Physiology of Respiratory System

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3rd year\ Lecture 3

Gas Exchange
and
Transport

Composition of Air

- Composition of air
  - 78.6% nitrogen, 20.9% oxygen, 0.04% carbon dioxide, 0% to 4% water vapor, depending on temperature and humidity, and minor gases argon, neon, helium, methane, and ozone

Composition of Air

- Dalton's law—the total atmospheric pressure is the sum of the contributions of the individual gases
  - Partial pressure: the separate contribution of each gas in a mixture
  - At sea level 1 atm of pressure = 760 mm Hg
  - Nitrogen constitutes 78.6% of the atmosphere, thus
    - P_{N_2} = 78.6% x 760 mm Hg = 597 mm Hg
    - P_{O_2} = 20.9% x 760 mm Hg = 159 mm Hg
    - P_{H_2O} = 0.5% x 760 mm Hg = 3.7 mm Hg
    - P_{CO_2} = 0.04% x 760 mm Hg = 0.3 mm Hg
    - $P_{N_2} + P_{O_2} + P_{H_2O} + P_{CO_2}$ = 760 mmHg

Composition of Air

- Composition of inspired air and alveolar is different because of three influences
  - Air is humidified by contact with mucous membranes
    - Alveolar PH_2O is more than 10 times higher than inhaled air
  - Freshly inspired air mixes with residual air left from previous respiratory cycle
    - Oxygen is diluted and it is enriched with CO_2
  - Alveolar air exchanges O_2 and CO_2 with the blood
    - PO_2 of alveolar air is about 65% that of inspired air
    - PCO_2 is more than 130 times higher

TABLE 22.4 Composition of Inspired (Atmospheric) and Alveolar Air

Gas	Inspired Air*		Alveolar Air	
N_2	78.6%	597 mm Hg	74.9%	569 mm Hg
O_2	20.9%	159 mm Hg	13.7%	104 mm Hg
H_2O	0.5%	3.7 mm Hg	6.2%	47 mm Hg
CO_2	0.04%	0.3 mm Hg	5.3%	40 mm Hg
Total	100%	760 mm Hg	100%	760 mm Hg

*Typical values for a cool clear day; values vary with temperature and humidity. Other gases present in small amounts are disregarded.

Alveolar Gas Exchange

- Alveolar gas exchange—the back-and-forth traffic of O_2 and CO_2 across the respiratory membrane
  - Air in the alveolus is in contact with a film of water covering the alveolar epithelium
  - For oxygen to get into the blood it must dissolve in this water
  - Pass through the respiratory membrane separating the air from the bloodstream
  - For carbon dioxide to leave the blood it must pass the other way
  - Diffuse out of the water film into the alveolar air

Alveolar Gas Exchange

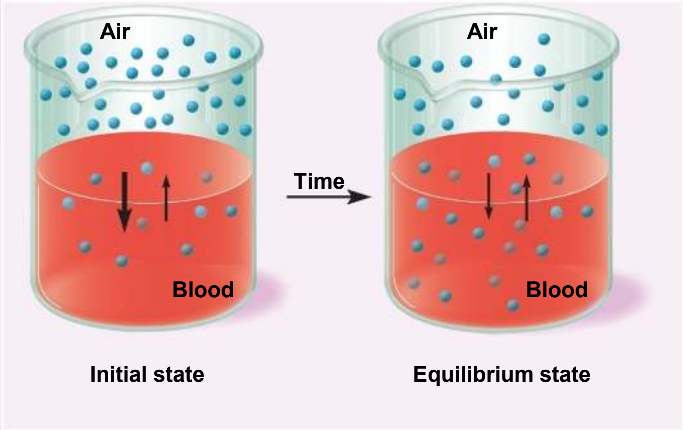
- Gases diffuse down their own concentration gradient until the partial pressure of each gas in the air is equal to its partial pressure in water
- Henry's law—at the air–water interface, for a given temperature, the amount of gas that dissolves in the water is determined by its solubility in water and its partial pressure in air
  - The greater the PO_2 in the alveolar air, the more O_2 the blood picks up
  - Since blood arriving at an alveolus has a higher PCO_2 than air, it releases CO_2 into the air

