Pulmonary Physiology: A Review

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Pulmonary Physiology

- Control of Breathing
- Mechanics/Work of Breathing
- Ventilation
- Gas transport (including pulmonary circulation)
- Gas Exchange (including diffusion of gas/gas transfer)

“When you can’t breathe, nothing else matters.”

Control of Breathing

- Keep PCO_2 40 mmHg awake
- Neural Control
- Chemical Control

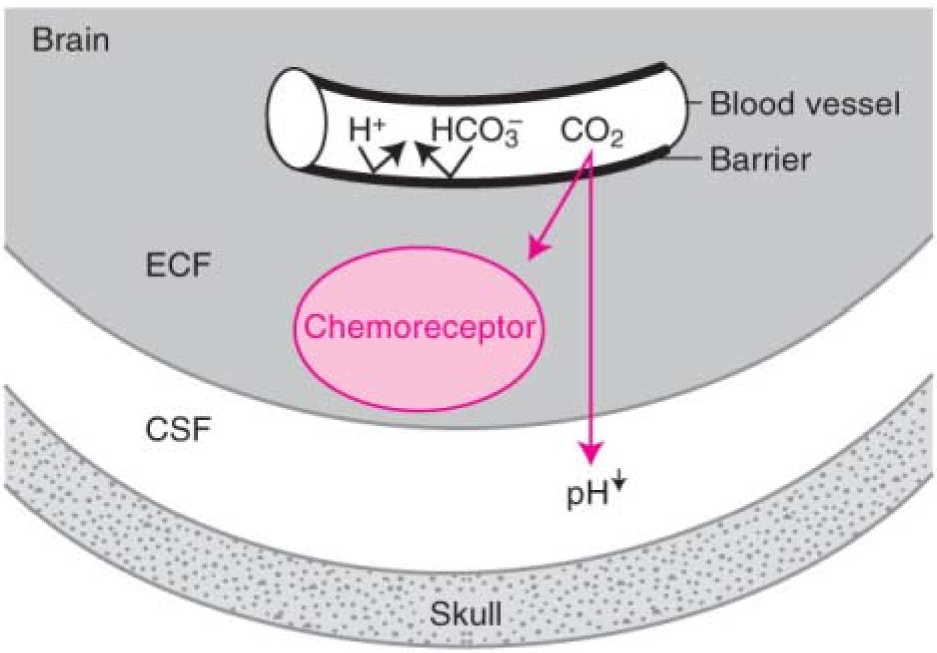
Neural Control

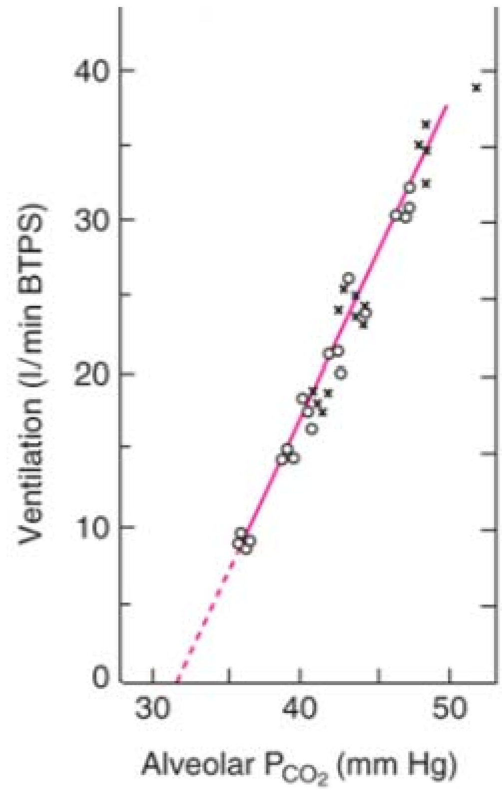
- Inspiratory inhibition reflex (Hering Breuer)
  - irritant, mechano, j receptors: stimulation in patients with, e.g., interstitial fibrosis, pulmonary embolism, atelectasis
- Stimulation of mechanoreceptors in airways: can cause tachypnea, bronchoconstriction

Chemical control

- CO_2 stimulation
- Hypoxemic stimulation
- H^+ stimulation

Chemical Control: CO_2 stimulation

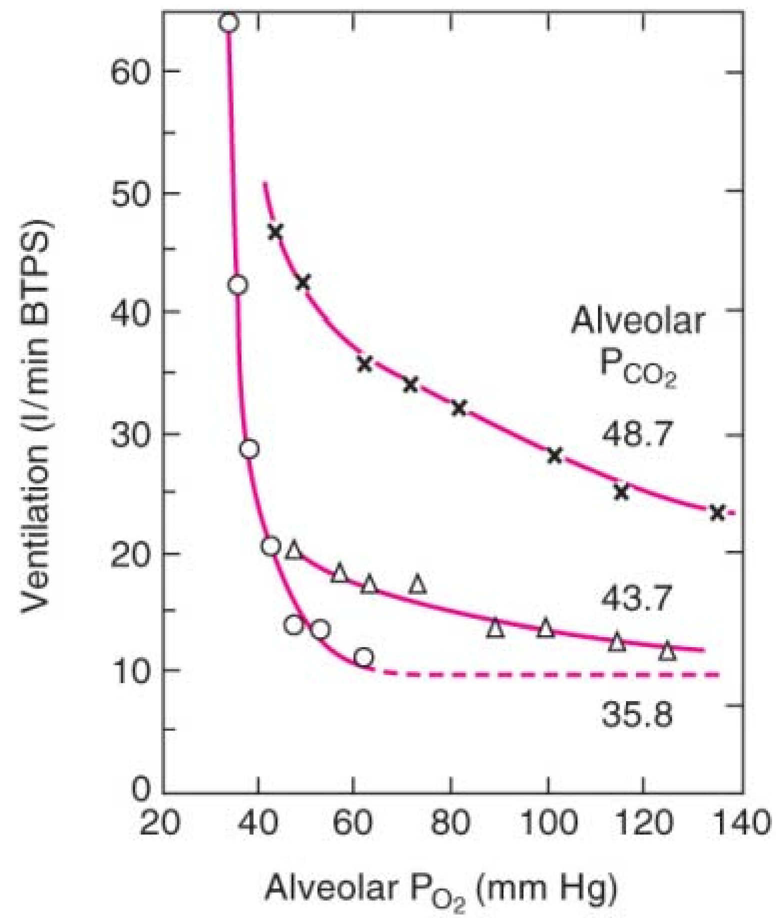




- Central >> peripheral chemoreceptors
- Chronically elevated $PaCO_2$ = increased ECF [$HCO3^-$] so acute increase in $PaCO_2$ will induce less of a change in [H^+] and therefore less stimulus to ventilation

