O_2 concentration and partial pressure in the alveoli

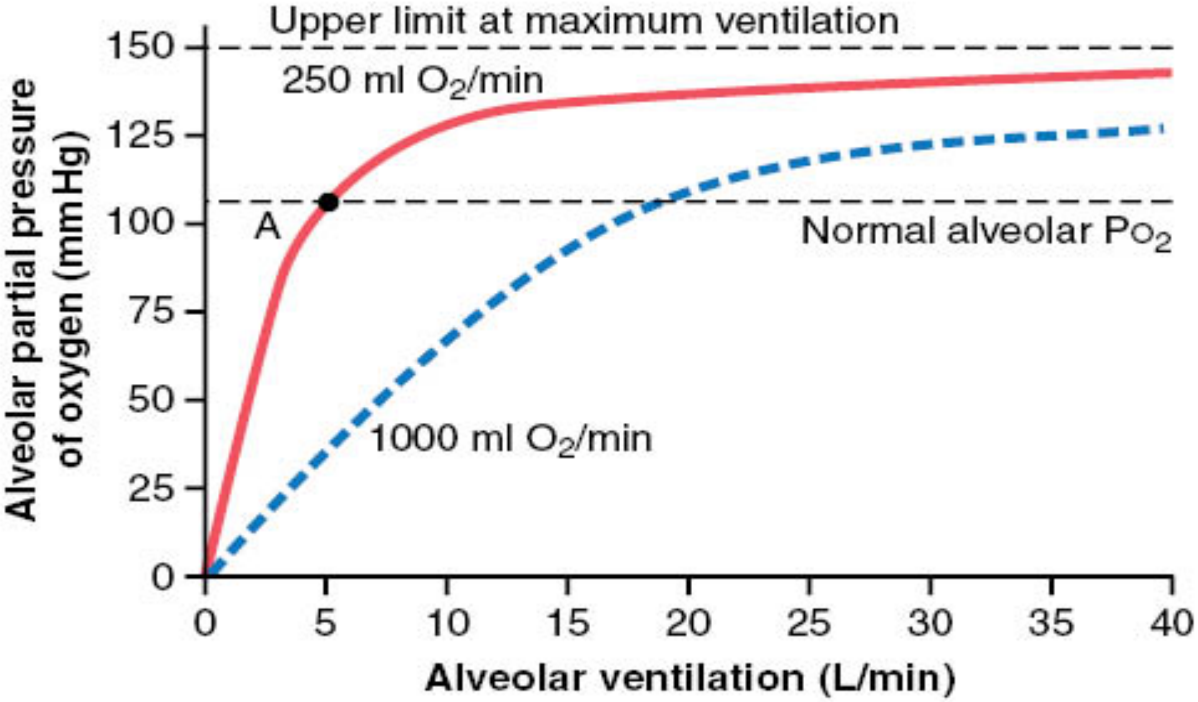


Figure 39-4 Effect of alveolar ventilation on the alveolar PO_2 at two rates of oxygen absorption from the alveoli—250 ml/min and 1000 ml/min. *Point A* is the normal operating point.

CO_2 concentration and partial pressure in the alveoli

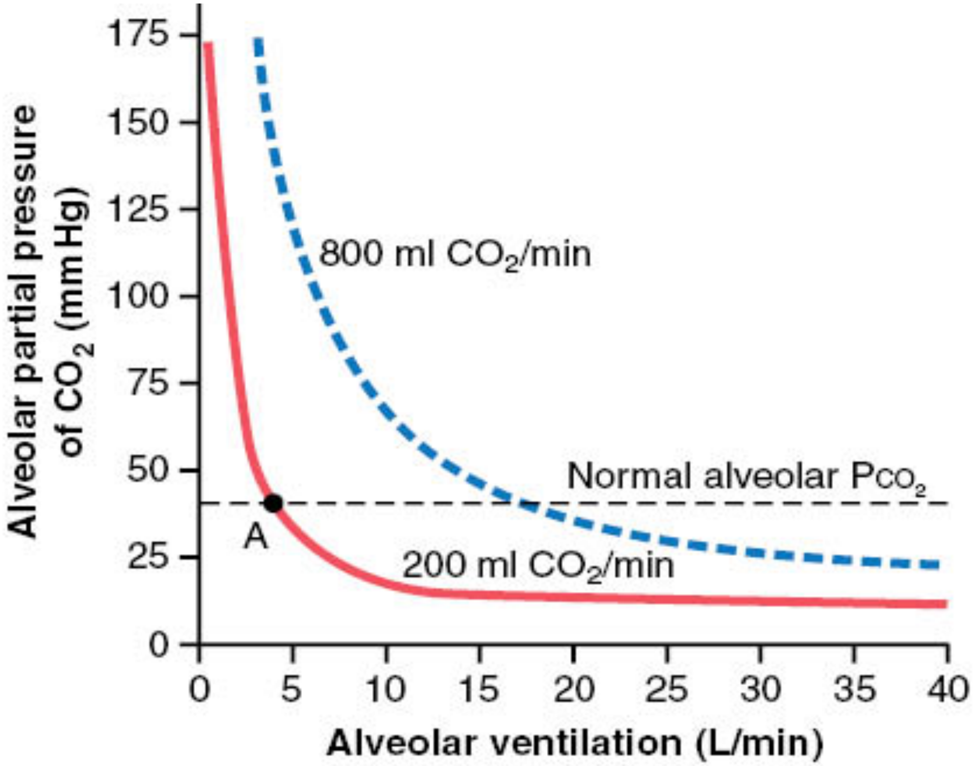
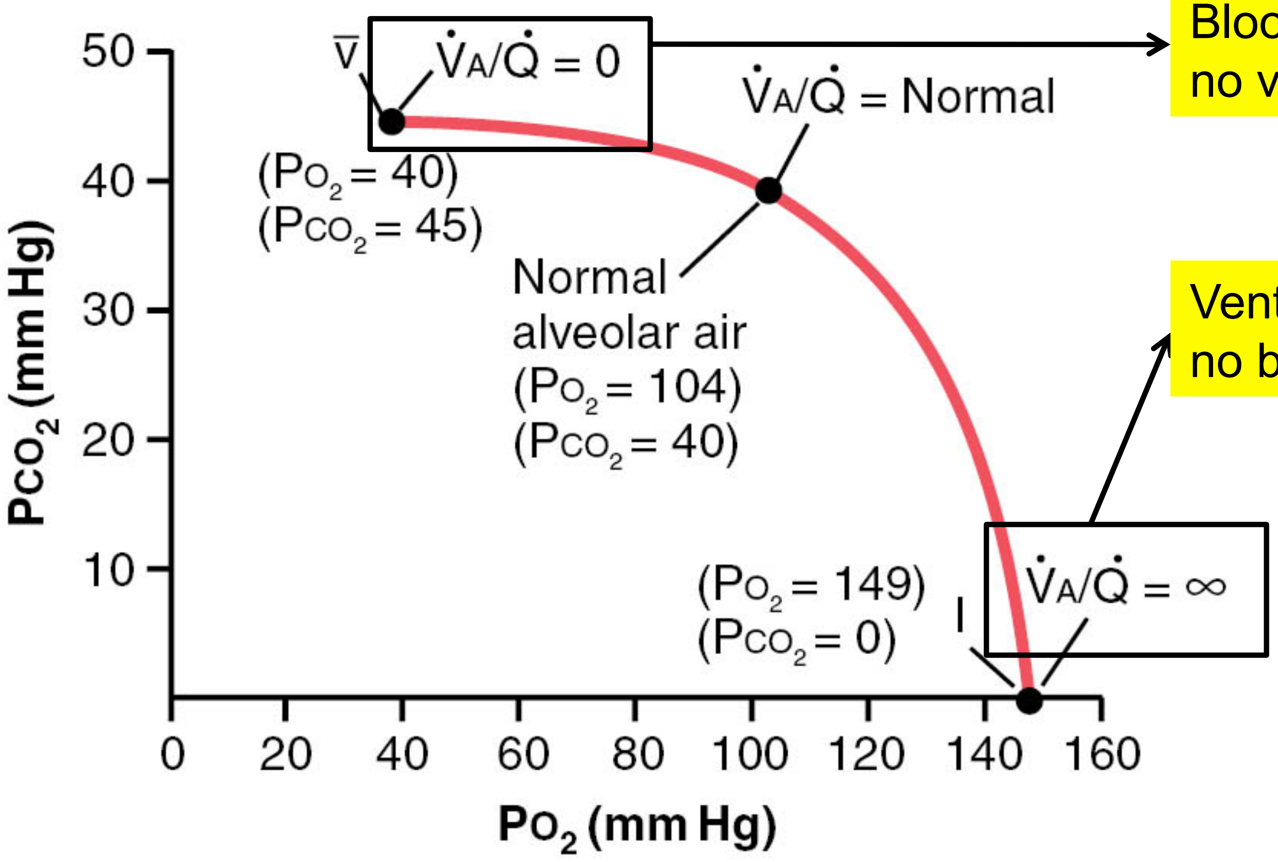


Figure 39-5 Effect of alveolar ventilation on the alveolar PCO_2 at two rates of carbon dioxide excretion from the blood—800 ml/min and 200 ml/min. *Point A* is the normal operating point.