Alveolar Gas Exchange

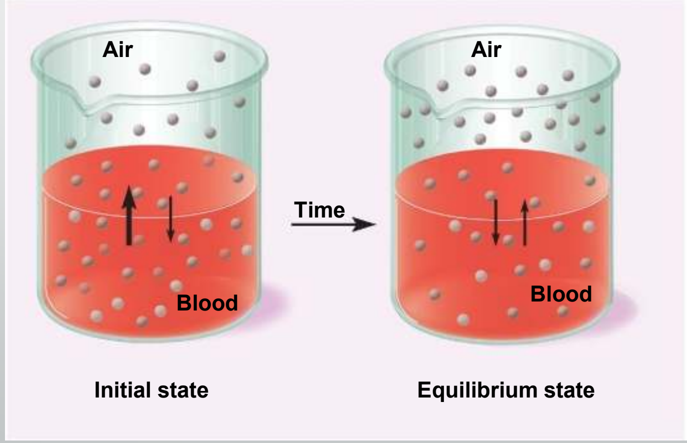
Cont. (Henry's Law)

- At the alveolus, the blood is said to unload CO_2 and load O_2
  - Unload CO_2 and load O_2 involves erythrocytes
  - Efficiency depends on how long an RBC stays in alveolar capillaries
    - 0.25 second necessary to reach equilibrium
    - At rest, RBC spends 0.75 second in alveolar capillaries
    - In strenuous exercise, 0.3 second, which is still adequate
- Each gas in a mixture behaves independently
- One gas does not influence the diffusion of another

Alveolar Gas Exchange



(a) Oxygen



(b) Carbon dioxide

Figure 22.19a,b

Alveolar Gas Exchange

- Pressure gradient of the gases
  - PO_2 = 104 mm Hg in alveolar air versus 40 mm Hg in blood
  - PCO_2 = 46 mm Hg in blood arriving versus 40 mm Hg in alveolar air

Alveolar Gas Exchange

Cont.

- Hyperbaric oxygen therapy: treatment with oxygen at greater than 1 atm of pressure
  - Gradient difference is more, and more oxygen diffuses into the blood
  - Treat gangrene, carbon monoxide poisoning

- At high altitudes the partial pressures of all gases are lower
  - Gradient difference is less, and less oxygen diffuses into the blood

Alveolar Gas Exchange

- Solubility of the gases
  - CO_2 is 20 times as soluble as O_2
    - Equal amounts of O_2 and CO_2 are exchanged across the respiratory membrane because CO_2 is much more soluble and diffuses more rapidly
  - O_2 is twice as soluble as N_2

Alveolar Gas Exchange

- Membrane surface area—100 mL blood in alveolar capillaries, spread thinly over 70 m^2
  - Emphysema, lung cancer, and tuberculosis decrease surface area for gas exchange

Alveolar Gas Exchange

- Membrane thickness—only 0.5 µm thick
  - Presents little obstacle to diffusion
  - Pulmonary edema in left ventricular failure causes edema and thickening of the respiratory membrane
  - Pneumonia causes thickening of respiratory membrane
  - Farther to travel between blood and air
  - Cannot equilibrate fast enough to keep up with blood flow

Alveolar Gas Exchange

- Ventilation–perfusion coupling—the ability to match ventilation and perfusion to each other
  - Gas exchange requires both good ventilation of alveolus and good perfusion of the capillaries
  - Ventilation–perfusion ratio of 0.8: a flow of 4.2 L of air and 5.5 L of blood per minute at rest

