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 $\text{PCO}_2$ 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

- $\text{CO}_2$ stimulation
- Hypoxemic stimulation
- $\text{H}^+$ stimulation
Chemical Control: CO₂ stimulation

- Central >> peripheral chemoreceptors
- Chronically elevated PaCO₂ = increased ECF [HCO₃⁻], so acute increase in PaCO₂ will induce less of a change in [H⁺] and therefore less stimulus to ventilation
Chemical Control: Hypoxemic Stimulation

- Peripheral chemoreceptors only
- Low $\text{PaO}_2 \rightarrow$ increased $V_E$
- The increase in $V_E$ is attenuated by the decreased $\text{PaCO}_2$ that results (see previous slide)
Chemical Control: Hydrogen ion stimulation

- Metabolic acidosis stimulates peripheral chemoreceptors
- Acute metabolic acidemia $\rightarrow$ increased $V_E$
- Chronic metabolic acidemia $\rightarrow$ 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

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

“Hysteresis”
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 showing elastin fibers in alveolar walls surrounding blood vessels.
Surface Tension of Alveolar Lining Fluid

• Surface Tension
  – **Technical definition:** “the force acting across an imaginary line 1 cm 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
Pulmonary Surfactant decreases 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

The graph shows the relationship between pressure in cm (H₂O) and the predicted total lung capacity (% predicted TLC) for different conditions:

- **Emphysema**: A dotted line indicating a significant change in the curve, especially at higher pressures.
- **Normal**: A solid line starting from 0% and gradually increasing to about 100%.
- **Interstitial fibrosis**: A solid line that increases more gradually compared to normal conditions.

The graph helps in understanding the effects of these conditions on lung function.
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 pressure
r = radius of the tube
η = viscosity
l = length of the tube
Airway Resistance is determined by Airway Caliber

Intraluminal: e.g., Secretions

Intramural: e.g., Edema

Extraluminal: e.g., Loss of radial traction
Application of the Alveolar Ventilation Equation

\[ P_{aCO_2} \propto \frac{V_{CO_2}}{V_A} \]

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 PIO₂+ decreased circulatory time) so that insufficient transfer of alveolar PO₂ occur

• Low alveolar volume, low Hgb, may result in low diffusing capacity as measured by transfer of CO, and low O₂ content, but not low PaO₂
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 ml$O_2$/liter blood = ~203 ml$O_2$/liter blood x $SaO_2$
Hypoxemia

• Low partial pressure of $O_2$ in blood (PaO$_2$) OR low $O_2$ content
Hypoxia

• Metabolic O₂ deficiency unable to meet tissue demands
• Hypoxia causes are:
  o “stagnant”, as with impaired blood flow; normal PaO₂ and SaO₂
  o “histocytotoxic”, as with metabolic impairment using O₂, such as cyanide poisoning; normal PaO₂ and SaO₂
  o “anemic”, as with low Hgb or carbon monoxide poisoning; normal PaO₂ and SaO₂
  o “hypoxic” or “hypoxemic”, as with impaired oxygenation such as low V/Q, shunt, diffusion block, or low PIO₂ such as high altitude; PaO₂ and SaO₂ decreased
Gas Transport: Pulmonary Circulation and Diffusion of Gas (Gas Transfer)

• Causes of Hypoxemia
  – Hypoventilation
  – Low PiO₂
  – Diffusion abnormality (must be severe if at rest)
  – V/Q mismatch
  – Shunt

• Note that low V/Q does not=shunt

• Degree of O₂ saturation depends on O₂ tension
Below PaO₂ 60 mmHg, O₂ 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

\[ P_{I}O_{2} = F_{i}O_{2} \times (P_{B} - P_{H_{2}O}) \]

\[ P_{A}O_{2} = P_{I}O_{2} - \frac{P_{A}CO_{2}}{R} + \left[ P_{A}CO_{2} \times F_{i}O_{2} \times \frac{(1-R)}{R} \right] \]

\[ P_{A}O_{2} \approx P_{I}O_{2} - \frac{P_{A}CO_{2}}{R} \]

- R=Respiratory Exchange Ratio: (gas R=CO₂ added to alveolar gas by blood/amount of O₂ 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?