Chemical Control: Hypoxemic Stimulation

- Peripheral chemoreceptors only
- Low $PaO_2 \rightarrow$ increased V_E
- The increase in V_E is attenuated by the decreased $PaCO_2$ that results (see previous slide)



Chemical Control: Hydrogen ion stimulation

- Metabolic acidosis stimulates peripheral chemoreceptors
- Acute metabolic acidemia → increased V_E
- Chronic metabolic acidemia → attenuated by ↓ $PaCO_2$

Chemical Control of Breathing

- When WOB elevated, PCO_2 not as potent a stimulus to breathe
- Sleep depresses ventilatory stimulation; $PaCO_2$ rises by several mmHg in sleep (most in REM sleep)

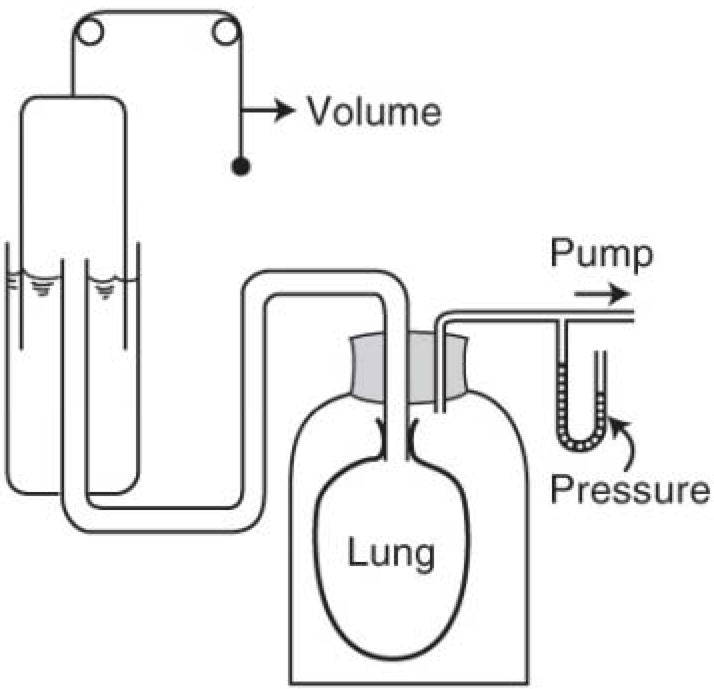
Mechanical Properties of the Respiratory System

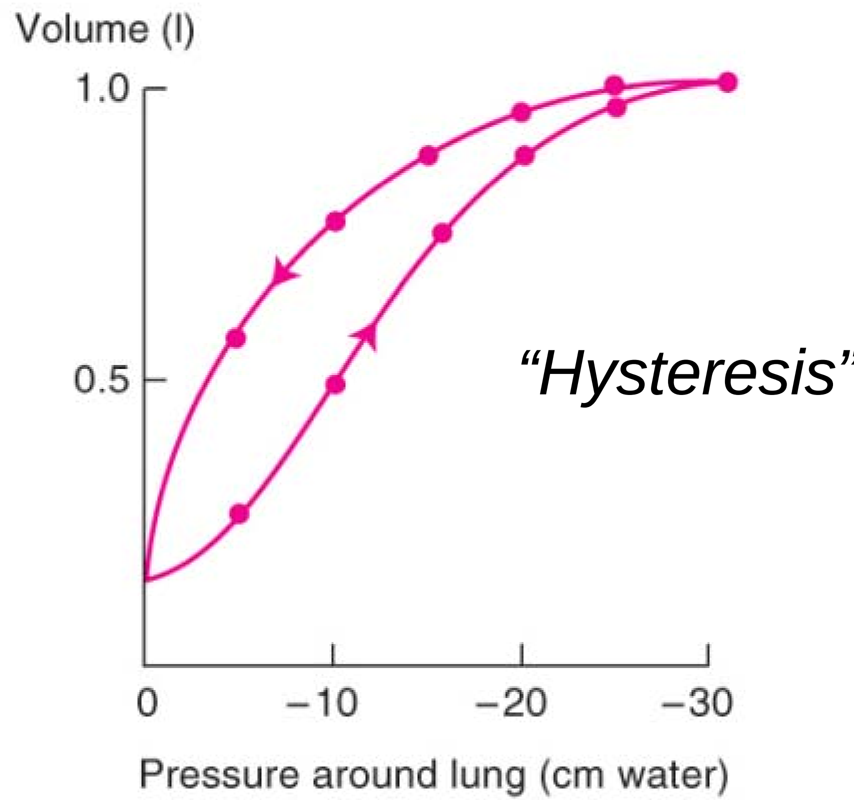
- Lung Compliance
- Chest Wall Compliance
- Airway Resistance

- In disease states, these mechanical properties are altered!!!

Lung Compliance

$$\text{Compliance} = \frac{1}{\text{Elastance}} = \frac{\Delta\text{volume}}{\Delta\text{pressure}}$$



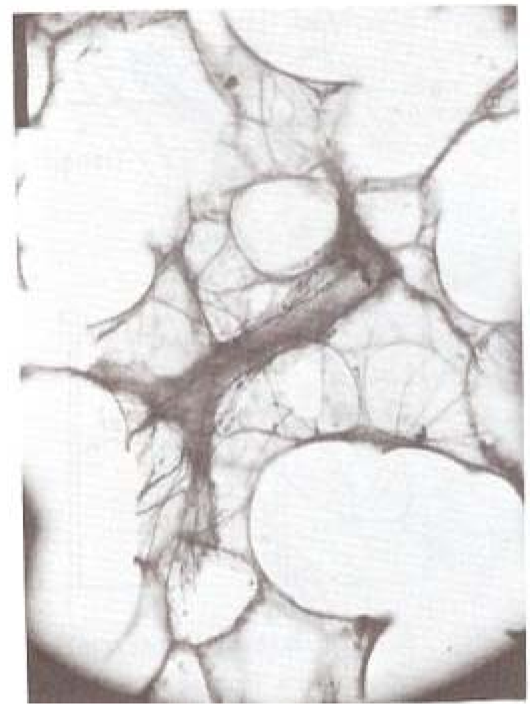


Two determinants of lung compliance

- Elastic properties of lung parenchyma
- Surface tension in alveoli

Elastic Properties of Lung Parenchyma

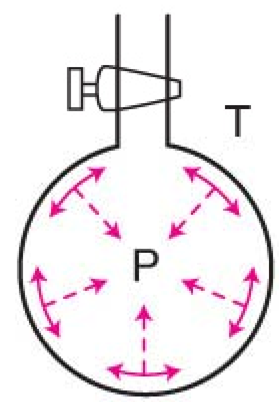
- Elastic fibers (easily stretched)
  - Elastin
  - Microfibrils
- Fibril forming collagens
  - Tensile strength
  - Types I, II, III, V, XI
- Geometric arrangement
  - "Nylon stocking" elasticity
    - Nylon stocking is easy to stretch
    - Nylon threads are difficult to stretch