Max/min alveolar ventilation-perfusion ratios



Blood flow but no ventilation

Ventilation but no blood flow

Figure 39-11

Biology 3UO3 - 2012
Animal Physiology

Transport of O_2 and CO_2 in blood and tissue fluids

__Readings:__
Chapter 40:
pgs. 495-504

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

O_2 and CO_2 transport

- Blood transports O_2 and CO_2 between the lungs and other tissues in the body
- These gases are transported in several forms:
  - Dissolved in the plasma
  - Chemically combined with hemoglobin
  - Converted into different molecules

Goals for today's lecture:

- Explore how O_2 is transported in the blood
- Explore how CO_2 is transported in the blood
- Understand the effect of variables such as partial pressure on O_2 and CO_2 transport

What you need to know (ie review)

- Definition of partial pressure
- Process of external and internal respiration
- Definition of a buffer

Sites of gas exchange

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

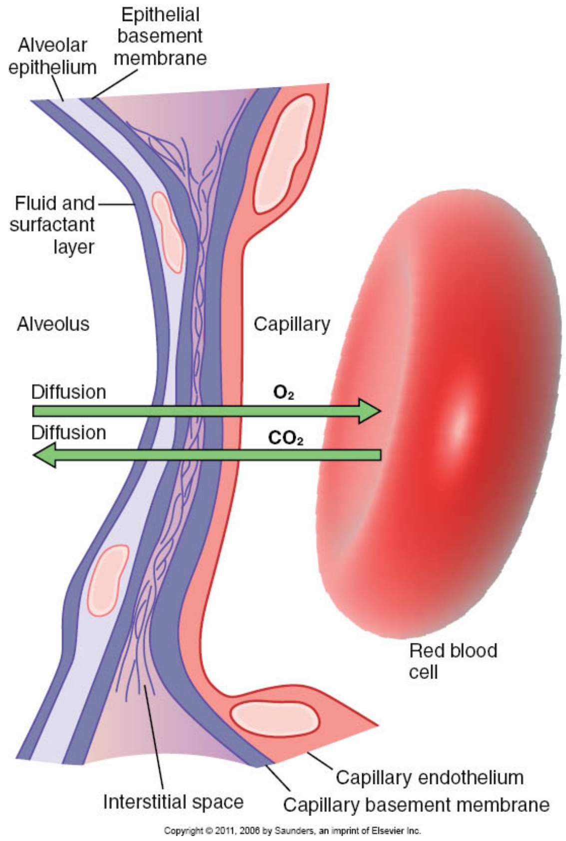
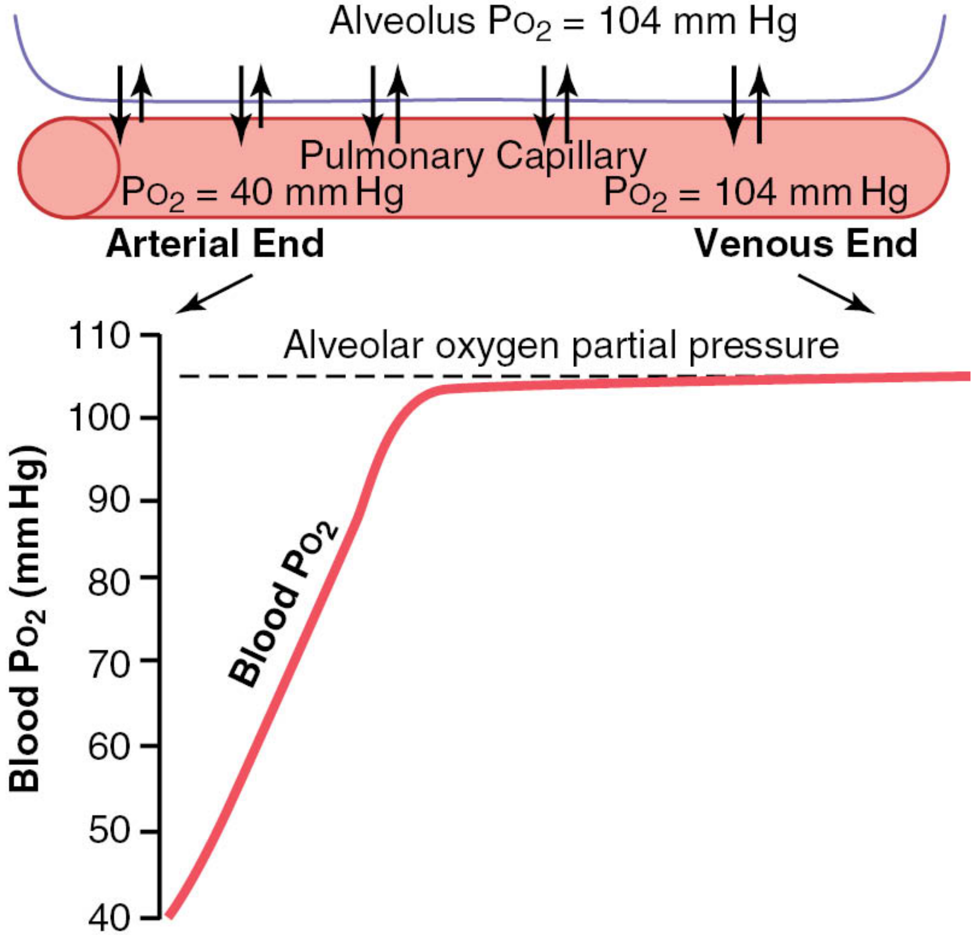


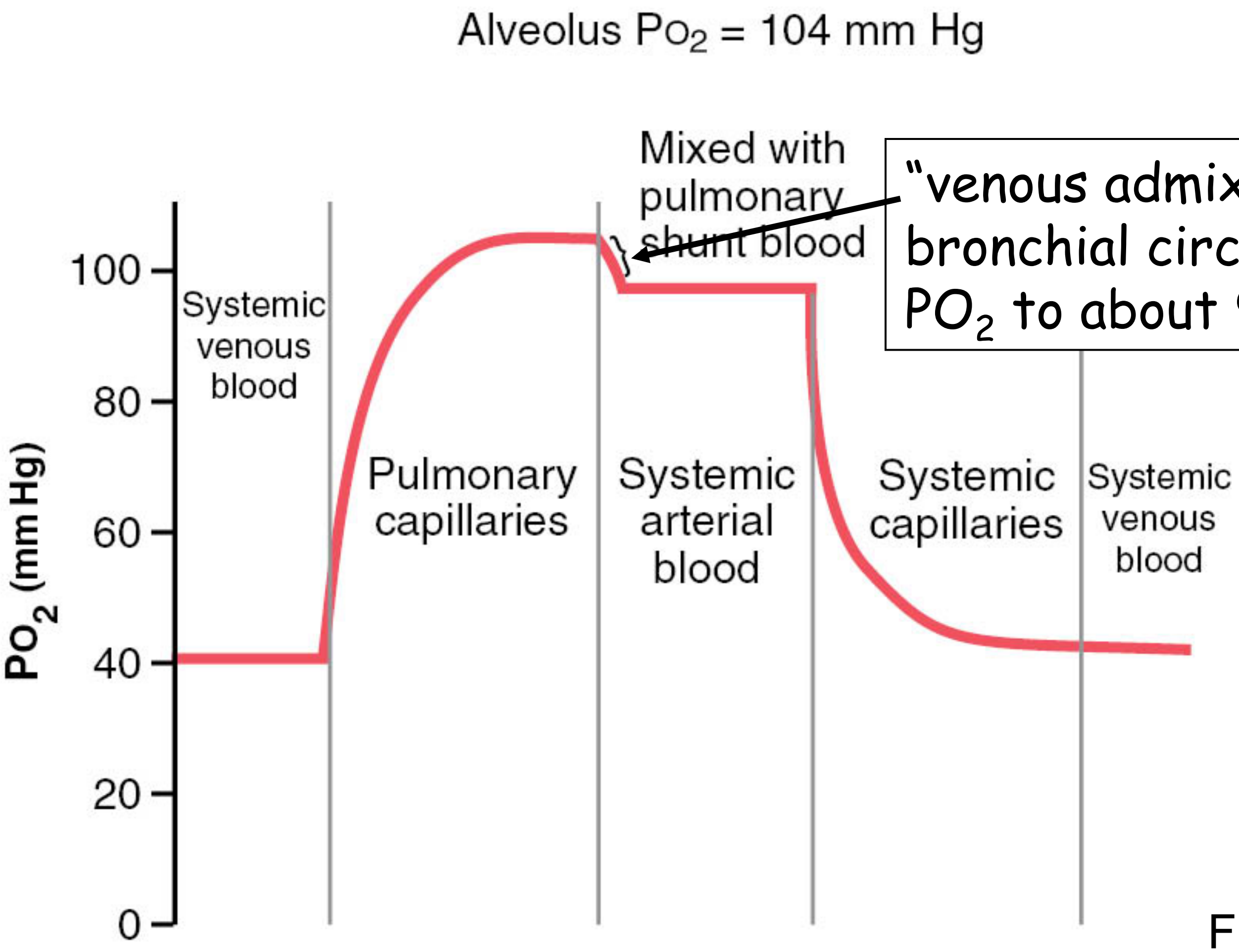
Figure 39-9

O_2 diffusion at Alveolus-Pulmonary Capillary Boundary



(The curve in this figure was constructed from data in Milhorn HT Jr, Pulley PE Jr: A theoretical study of pulmonary capillary gas exchange and venous admixture. Biophys J 8:337, 1968.)