Changes in Gases

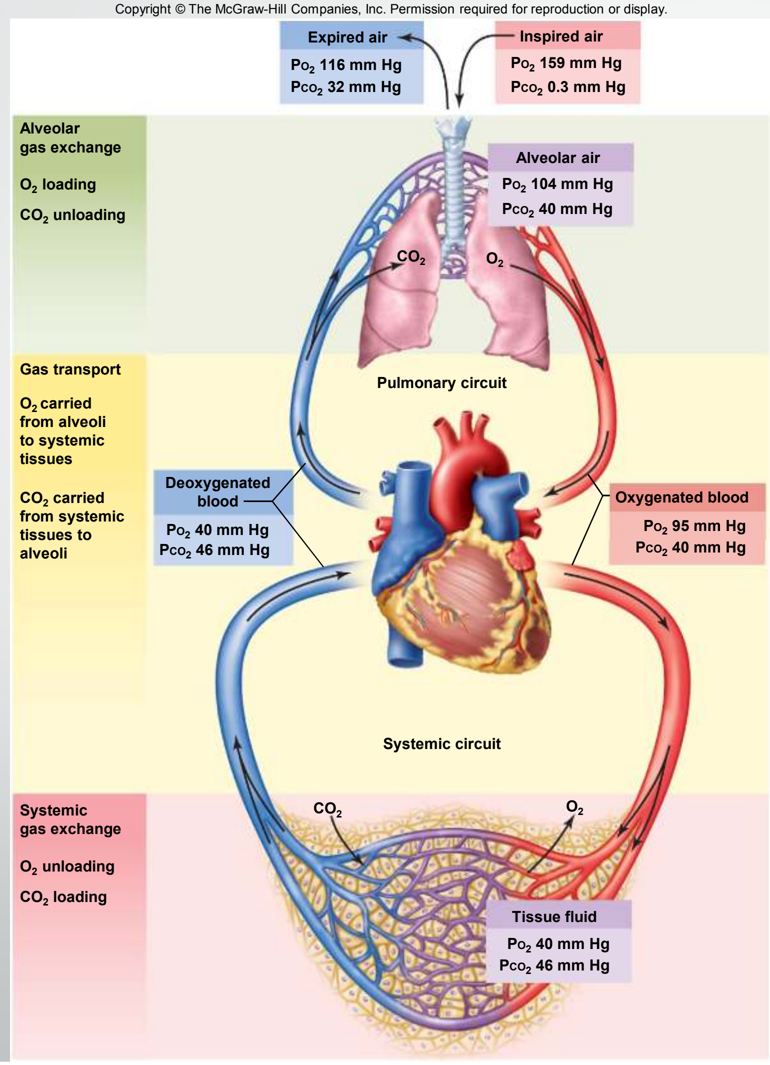


Figure 22.20

Oxygen Loading in Relation to Partial Pressure Gradient