Section of human lung sh
elastin fibers in alveolar w
surrounding blood vessel

Surface Tension of Alveolar Lining Fluid

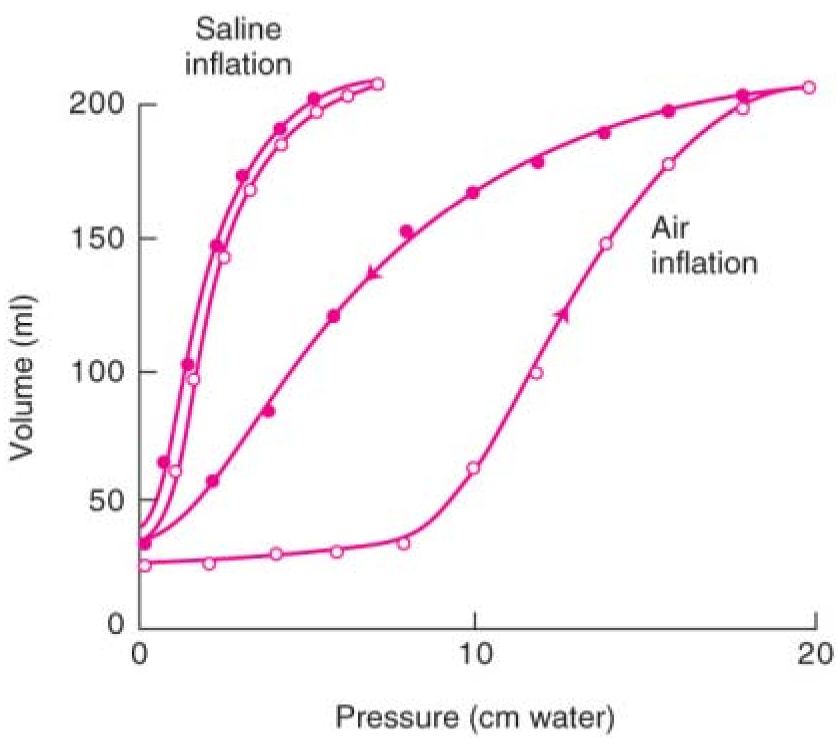
- Surface Tension
  - **Technical definition**: “the force acting across an imaginary line 1cm long in the surface of the liquid”
  - **Better definition**: the force that minimizes liquid surface area
  - Attractive forces are stronger between two liquid molecules than between gas and liquid molecules

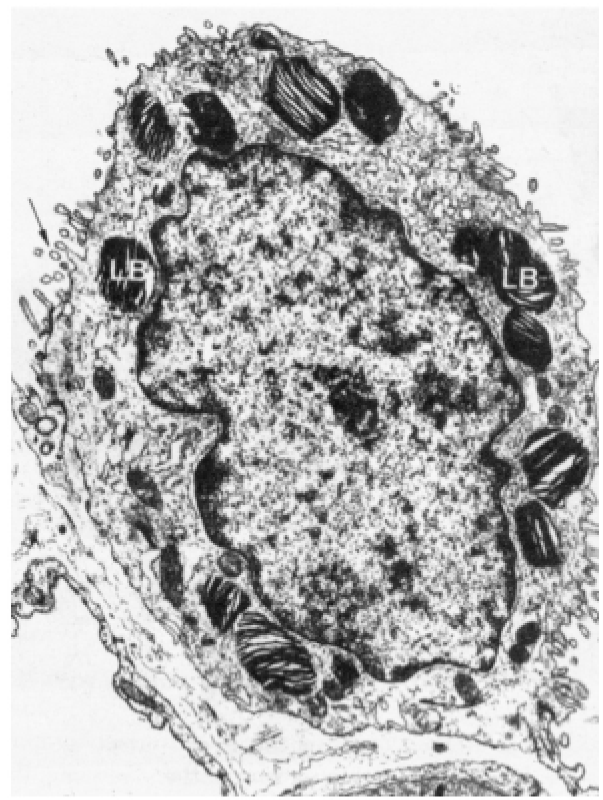


Soap bubble

Pulmonary Surfactant <u>decreases</u> Alveolar Surface Tension

- Type II pneumocytes produce surfactant
- Low surface tension = increased compliance

