Respiratory Mechanics and Introduction to Respiratory Physiology

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Disclosures

• Dr Burchfield has nothing to disclose
Basic Concept of Gas Pressures

- Atmosphere is filled with gas that applies a pressure of 760 mmHg pressure on its surroundings
  - 20.8% oxygen (160 mmHg)
  - Some gaseous water (47 mmHg)
  - Nitrogen (553 mmHg)
Basic Concept of Gas Pressures

\[ \text{Press}_{\text{Total}} = \text{press } H_2O + \text{press } O_2 + \text{press } N_2 \]
Gas Pressure Relationships in the Lung

- Nitrogen
- Oxygen
- Carbon dioxide
Gas Pressure Relationships in the Lung

• Alveolar gas equation
  – Calculation of the amount of oxygen at the alveoli

• Alveolar pO₂ = \( P_{A\ O₂} = [(P_B - P_{H₂O}) \times FiO₂] - P_{CO₂} \)

• \( P_{A\ O₂} = [(760-47) \times FiO₂] - (pCO₂)/R \)
  – Newborn, \( R \approx 1 \)

• \( P_{A\ O₂} = [(760-47) \times FiO₂] - pCO₂ \)
Calculate $P_{A\text{O}_2}$

- Inspired oxygen 50%
- Barometric pressure 760
- Water vapor pressure 47
- ABG 7.40/45/65

$$P_{A\text{O}_2} = [(760 - 47) \times \text{FiO}_2] - p\text{CO}_2$$

$$P_{A\text{O}_2} = (713 \times 0.5 ) - 45 = 317 \text{ torr}$$
Calculate $P_{A\text{O}_2}$

- You are hiking in Leadville, CO at an elevation of 10,000 ft. with a barometric pressure of 525 mmHg. The water vapor pressure is 47 mmHg. Since you are hyperventilating due to fatigue, your $pCO_2$ is 33 torr. What is your alveolar oxygen concentration?
- $P_{A\text{O}_2} = [(525-47) \times \text{FiO}_2] - \frac{pCO_2}{R}$
- $P_{A\text{O}_2} = (478 \times 0.21) - 33/0.8 = 59$ torr
  - Would be 67 torr if you ignore respiratory quotient
A-a Gradient (AaDO2)

- Alveolar - arterial gradient
- Alveolar oxygen (calculated) – arterial oxygen (measured)
ARS Question 1

• Gas flow in normal respiration occurs due to:
  1. Boyles Law
  2. Charles law
  3. LePlace Law
  4. Starling Law
Gas Flow

• Boyles Law
  – The pressure of a gas decreases as the volume that it is contained in increases
  – $P_\infty 1/V$
  – $P_1 V_1 = P_2 V_2$
Pulmonary Mechanics - Chest Wall

1. Barometric air pressure ($P_B$) is equal to alveolar pressure ($P_{alv}$) and there is no air movement.

2. Increased thoracic volume results in increased alveolar volume and decreased alveolar pressure. Barometric air pressure is greater than alveolar pressure, and air moves into the lungs.

$P_B = 760 \text{ mmHg}$

$P_A = 760 \text{ mmHg}$

$P_B = 760 \text{ mmHg}$

$P_A = 757 \text{ mmHg}$
Boyle's Law

In the smaller space the particles suffer more collisions with the walls of the container - it is this that we measure as 'pressure exerted by the gas'.

Pulling up increases the volume and decreases the pressure.

Pushing down decreases the volume and increases the pressure.
Boyles Law and Ventilation

![Diagram of human lungs and diaphragm showing the relationship between pressure (P), volume (V), and temperature (T) according to Boyle's Law.]
Boyles Law and Ventilation
Static Lung Forces

Pressures listed are relative and absolute.
Pulmonary Mechanics - Chest wall

Negative pressure due to chest wall stability balances elastic recoil...leads to FRC

\[ P_b = 760 \text{ mmHg} \]

\[ P_A = 760 \text{ mmHg} \]
Pulmonary Mechanics - Chest Wall

\[ P_b = 760 \text{ mmHg} \]

\[ P_A = 755 \text{ mmHg} \]

Chest Wall Expansion increases the (-) intrapleural pressure, with lung expansion and decrease in intrapulmonary pressure.
Adult vs Infant Mechanics