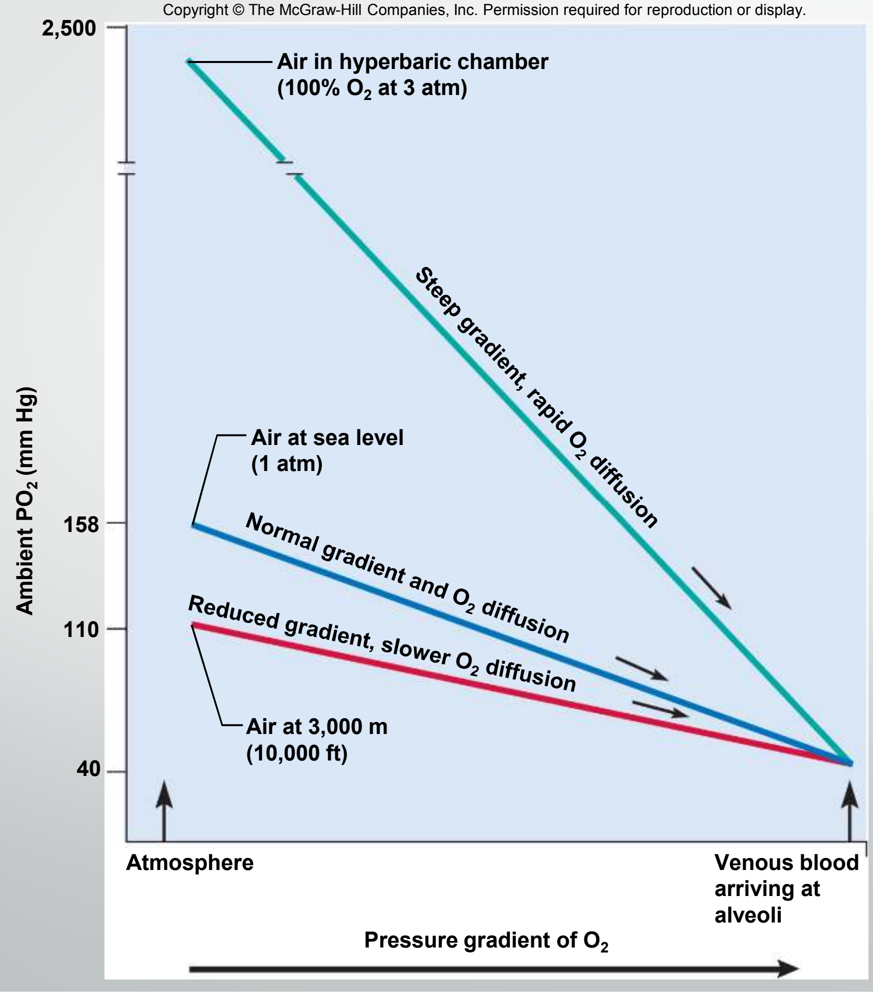


Figure 22.21

Pulmonary Alveoli in Health and Disease

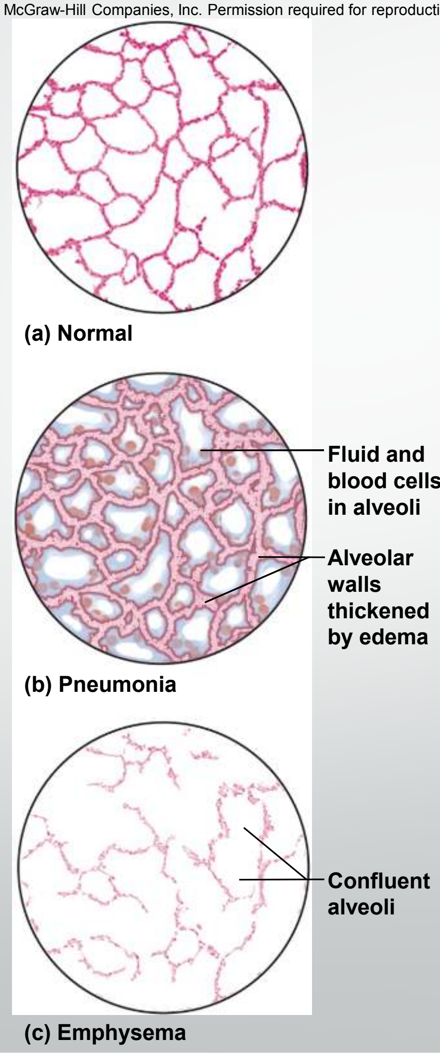