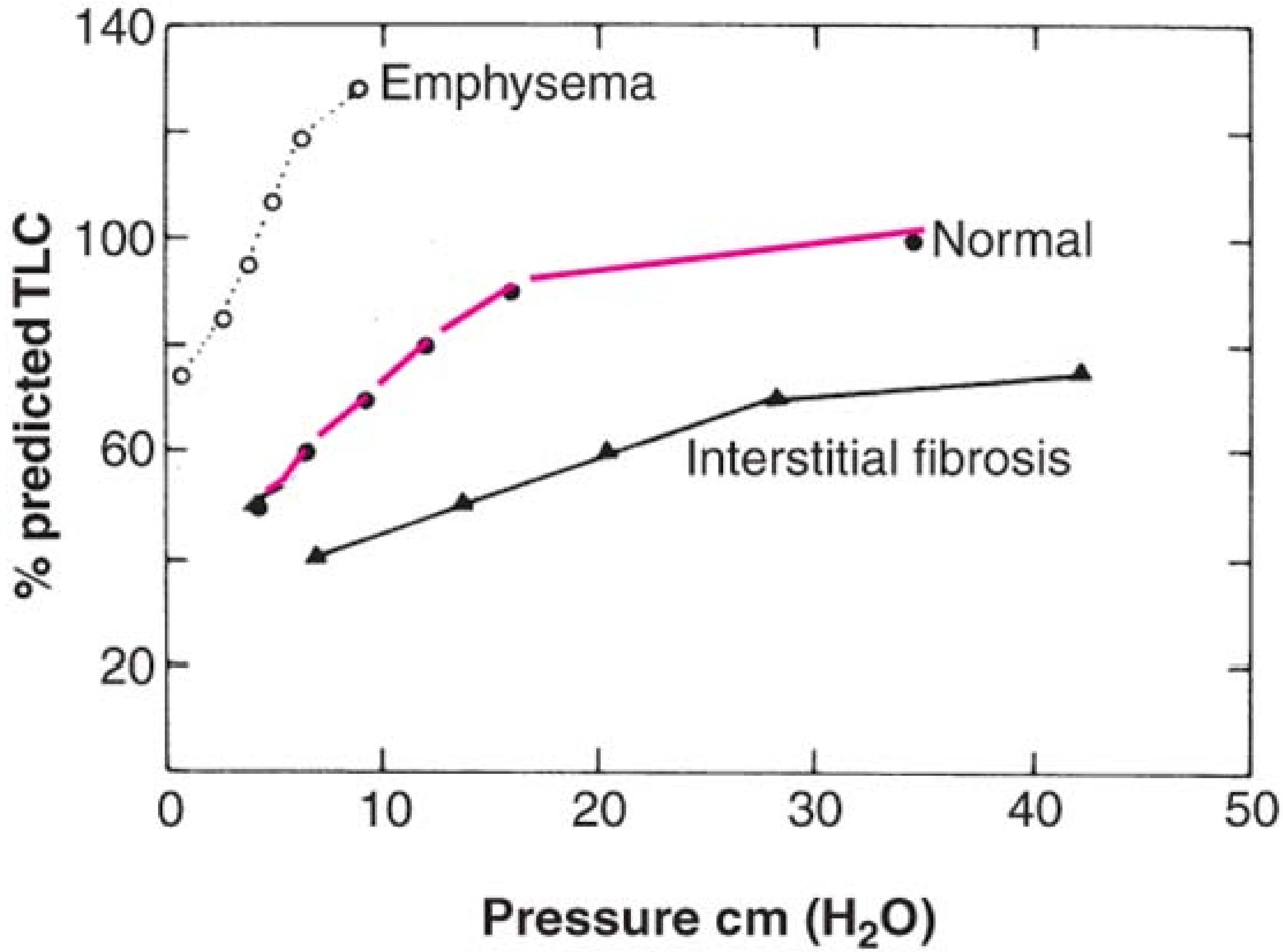




Clinical correlation

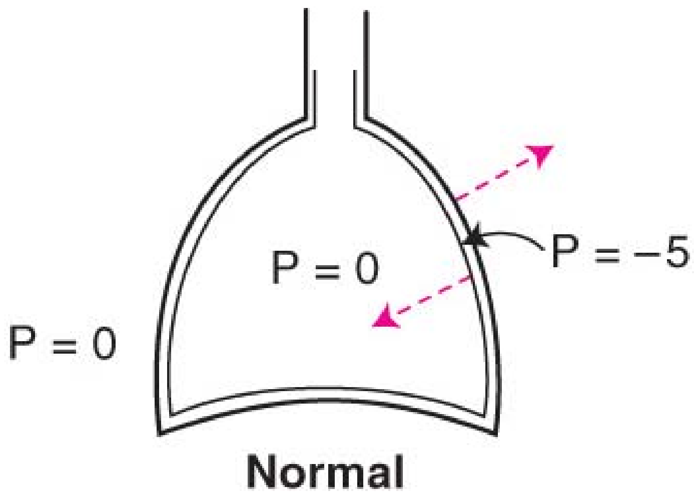
- What happens if…
  - the lung has too much interstitial water?
  - the lung has too much collagen?
  - the elastic tissue of the lung is partially destroyed?
  - the lung has too little surfactant?
  - all of the gas is removed from the right lower lobe?

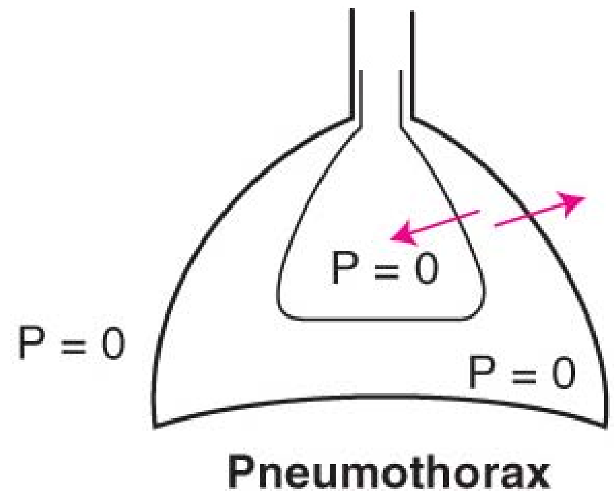
Pressure-Volume Curves



Chest Wall Compliance

- The chest wall is elastic too!





At FRC, chest wall elastic recoil (pulling outward) = lung elastic recoil (pulling inward)

Clinical correlation

- What happens if…
  - There is air in the pleural space?
  - There is too much liquid in the pleural space?
  - The visceral pleural is covered in scar tissue?