Blood in pulmonary capillaries equilibrates rapidly with PO_2 in alveoli (by the time it has passed about 1/3 the way down the capillary – safety margin)



"venous admixture" from bronchial circulation lowers PO_2 to about 95-100 mm Hg

Fig. 40-2

PO_2 ("driving force") changes from about 104 mm Hg at pulmonary capillaries to 40 mm Hg at systemic capillaries

PO_2 at systemic capillaries

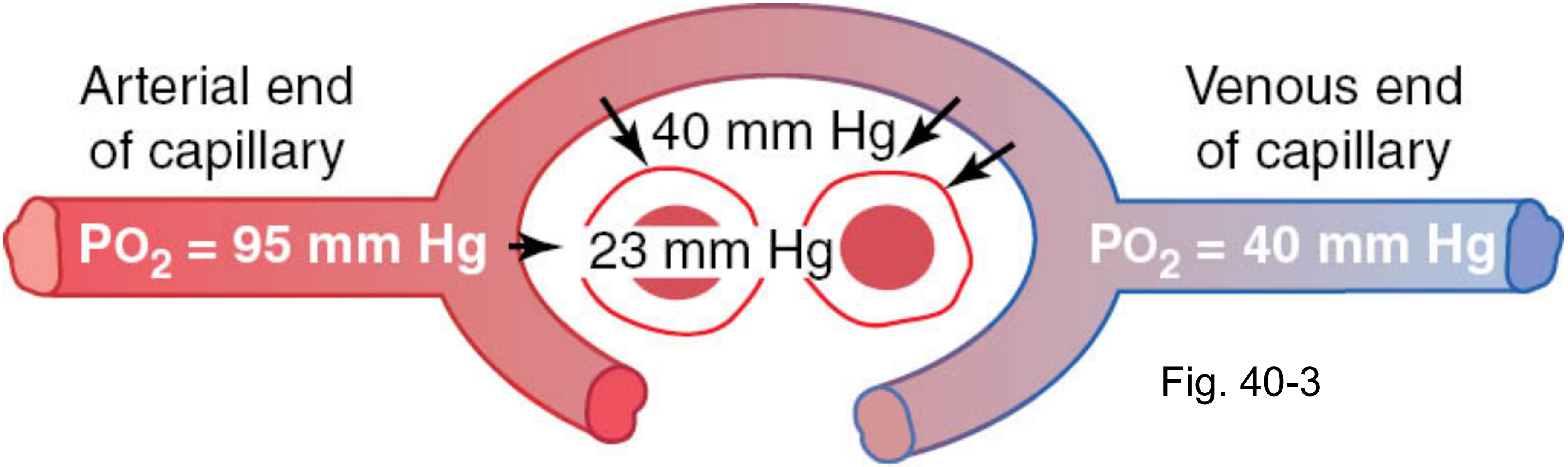


Fig. 40-3

Arterial blood passing through the systemic capillaries encounters a low PO_2 and gives up O_2 by diffusion along a PO_2 gradient

Blood leaving systemic capillaries has PO_2 close to equilibrium with that in the tissue/interstitial fluid.

Lower PO_2's mean that more O_2 will be unloaded to the tissues and result in lower venous PO_2 (~40 mm Hg at rest, but lower during exercise)

PCO_2 at systemic capillaries

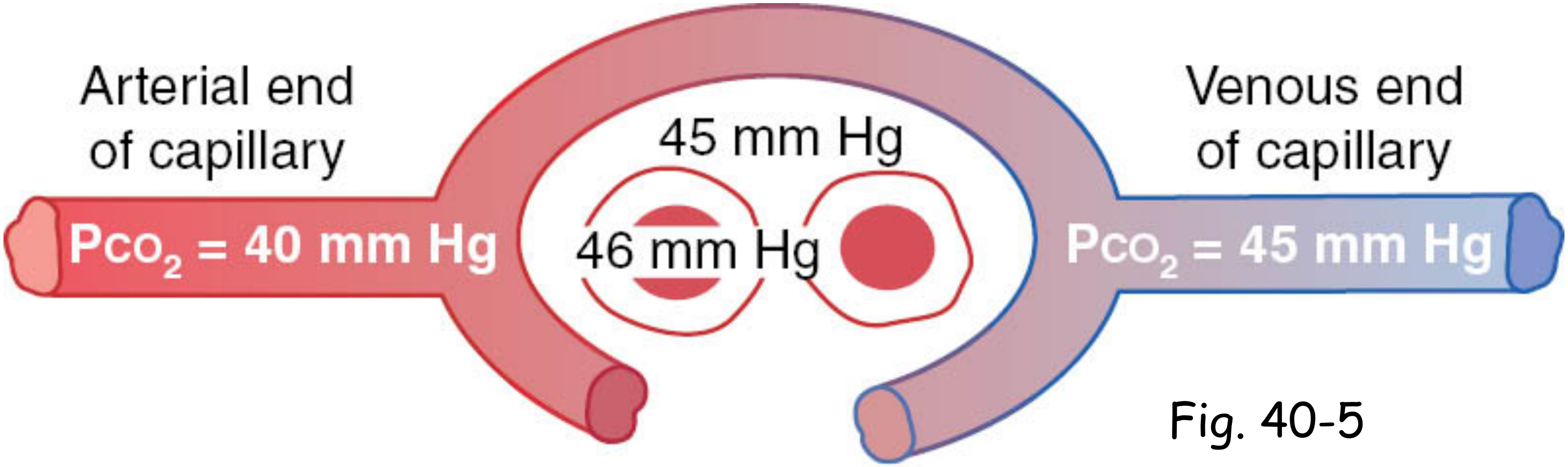


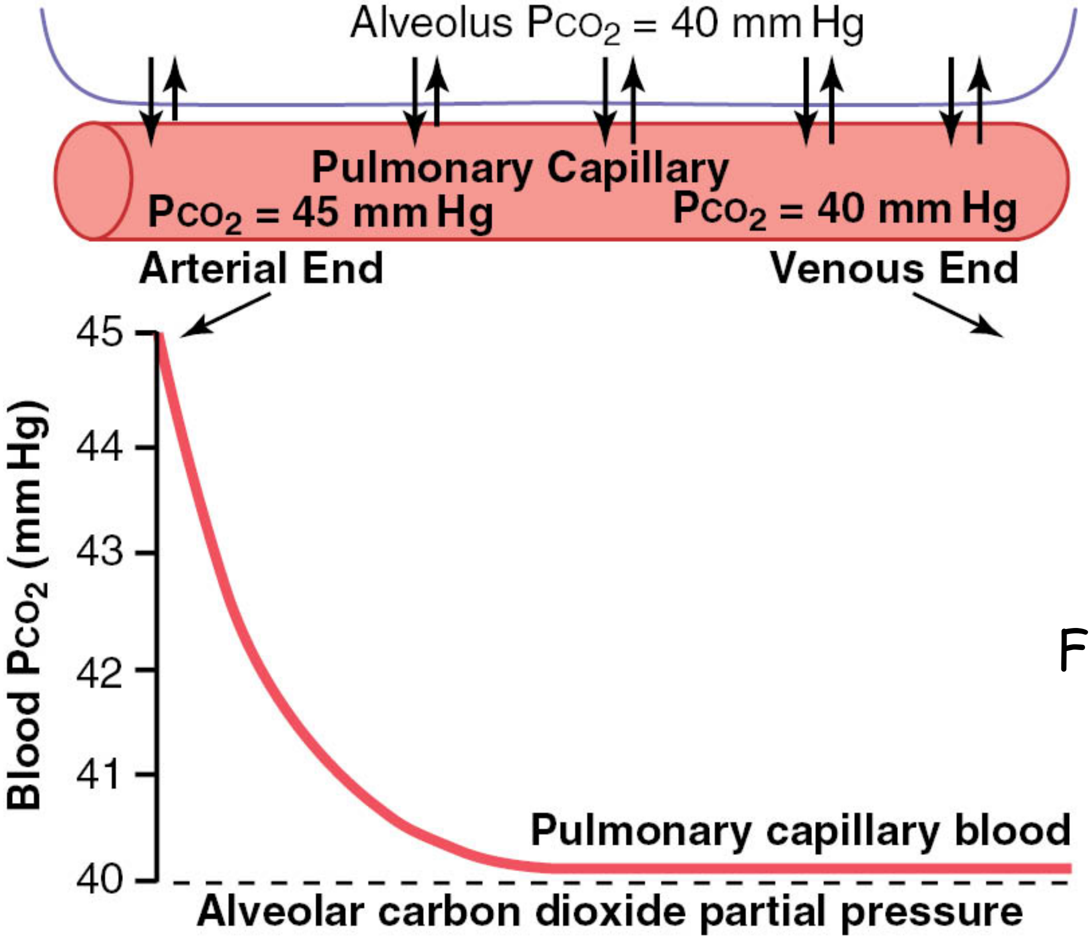
Fig. 40-5

Venous blood leaving systemic capillaries has PCO_2 at equilibrium with that in the interstitial fluid

The higher the tissue PCO_2, the more CO_2 will be given up by the tissues to the blood, & the higher will be venous PCO_2

Venous PCO_2 ~ 45 mm Hg at rest, but higher during exercise

CO_2 diffusion at Alveolus-Pulmonary Capillary Boundary



(This curve was constructed from data in Milhorn HT Jr, Pulley PE Jr: A theoretical study of pulmonary capillary gas exchange and venous admixture. Biophys J 8:337, 1968.)