"Retractions"
Deadspace

- **Anatomical**
  - gas in the conducting areas of the respiratory system
  - air does not come into contact with the alveoli

- **Alveolar dead space**
  - air contacting alveoli without blood flow in their adjacent pulmonary capillaries
  - ventilation without perfusion

- **Physiological deadspace** = anatomic + alveolar

- Can be calculated by the Bohr equation
Deadspace Calculation

\[
\frac{V_d}{V_t} = \frac{P_{a\text{CO}_2} - P_{e\text{CO}_2}}{P_{a\text{CO}_2}}
\]

Vd is dead space volume
Vt is tidal volume
PaCO2 is the carbon dioxide in the arterial blood
PeCO2 is the partial pressure of carbon dioxide in the expired air.
Alveolar Dead Space

A = Hydrostatic pressure failure
B = Normal
C = Embolus
D = Emphysema
E = Pre-capillary constriction

Pulmonary arterial pressure head
ARS Question 2

• Compliance is
  1. Change in volume/change in resistance
  2. Change in resistance/change in volume
  3. Change in volume/change in resistance
  4. Change in volume/change in pressure
  5. An office that makes sure I bill correctly
Compliance

• A measure of elasticity or distensibility

• Compliance = \( \frac{\Delta \text{Volume}}{\Delta \text{Pressure}} \)

• Compliance = \( \frac{\Delta \text{Volume}}{\Delta \text{Pressure}} \)

• Compliance = \( \frac{\Delta \text{Volume}}{\Delta \text{Pressure}} \)
Compliance

• Static Compliance
  – Measured during no gas flow (i.e., no $\Delta V$)
  – Reflects the elastic properties of the lung
    • Tendency to recoil toward its original dimensions after removing distending pressure

• Dynamic Compliance
  – Measured during continuous breathing
  – Reflects elastic as well as resistive components
  – Measures from end of expiration to the end of inspiration for a given volume
So, what is the net affect of decreased compliance in a neonate with RDS?

\[ \text{Compliance} = \frac{\Delta \text{ Volume}}{\Delta \text{ Pressure}} \]

1. For same pressure gradient, the tidal volume will be reduced
2. …or to maintain a tidal volume, the pressure gradient must increase
Pressure-Volume Relationships

- Low FRC—RDS or atelectasis
- Normal FRC
- High FRC, over expanded
- Low compliance or “non-compliant”
- Normal compliance or “compliant”

ΔP

ΔV

Volume

Pressure
Pressure-Volume Relationships

Hysteresis:
different pathways for inspiration and expiration
Due to the effects of surfactant
Pressure Volume Relationships

- Normal Lung and Compliance
- Neonatal RDS—Decreased Compliance
Lung Volumes measured with a spirometer during quiet breathing with one maximum breath. Values shown are for an average-sized healthy young male.

- **RV**  Residual volume
- **ERV**  Expiratory reserve volume
- **IRV**  Inspiratory reserve volume
- **TLC**  Total lung capacity
- **FRC**  Functional residual capacity
- **TV**  Tidal volume
- **VC**  Vital capacity

**Fig 1**
Comparison of Lung Mechanics

• Neonate
  - ↑ RR
  - ↑ Minute ventilation
    • TV x RR
  - ↑ Alveolar ventilation
    • (TV-Deadspace) x RR
  - ↑ Oxygen consumption

• Adult
  - ↑ TV
  - ↑ Total lung capacity
  - ↑ Inspiratory capacity
  - ↑ Vital capacity
ARS Question 3

• All of the following are true about Resistance EXCEPT:

1. It is a property typically dealing with flow through tubes
2. Is directly related to length
3. Goes up to the 4th power with changing the radius
4. Involves the viscosity of the substance
Resistance

- \( R = \frac{\Delta P}{\dot{V}} \)
- Typically think of the effects of resistance on either flow or pressure
Resistance

\[ R = \frac{\Delta P}{\dot{V}} \quad \rightarrow \quad \dot{V} = \frac{\Delta P}{R} \]
Resistance

\[ R \propto L \times \frac{\eta}{r^4} \]

- Length of tube
- Length of airway
- Viscosity
  - Air
  - Helium
- Radius
  - ET Tube
  - Airways
Resistance
Lung Anatomy and Shunts