Airway Resistance during Laminar Flow

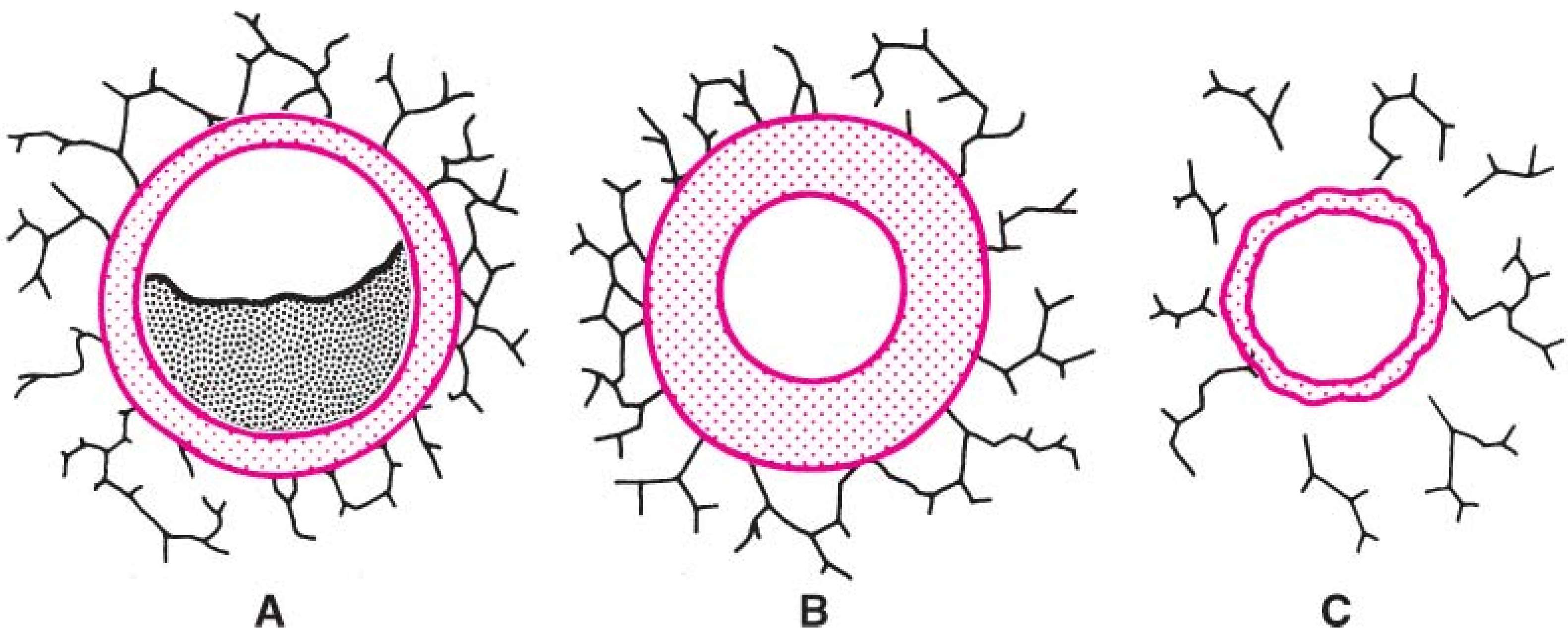
Ohm's Law

$$\dot{V} = \frac{\Delta P}{R}$$

$$R = \frac{8\eta l}{\pi r^4}$$

V = flow rate
ΔP = driving pressu
r = radius of the tub
η = viscosity
l = length of the tub

Airway Resistance is determined by Airway <u>Caliber</u>



Intraluminal:
e.g., Secretions

Intramural:
e.g., Edema

Extraluminal:
e.g., Loss of radial tractio

Application of the Alveolar Ventilation Equation

$$P_aCO_2 \propto \frac{\dot{V}_{CO_2}}{\dot{V}_A}$$

What happens if…

1. Dead space increases (minute ventilation held constant)
2. Minute ventilation increases (V_D is constant)
3. CO_2 production increases

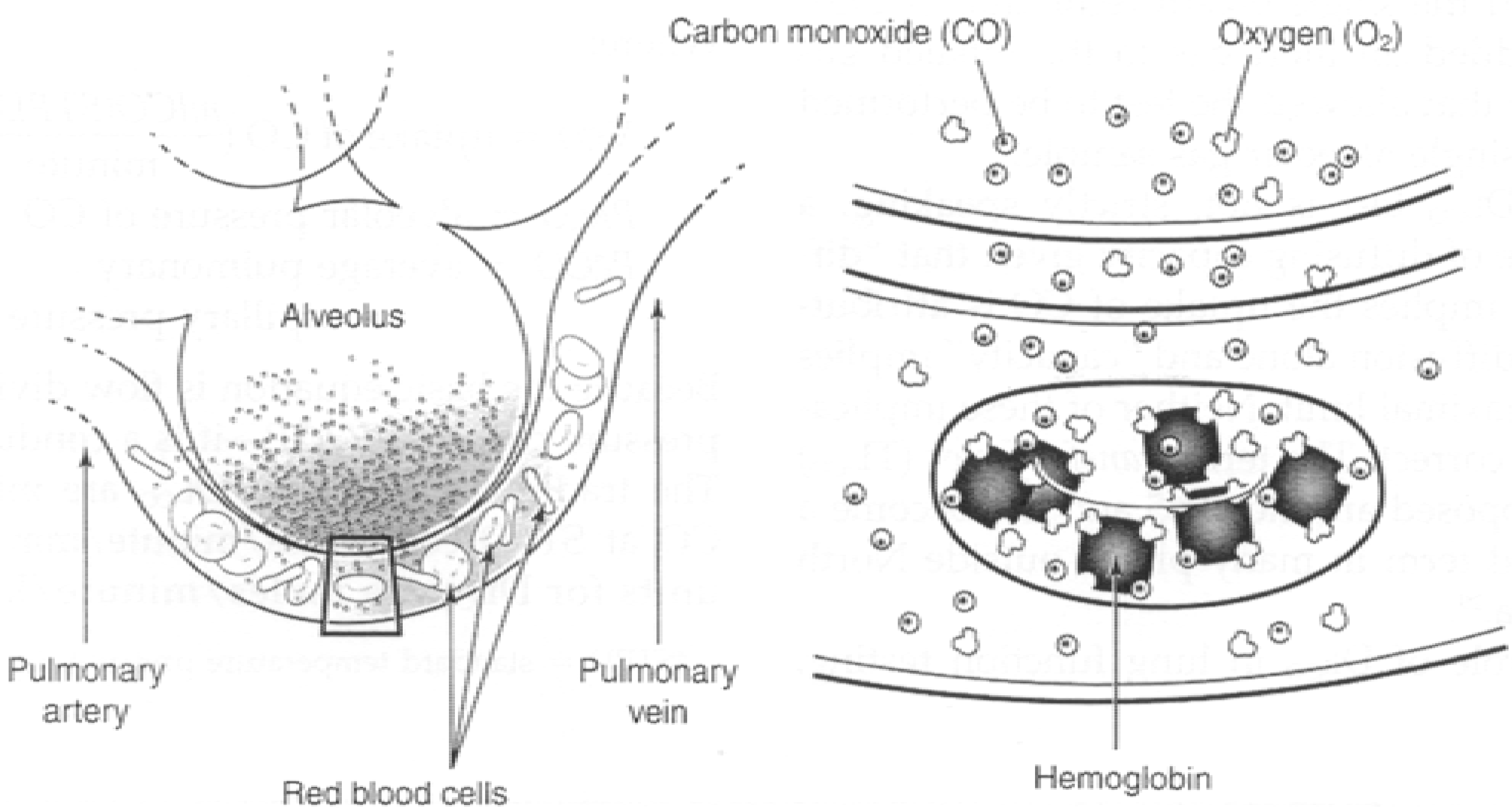
Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)

- Conduction of blood coming from the tissues through the alveolar capillaries so that O_2 can be added and CO_2 removed.
- Pulmonary vessels=low pressures and low resistance to flow (thin walled)
- Resistance=driving pressure/flow (Q)
- Most resistance in the arterioles and capillaries
- Driving pressure=pressure at the beginning of the pulmonary circulation (the pulmonary artery) and other end (left atrium); normally, eg, blood flow 6 L/min and mean driving pressure of 9 mmHg, resistance is 9mmHg/6 L/min, or 1.5 mmHg/L/min (~10% of systemic pressure).

Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)

- Pulmonary capillary blood volume increases during inspiration and exercise
- Reduced when patients receive mechanical ventilation (intrathoracic pressure is raised, thus impeding venous return to the heart)
- Patients with increased pulmonary pressure (eg pulmonary hypertension, pulmonary embolism)=cardiodynamic consequences as well as disturbance of gas transfer

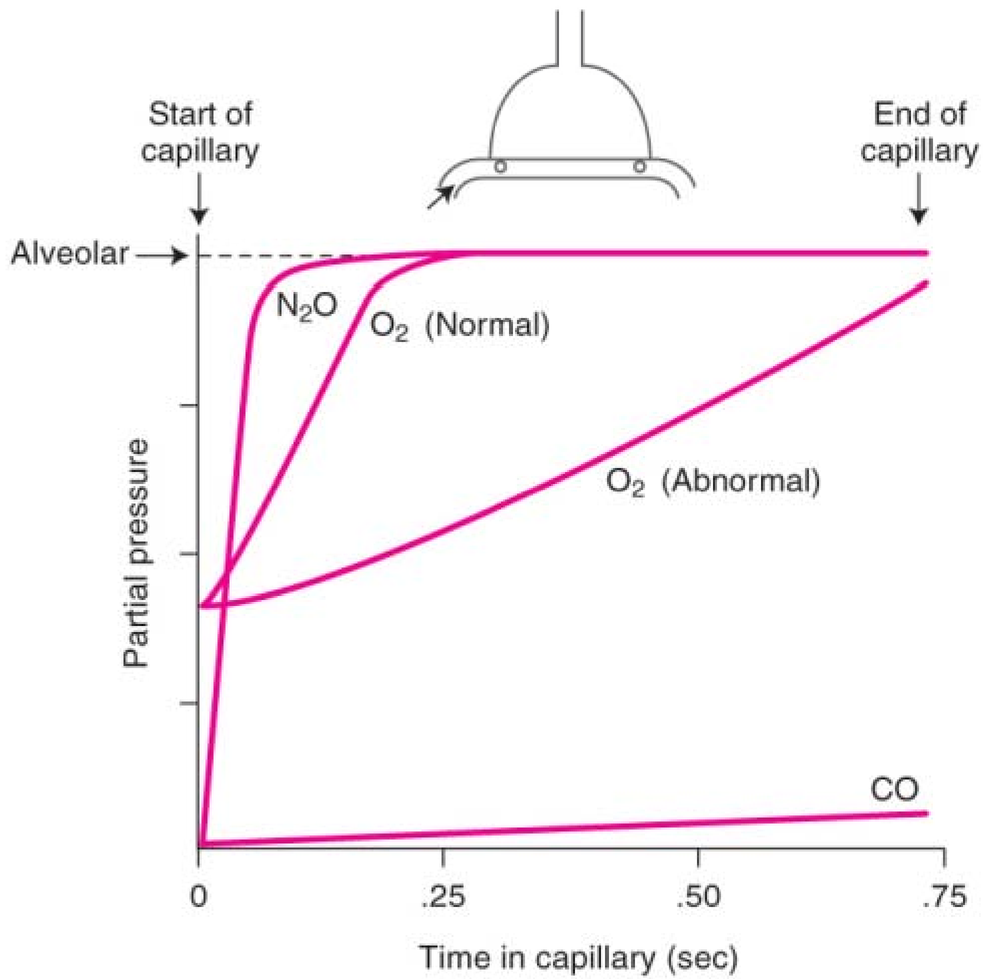
Diffusing Capacity (Transfer Factor)



Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)

- Transfer of O_2 and CO_2 between alveolar gas and pulmonary capillary blood is entirely passive
- The *rate of diffusion* of gas across alveolar-capillary barrier is determined by
  - solubility of gas in liquid
  - density of gas
  - partial pressure difference between alveolar air and pulmonary capillary blood
  - surface area available for diffusion
- CO_2 diffusion not a clinical problem because CO_2 much more soluble and diffusible than oxygen between air and blood
- Total diffusing capacity includes uptake by hemoglobin and rate of flow

Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)



“Diffusion Capacity” vs Diffusion

- Note that: decreased diffusing capacity/gas transfer abnormality can result from numerous abnormalities not having anything to do with diffusion block itself

“Diffusion Capacity” vs Diffusion

- So when we say diffusion abnormality=cause of hypoxemia, we mean those abnormalities which involve some form of diffusion block, or other inability to transfer gas completely (eg, low PIO_2+ ***decreased*** circulatory time) so that insufficient transfer of alveolar PO_2 occur
- Low alveolar volume, low Hgb, may result in low diffusing capacity as measured by transfer of CO, and low O_2 content, but not low PaO_2

Gas Transport: CO_2

- CO_2 in physical solution: most carried in RBCs either as bicarbonate, or bound to Hgb (carbaminoHgb)
- Some is dissolved in plasma

Gas Transport:Oxygen

- O_2 combined with Hgb in RBCs, and dissolved O_2 in physical solution in the plasma
- Normal: 1 gm of Hgb able to combine chemically with 1.34 ml O_2
- Thus: O_2 capacity=1.34 ml O_2 /gmHgb
- If 15 gm Hgb/100 ml blood, O_2 capacity=20 ml O_2 /100 ml blood=200 ml O_2 /liter blood
- Dissolved O_2 = .003 ml O_2 /100 ml blood/mmHg PaO_2
- **CaO_2 =SaO_2 x [O_2 capacity] + dissolved O_2**
- If PaO_2 =100 mmHg, and Hgb=15, then O_2 content = 200 ml O_2 /liter blood + 3 mlO_2/liter blood=~203 mlO_2/liter blood x SaO_2