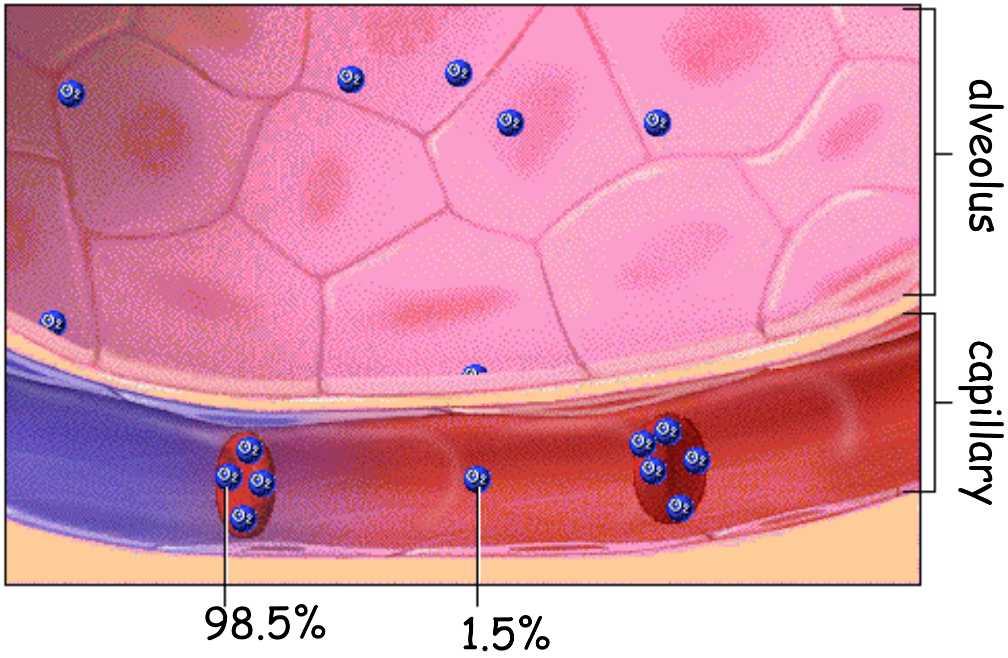
Fig. 40-6

Reciprocal process occurs with CO_2, but PCO_2 gradients are much smaller than PO_2 gradients (CO_2 ~20 times more soluble than O_2)

O2 transport during external respiration

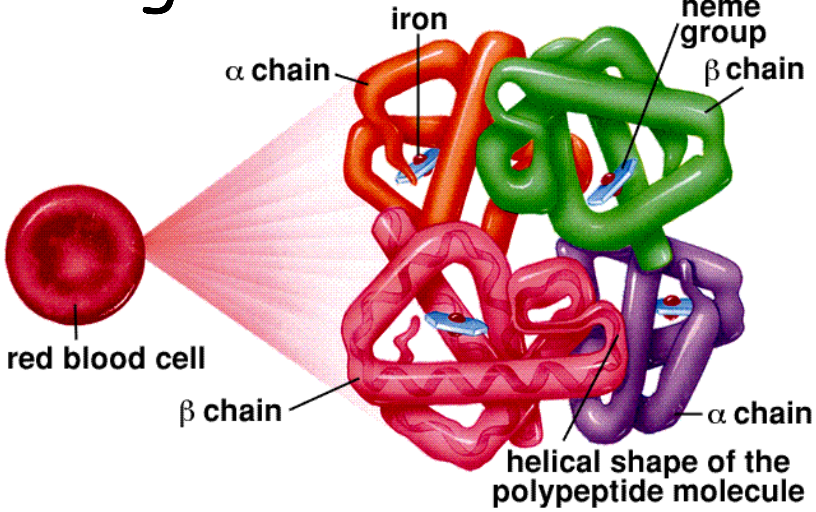
- O_2 has low solubility, little dissolves in plasma

- majority of O_2 combines with hemoglobin



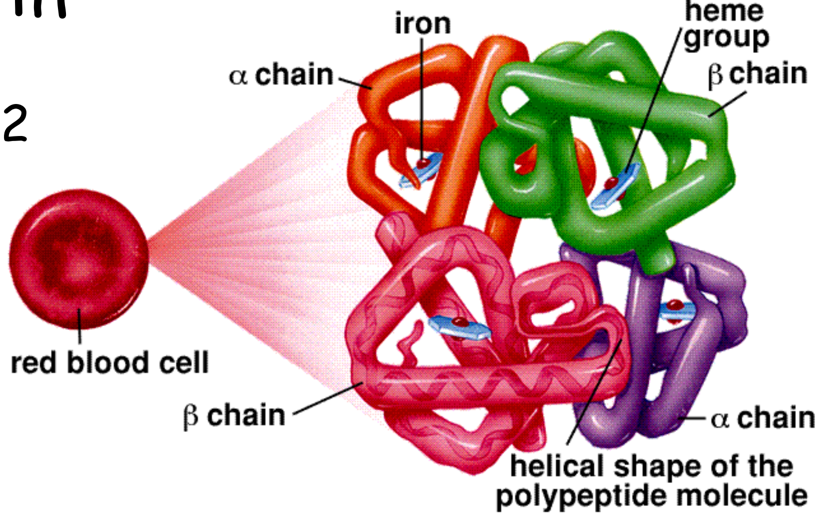
Hemoglobin

- Each red blood cell (RBC) has approx. 250 million hemoglobin (Hb) molecules
- Hb composed of four polypeptide subunits with heme groups containing Fe2+
- A single Hb can transport up to four O_2's



Hemoglobin

- With four O_2 bound, Hb is fully saturated
- If less then four O_2 bound, partially saturated
- O_2 binding occurs in response to high PO_2
- O_2 unloading in response to low PO_2

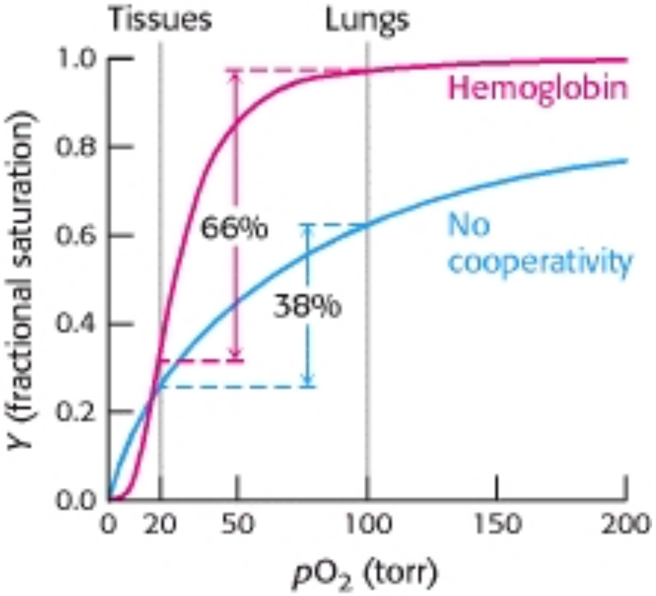


Hemoglobin

- When oxygen binds to hemoglobin it is referred to as oxyhemoglobin

- **Allosteric modulation**:

Conformational changes due to first O_2 binding facilitates cooperative binding



In other words, Hb affinity for O_2 increases as its saturation increases

Oxyhemoglobin and deoxyhemoglobin

$$\underset{\text{(deoxyhemoglobin)}}{\mathrm{Hb}} \quad + \quad \mathrm{O_2} \quad \underset{\text{tissues}}{\overset{\text{lungs}}{\rightleftarrows}} \quad \underset{\text{(oxyhemoglobin)}}{\mathrm{HbO_2}}$$

Similar to what we observe for O_2 loading, Hb's affinity for O_2 decreases as its saturation decreases