Figure 22.22

Ventilation–Perfusion Coupling

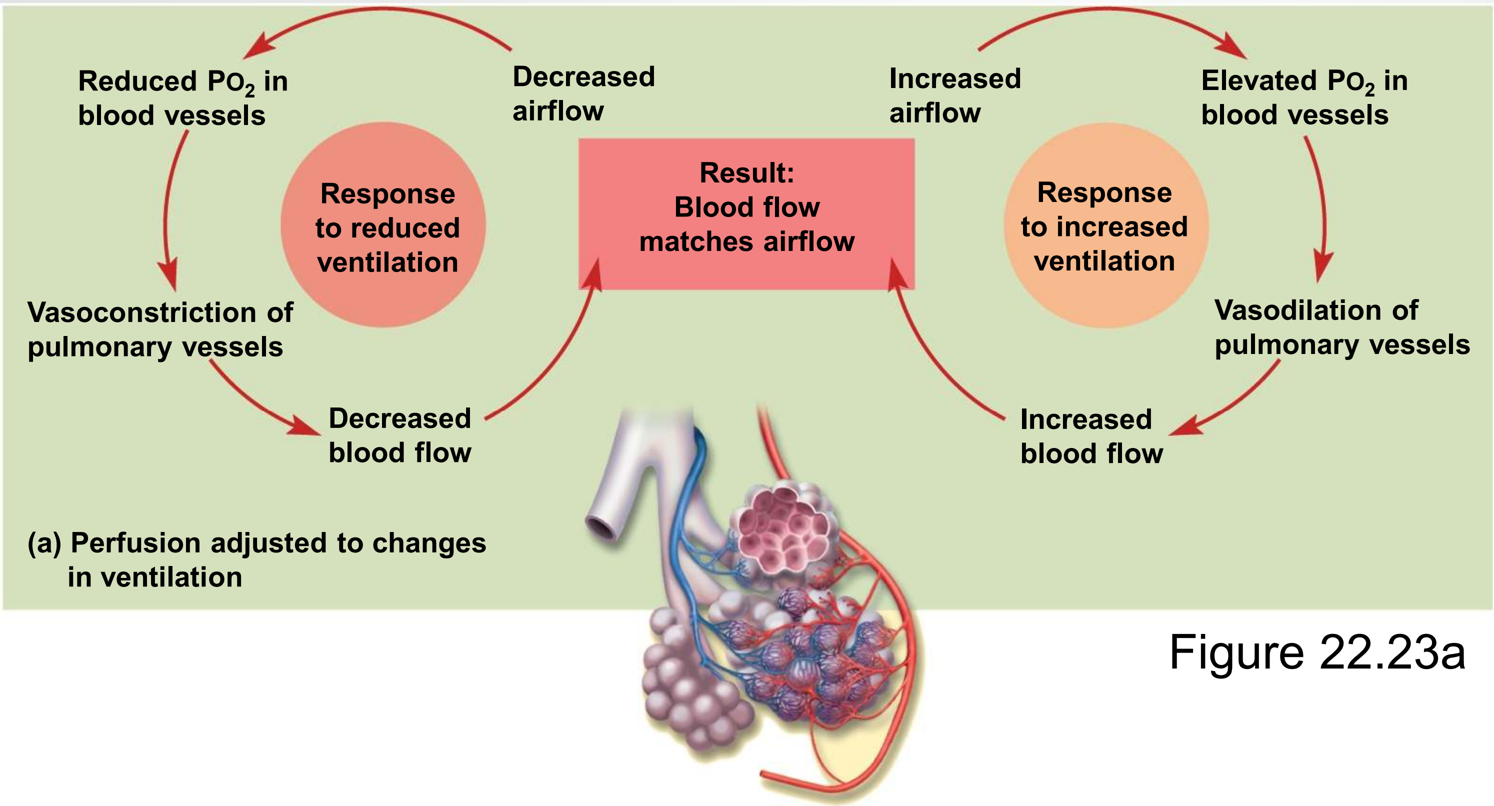
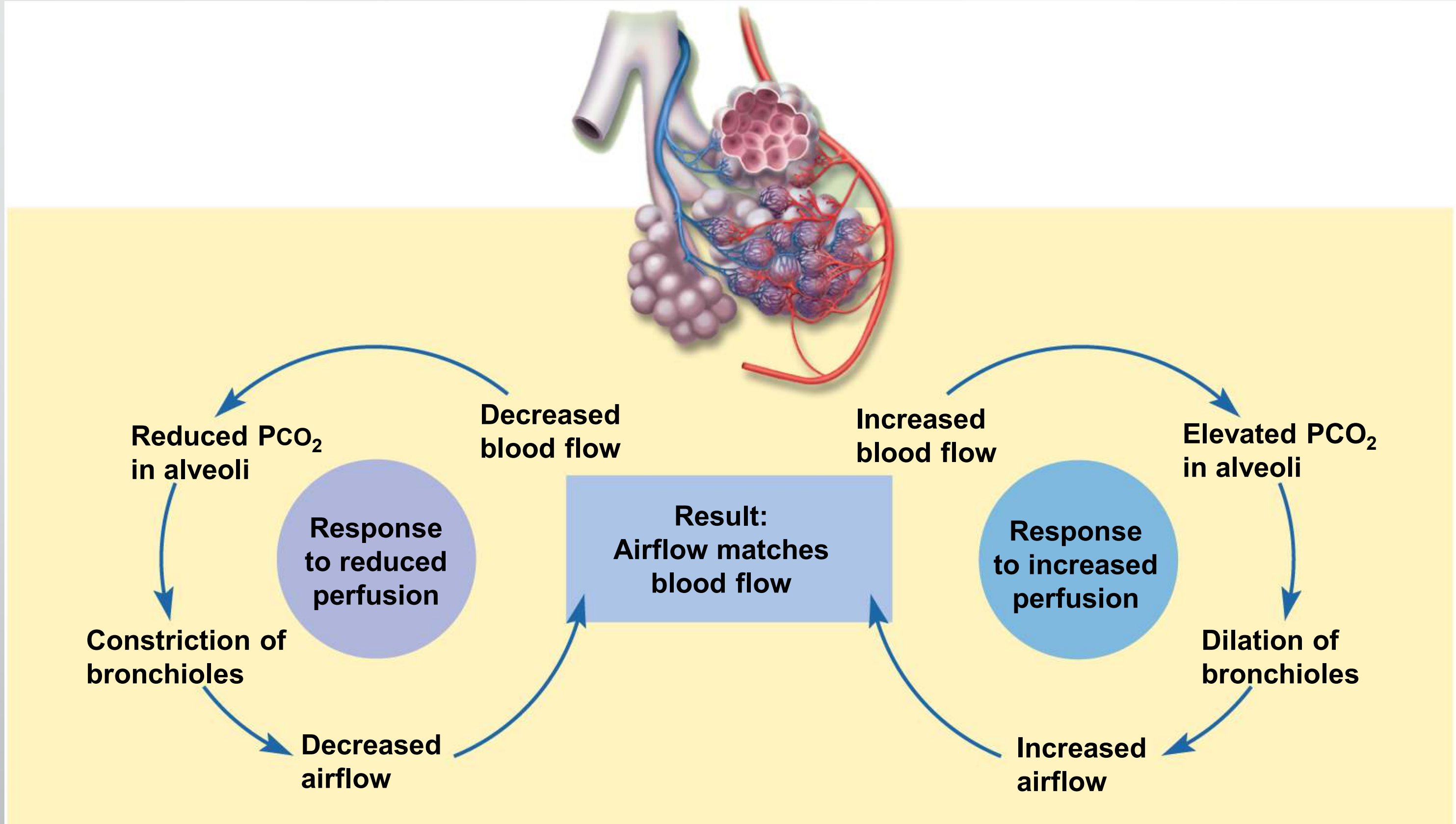