Hypoxemia

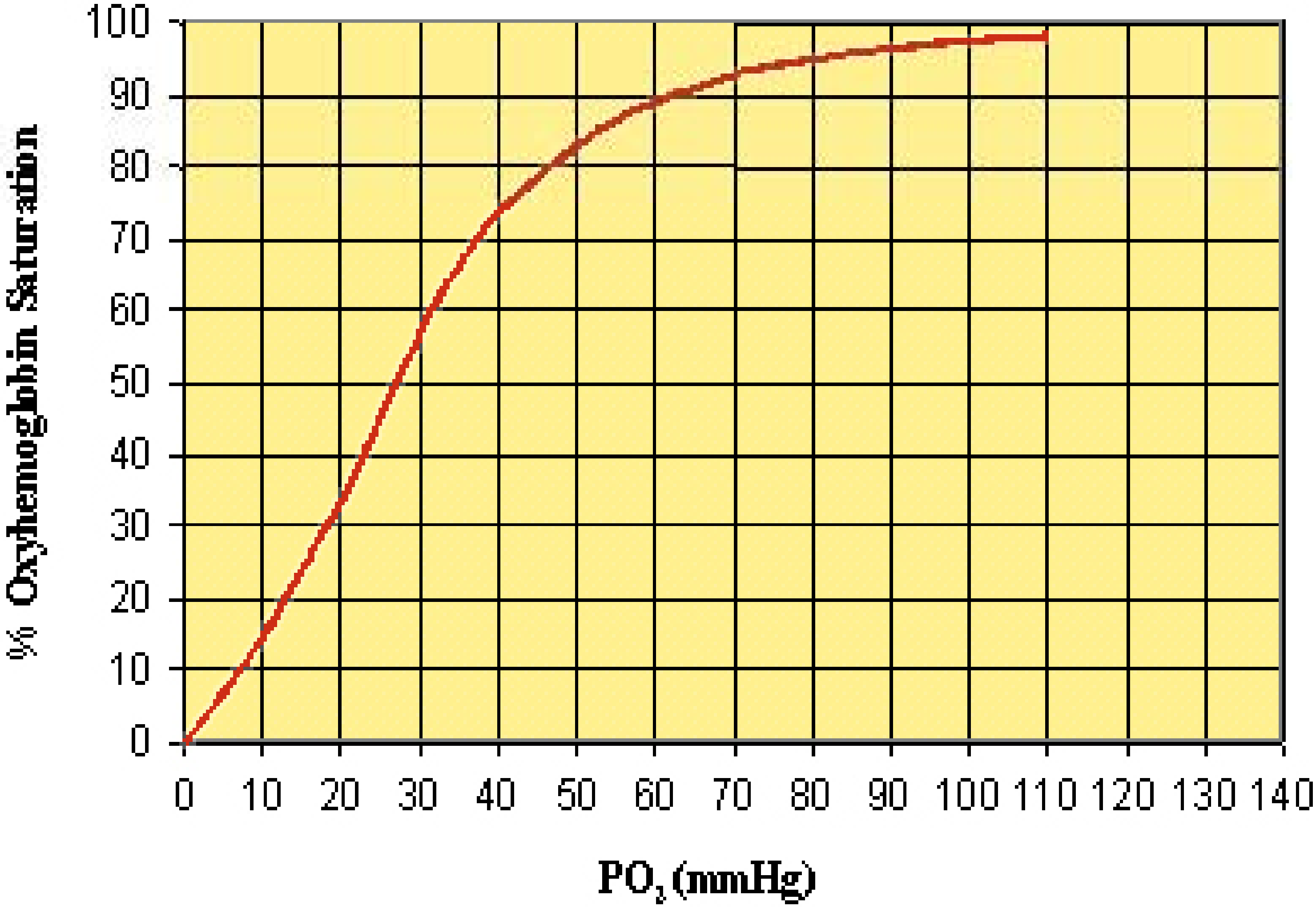
- Low partial pressure of O_2 in blood (PaO_2) OR low O_2 content

Hypoxia

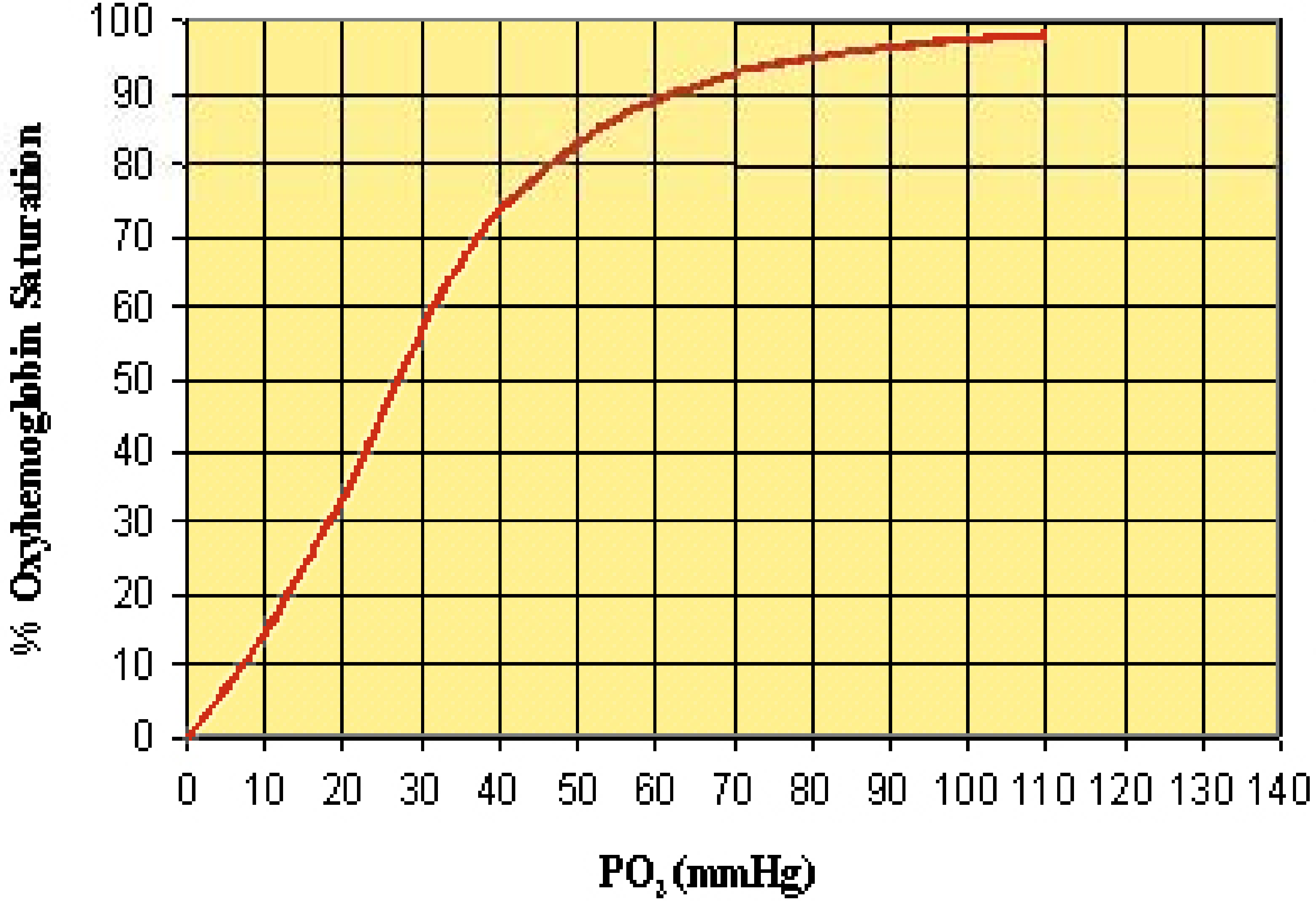
- Metabolic O_2 deficiency unable to meet tissue demands
- Hypoxia causes are:
  - "stagnant", as with impaired blood flow; normal PaO_2 and SaO_2
  - "histocytoxic",as with metabolic impairment using O_2, such as cyanide poisoning; normal PaO_2 and SaO_2
  - "anemic", as with low Hgb or carbon monoxide poisoning; normal PaO_2 and SaO_2
  - "hypoxic" or "hypoxemic", as with impaired oxygenation such as low V/Q, shunt, diffusion block, or low PIO_2 such as high altitude; PaO_2 and SaO_2 decreased

Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)

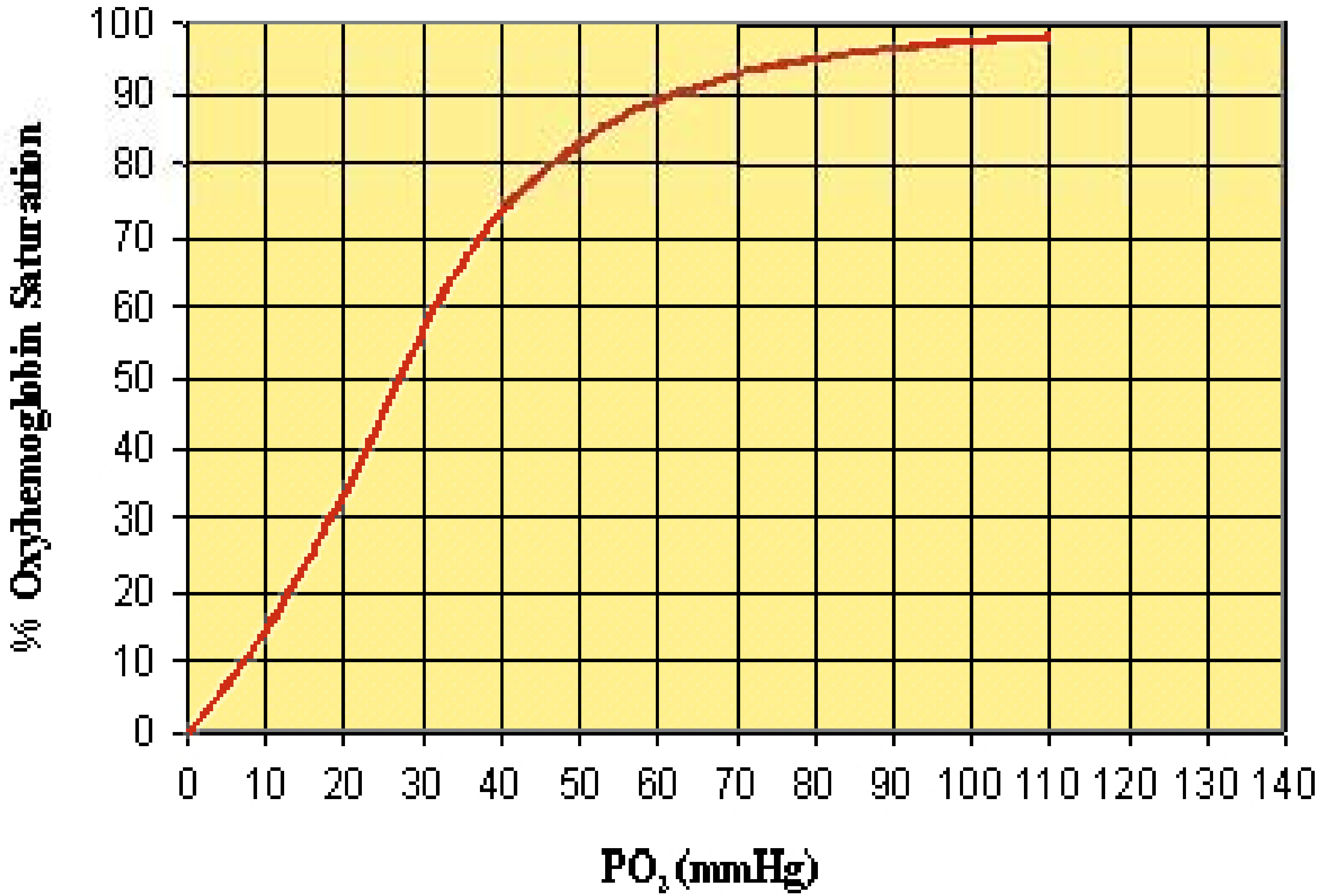
- Causes of Hypoxemia
  - Hypoventilation
  - Low PiO_2
  - Diffusion abnormality (must be severe if at rest)
  - V/Q mismatch
  - Shunt
- Note that low V/Q does not=shunt
- Degree of O_2 saturation depends on O_2 tension



- Below PaO_2 60 mmHg, O_2 sat and content decrease rapidly
- (ie, rapid dissociation and tissue unloading)



- Right shift=decreased O2 affinity (decreased SaO2) for a given PaO2
- (ie, more tissue unloading: increased temp, 2,3 DPG, PCO2, low pH)



- Left shift=increased O2 affinity (increased SaO2) for a given PaO2
- (ie, less tissue unloading: low 2,3 DPG, high CO, low temp, methHgb, fetal Hgb)

Physiologic Causes of Hypoxemia

- **Widening of $AaDO_2$**
  - Diffusion Abnormality
  - V/Q mismatch
  - Shunt

- **No widening of $AaDO_2$:**
  - Hypoventilation
  - Low PIO_2
    - may contribute to widening if impaired diffusion

Alveolar Gas Equation

$$P_I O_2 = F_i O_2 \times (P_B - P_{H_2O})$$

$$P_A O_2 = P_I O_2 - \frac{P_A CO_2}{R} + \left[P_A CO_2 \times F_I O_2 x \frac{(1-R)}{R} \right]$$

$$\boxed{P_A O_2 \approx P_I O_2 - \frac{P_A CO_2}{R}}$$

- R=Respiratory Exchange Ratio: (gas R=CO_2 added to alveolar gas by blood/amount of O_2 removed from alveolar gas by blood; low V/Q=low R); normal=0.8

Two patients breathing room air at sea level:

1. PaO_2=40 mmHg, $PaCO_2$=90 mmHg:

2. PaO_2=40 mmHg, $PaCO_2$=22 mmHg:

Calculate the Alveolar-arterial PO2 gradient

What is the pulmonary pathophysiology?