Oxygen-hemoglobin dissociation curve

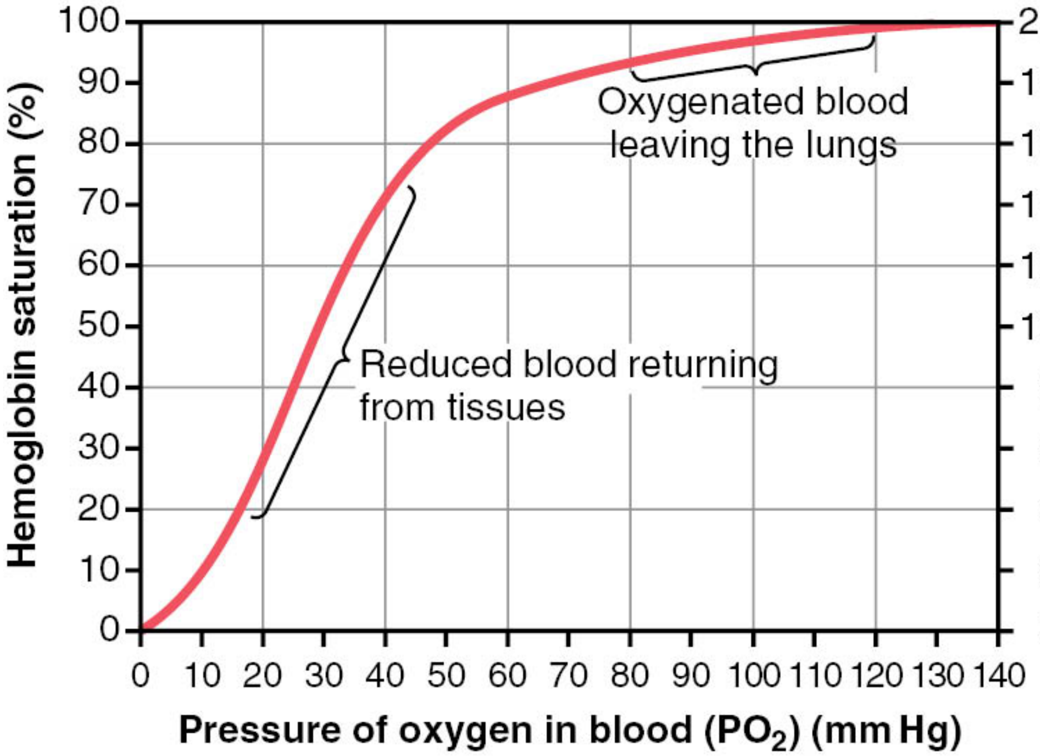


Figure 40-8

- Hb saturation determined by PO_2 (variable in organs)
- Notice the sigmoidal shape of the curve – flat slope at high PO_2 and steep slope at low PO_2

Oxygen-hemoglobin dissociation curve

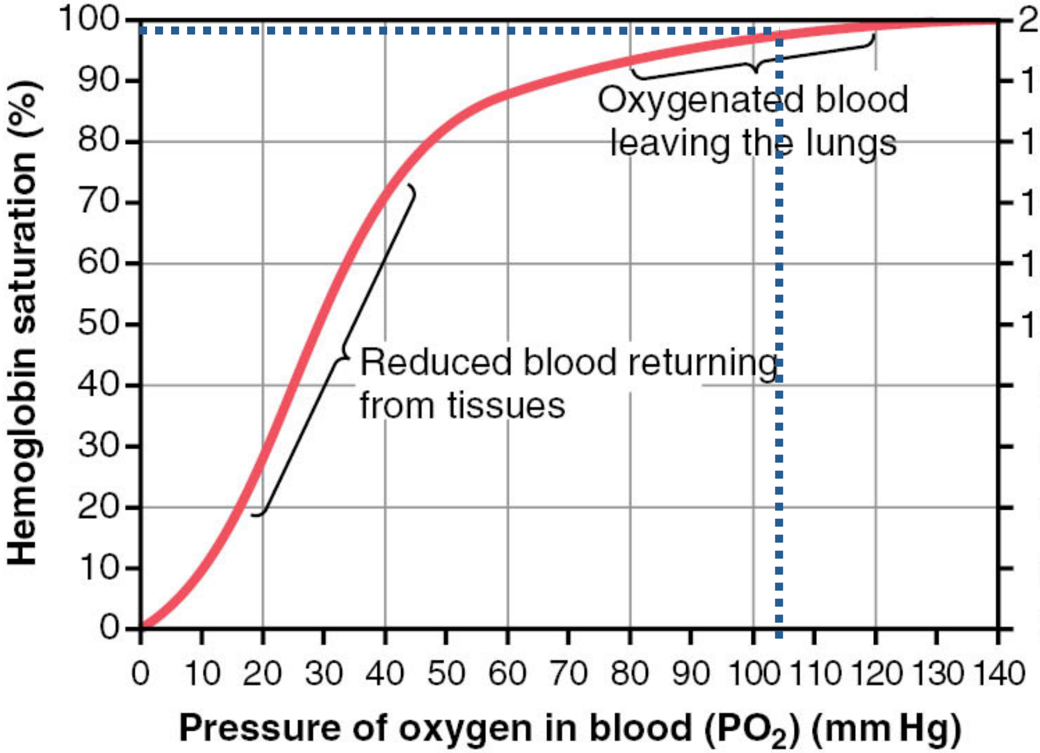


Figure 40-8

- In the alveoli: PO_2 = 104 mm Hg
  Hb = 98% saturated

Oxygen-hemoglobin dissociation curve

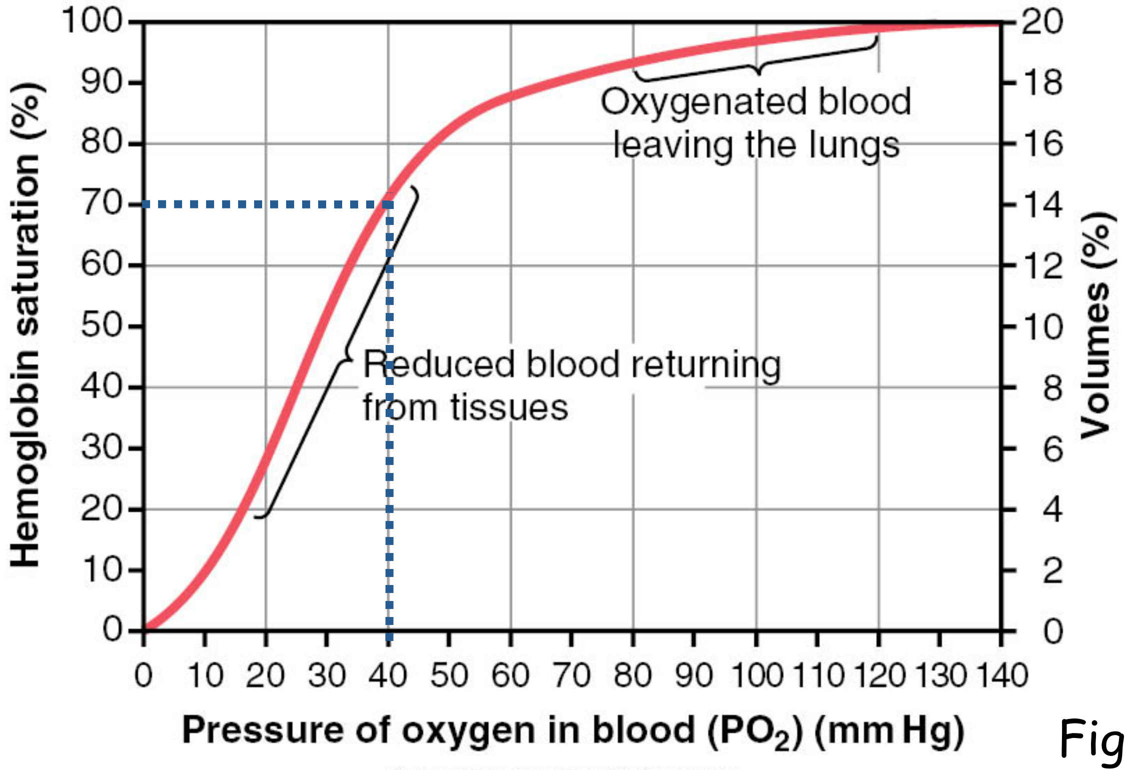
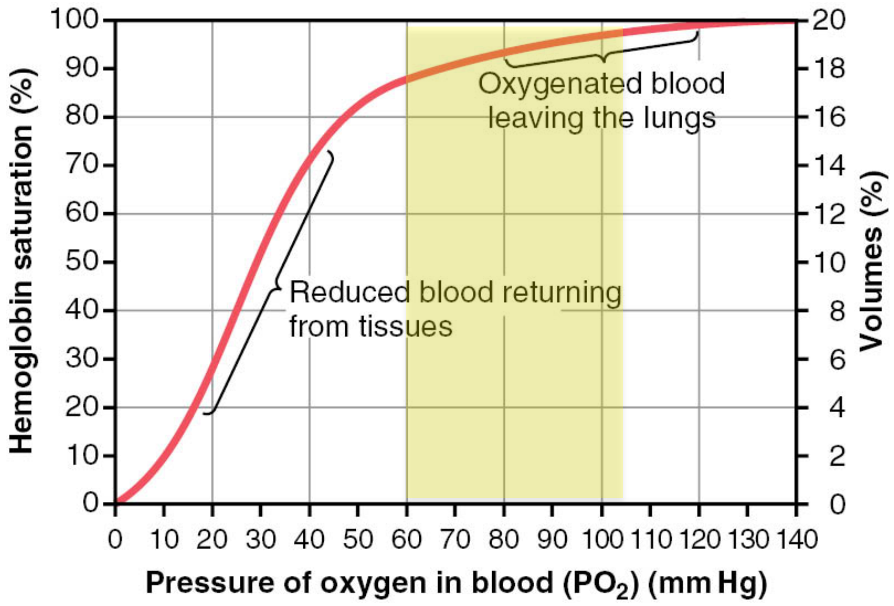