Figure 22.23a

Ventilation–Perfusion Coupling



(b) Ventilation adjusted to changes in perfusion

Figure 22.23b

Gas Transport

- Gas transport—the process of carrying gases from the alveoli to the systemic tissues and vice versa

- Oxygen transport
  - 98.5% bound to hemoglobin
  - 1.5% dissolved in plasma

- Carbon dioxide transport
  - 70% as bicarbonate ion
  - 23% bound to hemoglobin
  - 7% dissolved in plasma

Oxygen

- Arterial blood carries about 20 mL of O_2 per deciliter
  - 95% bound to hemoglobin in RBC
  - 1.5% dissolved in plasma

Oxygen

- Hemoglobin—molecule specialized in oxygen transport
  - Four protein (globin) portions
    - Each with a heme group which binds one O_2 to the ferrous ion (Fe^{2+})
    - One hemoglobin molecule can carry up to 4 O_2
    - Oxyhemoglobin (HbO_2)—O_2 bound to hemoglobin
    - Deoxyhemoglobin (HHb)—hemoglobin with no O_2
    - 100% saturation Hb with 4 O_2 molecules
    - 50% saturation Hb with 2 O_2 molecules

Carbon Dioxide

- Carbon dioxide transported in three forms
  - Carbonic acid, carbamino compounds, and dissolved in plasma
- 90% of CO_2 is hydrated to form carbonic acid
  - $CO^2 + H_2O \rightarrow H_2CO_3 \rightarrow HCO3^- + H^+$
  - Then dissociates into bicarbonate and hydrogen ions
- 5% binds to the amino groups of plasma proteins and hemoglobin to form carbamino compounds—chiefly carbaminohemoglobin ($HbCO_2$)
  - Carbon dioxide does not compete with oxygen
  - They bind to different moieties on the hemoglobin molecule
  - Hemoglobin can transport O_2 and CO_2 simultaneously

