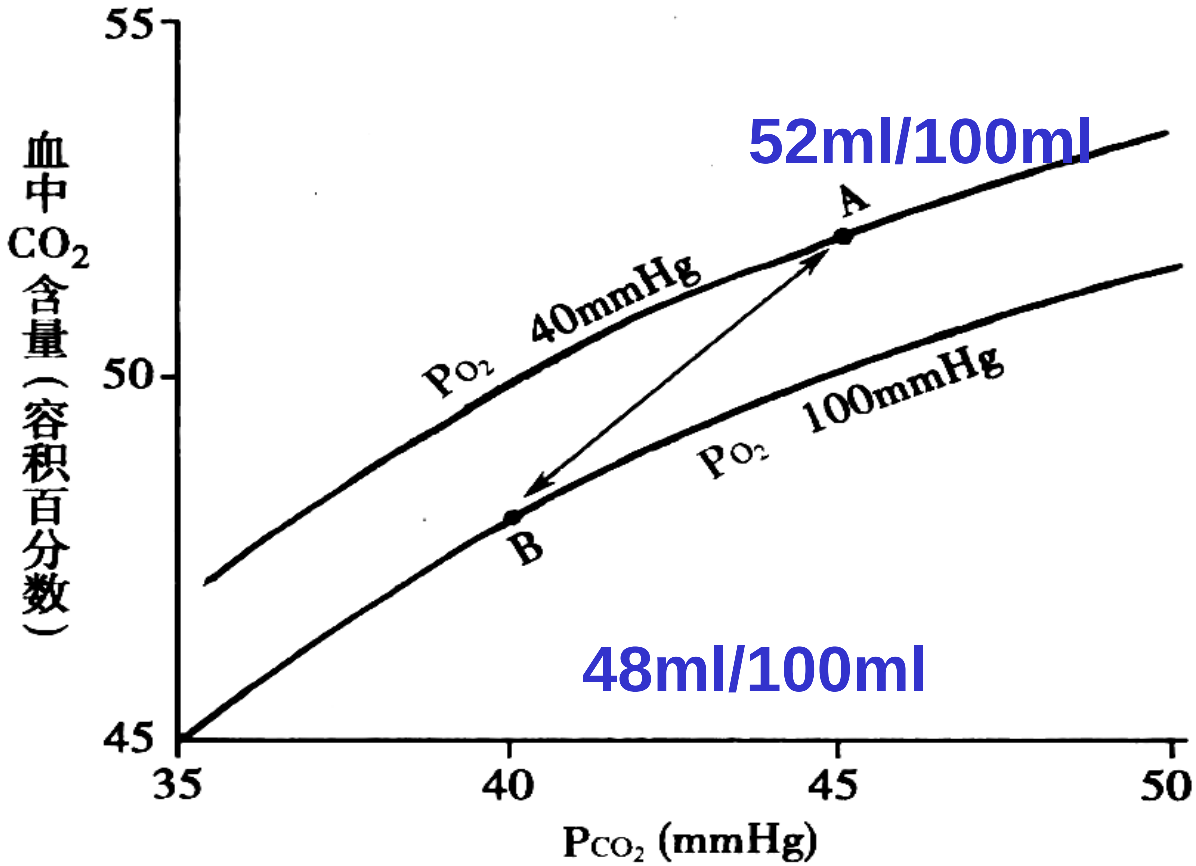


图 5-15 CO_2 解离曲线

A:静脉血 B:动脉血 （1mmHg＝0. 133kPa）