Figure 40-8

- In the tissues: PO_2 = 40 mm Hg
  Hb = 70% saturated

Hb saturation at higher PO_2

In the lungs:

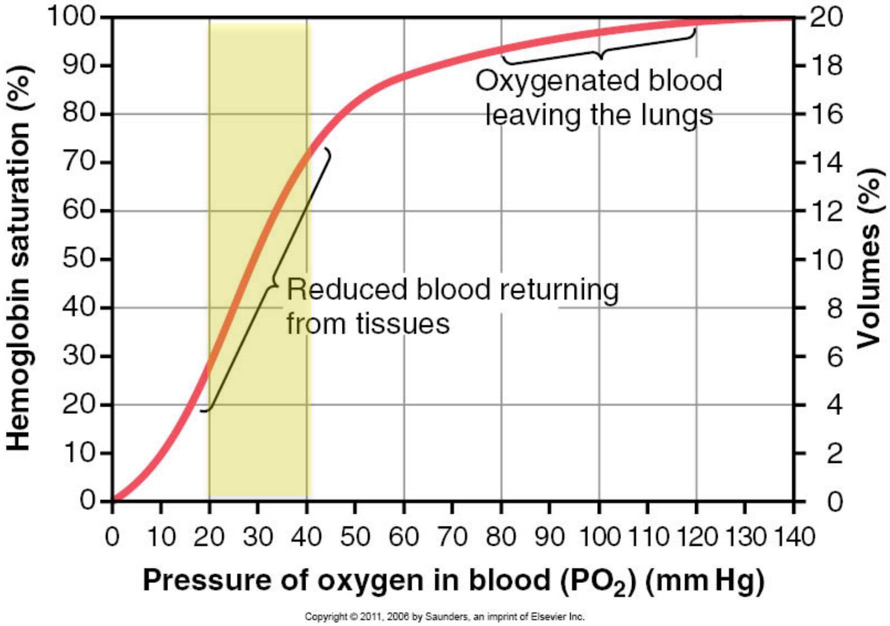


- At sea level, Hb is 98% saturated
- At higher elevations or in some cardiopulmonary diseases, Hb remains >90% saturated
- The flat slope indicates Hb ability to maintain high O_2 binding affinity over higher PO_2!!!

Hb saturation at lower PO_2

In the tissues:

- PO_2 of 40 mm Hg typical in resting organs, so Hb remain 75% saturated



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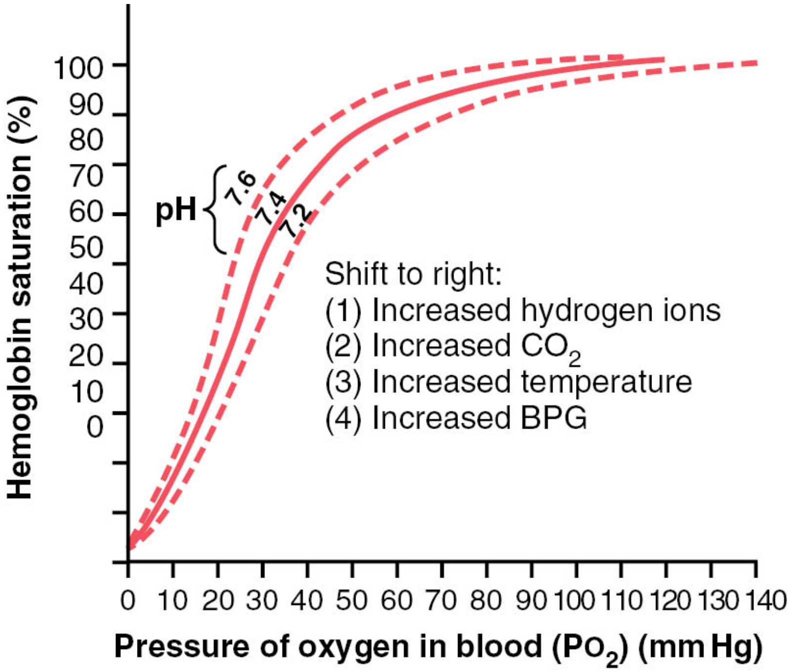
- PO_2 of highly active tissues (e.g. vigorously contracting muscle) uses more O_2 and has lower PO_2, thus Hb are 30% saturated

- This allows O_2 unloading to match oxygen demand!!!

Factors altering Hb saturation

- In addition to PO_2, four other factors influence Hb saturation
  - i. pH
  - ii. PCO_2
  - iii. temperature
  - iv. 2,3 biphosphoglycerate

Bohr effect



Shift to right:
(1) Increased hydrogen ions
(2) Increased CO_2
(3) Increased temperature
(4) Increased BPG

Figure 40-10

- These additional factors are related to increased tissue activity (e.g. exercise)

The effect of temperature

- At decreased temperature, the O_2-Hb dissociation curve shifts to the left

- Similarly, ↑pH, ↓pCO_2, and ↓2,3 BPG will cause shift to the left

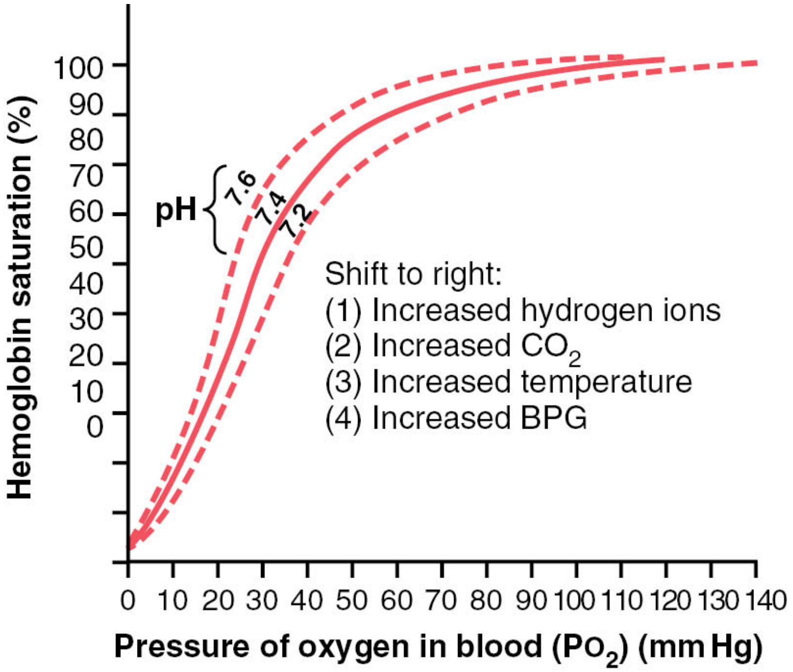
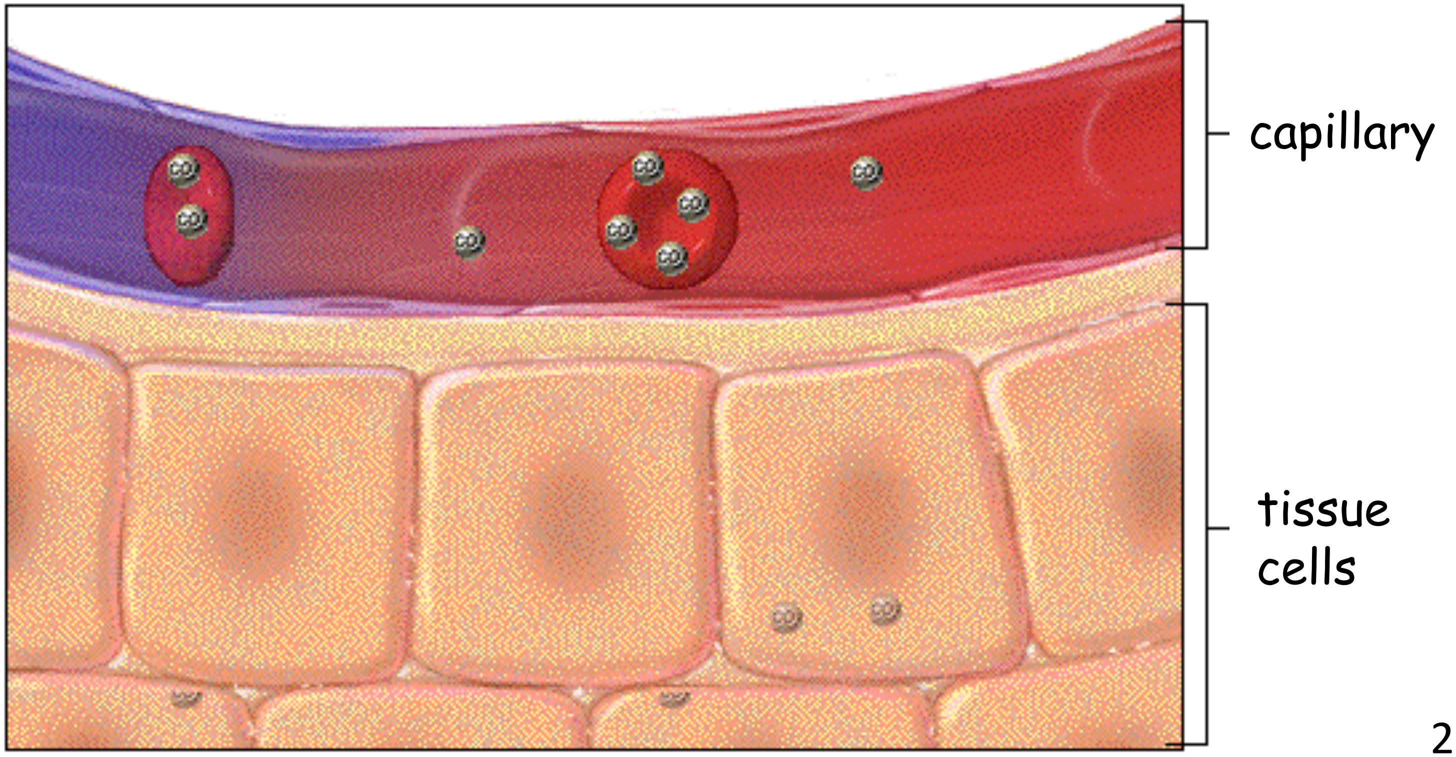