Carbon Dioxide

- 5% is carried in the blood as dissolved gas
- Relative amounts of CO_2 exchange between the blood and alveolar air differs
  - 70% of exchanged CO_2 comes from carbonic acid
  - 23% from carbamino compounds
  - 7% dissolved in the plasma
    - Blood gives up the dissolved CO_2 gas and CO_2 from the carbamino compounds more easily than CO_2 in bicarbonate

Carbon Monoxide Poisoning

- Carbon monoxide (CO)—competes for the O_2 binding sites on the hemoglobin molecule
- Colorless, odorless gas in cigarette smoke, engine exhaust, fumes from furnaces and space heaters
- Carboxyhemoglobin—CO binds to ferrous ion of hemoglobin
  - Binds 210 times as tightly as oxygen
  - Ties up hemoglobin for a long time
  - Nonsmokers: less than 1.5% of hemoglobin occupied by CO
  - Smokers: 10% in heavy smokers
  - Atmospheric concentrations of 0.2% CO is quickly lethal

Oxyhemoglobin Dissociation Curve

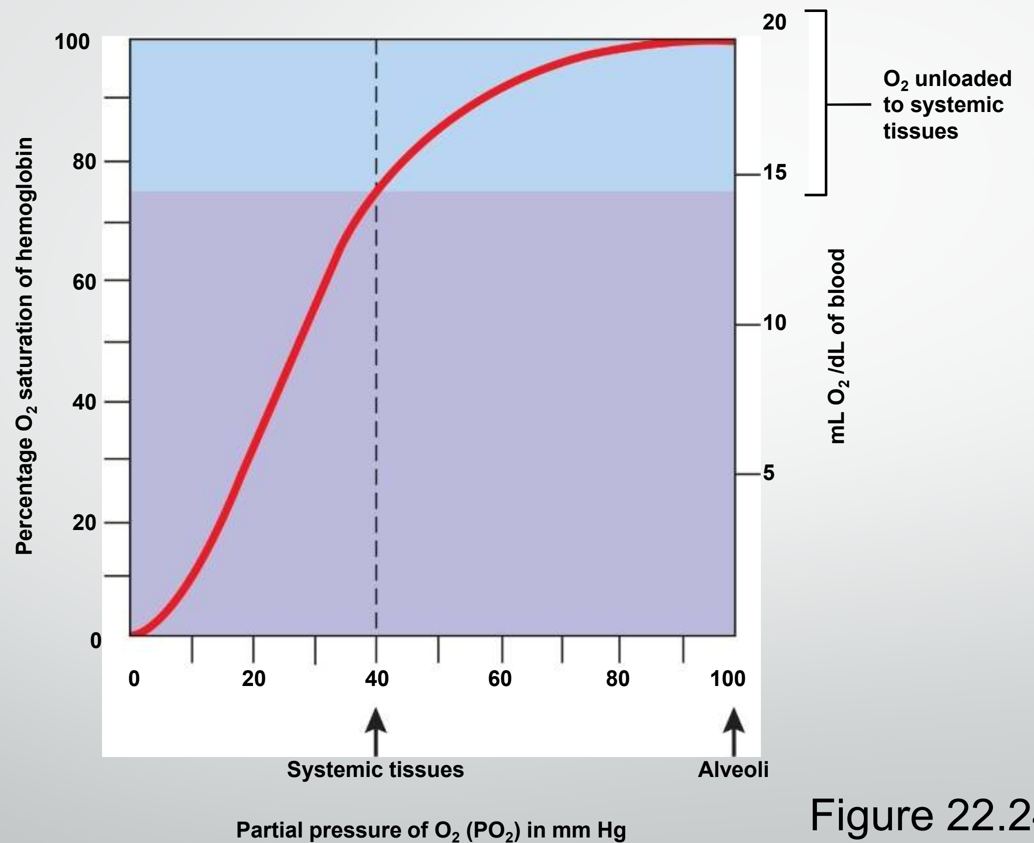


Figure 22.24

Relationship between hemoglobin saturation and PO_2