Figure 40-10

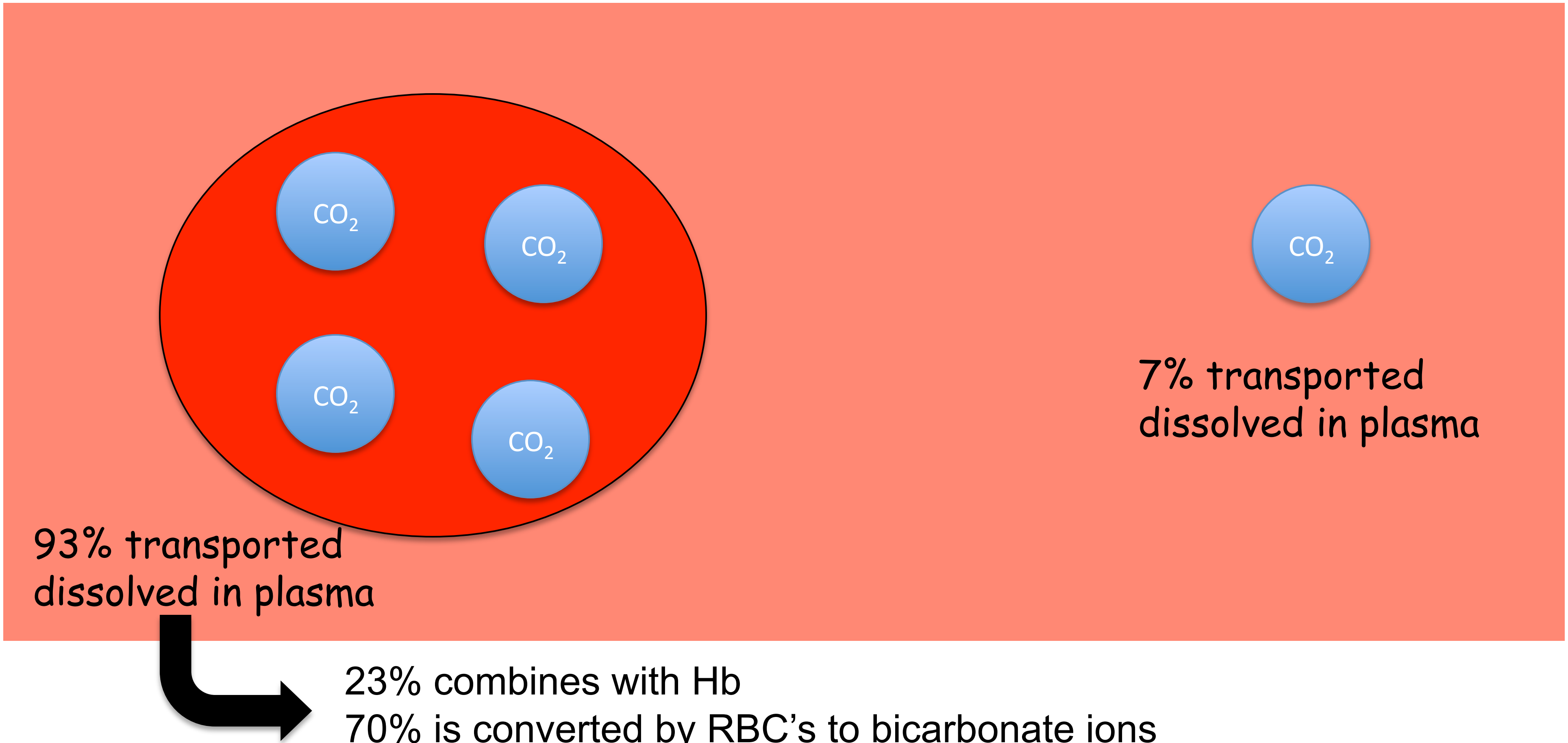
Sites of gas exchange

CO_2 transport during internal respiration:

- CO_2 produced by cells throughout the body
- CO_2 diffuses into systemic capillaries from cells



CO_2 transport in the blood



7% transported dissolved in plasma

93% transported dissolved in plasma

23% combines with Hb
70% is converted by RBC’s to bicarbonate ions

CO_2 transport: carbaminohemoglobin (tissues)

$$\underset{\text{(deoxyhemoglobin)}}{Hb} + CO_2 \xrightarrow{\text{High } PCO_2} \underset{\text{(carbaminohemoglobin)}}{HbCO_2}$$

$HbCO_2$ forms in areas of high PCO_2 as blood flows through the systemic capillaries

↑PCO_2 causes O_2 displacement from Hb (Bohr effect)

CO_2 transport: carbaminohemoglobin (lungs)

$$\underset{\text{(deoxyhemoglobin)}}{Hb} + CO_2 \xleftarrow[\text{Low } PCO_2]{\text{------}} \underset{\text{(carbaminohemoglobin)}}{HbCO_2}$$

Reaction is reversible, and in low PCO_2 (i.e. lungs), CO_2 dissociates from $HbCO_2$

↑PO_2 causes CO_2 displacement from Hb since more acidic (Haldane effect)

CO_2 transport: bicarbonate ions (tissues)

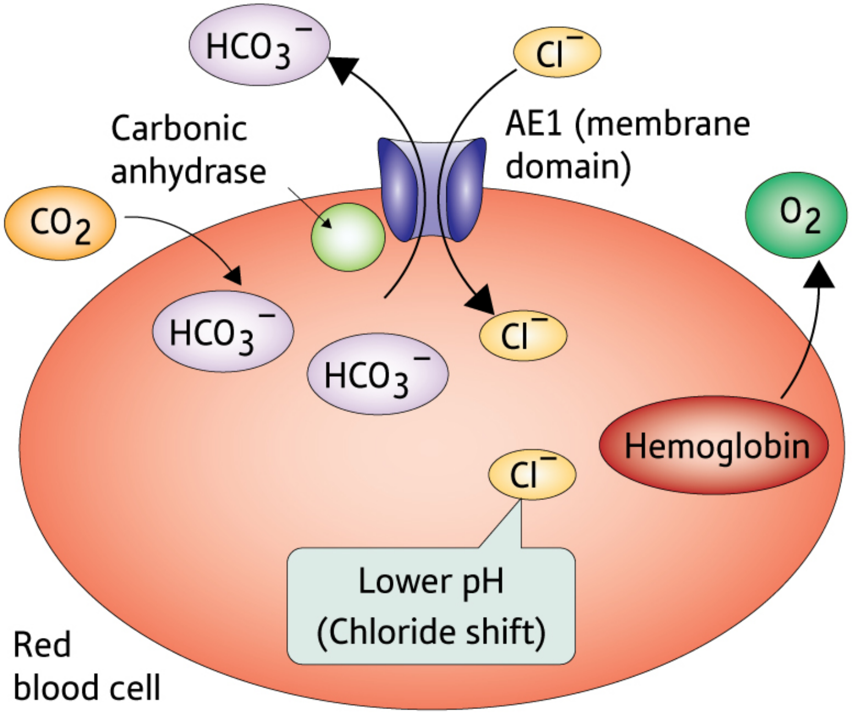
$$H_2O + CO_2 \underset{\cancel{\text{slow}}}{\overset{\text{carbonic anhydrase}}{\underset{\text{fast}}{\rightleftharpoons}}} H_2CO_3 \underset{\text{fast}}{\rightleftharpoons} H^+ + HCO_3^-$$

- Regions of high PCO_2, CO_2 combines with H_2O to form carbonic acid, catalyzed by CA (increased 5000-fold, otherwise slow reaction)

- Carbonic acid quickly dissociates into H^+ and HCO_3^-

CO_2 transport: bicarbonate ions (tissues)

$$H_2O + CO_2 \overset{\text{carbonic anhydrase}}{\underset{\cancel{\text{slow}}}{\overset{\text{fast}}{\rightleftharpoons}}} H_2CO_3 \underset{\text{fast}}{\rightleftharpoons} H^+ + HCO_3^-$$



CO_2 transport: bicarbonate ions (lungs)

$$H_2O + CO_2 \underset{\cancel{\text{slow}}}{\overset{\substack{\text{carbonic}\\\text{anhydrase}\\\text{fast}}}{\rightleftharpoons}} H_2CO_3 \underset{\text{fast}}{\rightleftharpoons} H^+ + HCO_3^-$$

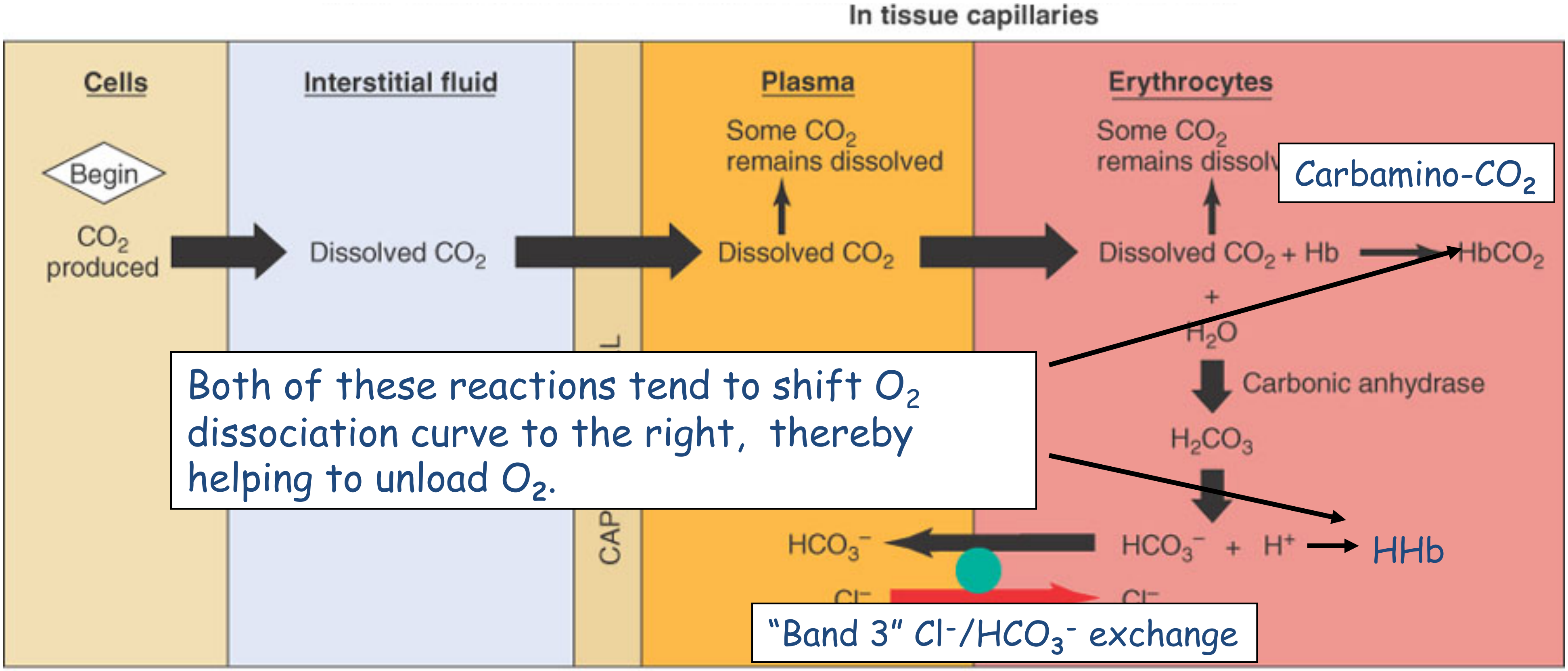
- Regions of low PCO_2, CO_2 diffuses out of plasma and into alveoli
- PCO_2 is lowered and reaction moves to the left
- Bicarbonate ions enter RBC's and Cl^- exits

CO_2 transport: bicarbonate ions (lungs)

$$H_2O + CO_2 \overset{\text{carbonic anhydrase}}{\underset{\cancel{\text{slow}}}{\overset{\text{fast}}{\rightleftharpoons}}} H_2CO_3 \underset{\text{fast}}{\rightleftharpoons} H^+ + HCO_3^-$$

- H^+ ions released by Hb and combine with HCO_3^- forming carbonic acid
- Carbonic acid breaks down into CO_2 and H_2O (also catalyzed by CA)

In tissue capillaries



Cells | **Interstitial fluid** | CAPILLARY WALL | **Plasma** | **Erythrocytes**

Begin

CO_2 produced → Dissolved CO_2 → Dissolved CO_2 → Dissolved CO_2 + Hb → $HbCO_2$

Some CO_2 remains dissolved

Some CO_2 remains dissolved

Carbamino-CO_2

+ H_2O

Carbonic anhydrase

H_2CO_3

HCO_3^- + H^+ → HHb

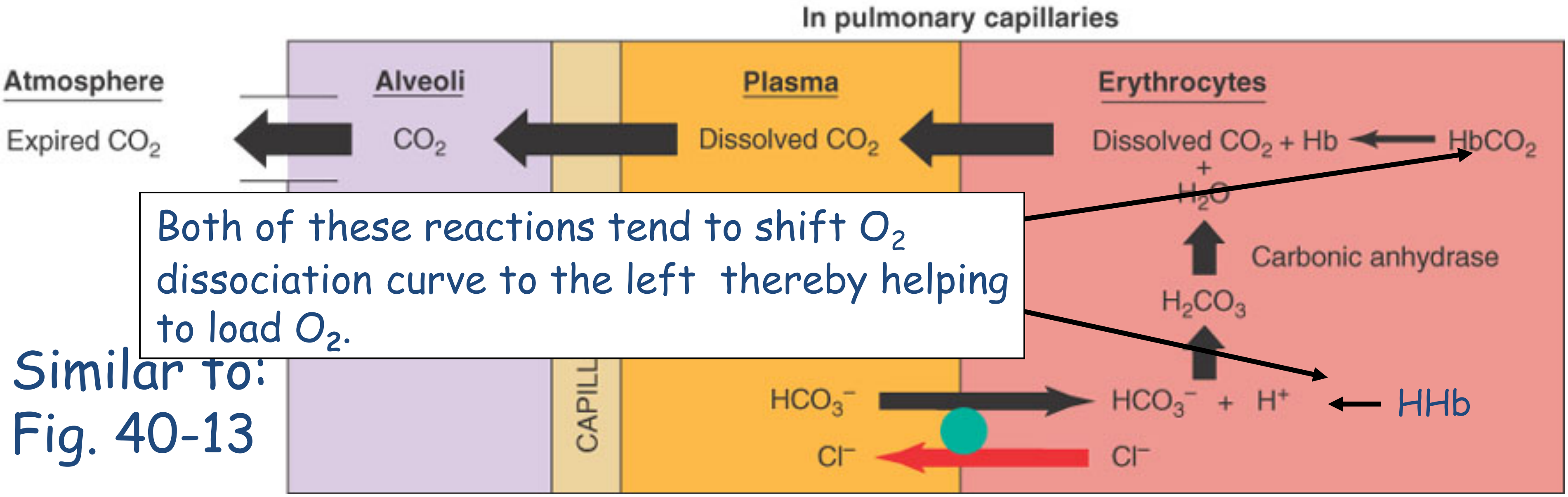
HCO_3^- ← HCO_3^-

Cl^- → Cl^-

“Band 3” Cl^-/HCO_3^- exchange

Both of these reactions tend to shift O_2 dissociation curve to the right, thereby helping to unload O_2.

In pulmonary capillaries



Atmosphere | **Alveoli** | CAPILLARY WALL | **Plasma** | **Erythrocytes**

Expired CO_2 ← CO_2 ← Dissolved CO_2 ← Dissolved CO_2 + Hb ← $HbCO_2$

+ H_2O

Carbonic anhydrase

H_2CO_3

HCO_3^- + H^+ ← HHb

HCO_3^- → HCO_3^-

Cl^- ← Cl^-

Both of these reactions tend to shift O_2 dissociation curve to the left thereby helping to load O_2.

Similar to:
Fig. 40-13

Summary

- O_2 is transported in two ways:
  - Dissolved in plasma
  - Bound to Hb as oxyhemoglobin

- O_2 saturation of hemoglobin is affected by:
  - PO_2
  - pH
  - temperature
  - PCO_2
  - BPG

Summary

- CO_2 is transported in three ways:
    - Dissolved in plasma
    - Bound to Hb as carbaminohemoglobin
    - Converted to bicarbonate ions

- O_2 loading facilitates CO_2 unloading from Hb (Haldane effect)

- CO_2 loading, through formation of H^+ ions, facilitates O_2 unloading from Hb (Bohr effect)