Normal $V_A / Q_P$

Low $V_A / Q_P$

Shunt
Three Alveoli And Gas Exchange

- Mucous plug
- Trapped air

\[ \frac{V_A}{Q} = 0 \]

- \( P_{\text{CO}_2} \): 6.1
- \( P_{\text{O}_2} \): 6

- \( \frac{V_A}{Q} = 1.0 \)

- \( P_{\text{CO}_2} \): 6.1
- \( P_{\text{O}_2} \): 6

- \( \frac{V_A}{Q} = \infty \)

- \( P_{\text{O}_2} \): 5.3
- \( P_{\text{CO}_2} \): 14.4

- Embolus
- No bloodflow

Fig. 14-2
Physiologic Shunt or Intrapulmonary shunt

\[ \text{AaDO}_2 = 125 - 40 = 85 \text{ mmHg} \]
Venous-Arterial Shunt

- Anatomical dead space
  - $P_{\text{O}_2} = 150$
  - $P_{\text{CO}_2} = 0$

- Pulmonary veins
  - $P_{\text{pVO}_2} = 60$
  - $P_{\text{pVO}_2} = 39$

- Pulmonary arteries
  - $P_{\text{aO}_2} = 102$
  - $P_{\text{aCO}_2} = 40$

- Venous blood
  - $P_{\text{vO}_2} = 40$
  - $P_{\text{vCO}_2} = 46$

- Arterial blood
  - $P_{\text{aO}_2} = 102$
  - $P_{\text{aCO}_2} = 40$

- Pulmonary arteries and veins:
  - $P_{\text{O}_2} = 40$
  - $P_{\text{CO}_2} = 46$

- Pulmonary artery
  - $P_{\text{aO}_2} = 102$
  - $P_{\text{aCO}_2} = 40$

- Pulmonary vein
  - $P_{\text{pVO}_2} = 60$
  - $P_{\text{pVO}_2} = 39$

- Venous system
  - $P_{\text{vO}_2} = 40$
  - $P_{\text{vCO}_2} = 46$
Ventilation Perfusion Matching

(a) Normally perfusion of blood past alveoli is matched to alveolar ventilation to maximize gas exchange.
Low V/Q

(b) Ventilation-perfusion mismatch caused by under-ventilated alveoli.

If ventilation decreases in a group of alveoli, $P_{CO_2}$ increases and $P_{O_2}$ decreases. Blood flowing past those alveoli does not get oxygenated.
Hypoxic Pulmonary Vasoconstriction

(c) Local control mechanisms try to keep ventilation and perfusion matched.

Decreased tissue $P_{O_2}$ around underventilated alveoli constricts their arterioles, diverting blood to better ventilated alveoli.

Blood flow diverted to better ventilated alveoli
Ventilation/Perfusion Relationships

Shunt
R--->L at PDA, foramen ovale

Hypoventilated lung unit

Normal

Hyperventilation
Factors Regulating Ventilation-Perfusion Matching

• Changes in Pulmonary Artery Pressure
  – Hypoxic Pulmonary Vasoconstriction and V/Q matching
  – Pulmonary vasoconstriction and V/Q mismatching

• Distribution of Ventilation
Hypoxic Pulmonary Vasoconstriction

- Occurs at higher PAO$_2$ than adults
- More vigorous response than adults

Low V/Q Unit
Low PO$_2$

$Q_1 = Q_2$,
ARS Question 4

• Time constant of the lung is
  1. Compliance x resistance
  2. Is high in acute RDS
  3. Is low in meconium aspiration syndrome
  4. Is important only in the weaning phase of mechanical ventilation
Time Constants

• Compliance = $\Delta$Volume/ $\Delta$Pressure

• $\Delta$Volume = Compliance x $\Delta$Pressure
  – However, there must be a TIME element involved for the $\Delta$Volume to occur.

• The time necessary to deflate 63% of its volume is called the time constant
Time Constant

Mathematical Product:

time constant = compliance x resistance
Time Constant

- \( TC = R \times C \)
  - \( R = \frac{P}{V} = \text{Resistance} \)
  - \( C = \frac{V}{P} = \text{Capacitance} \)
- \( TC = \text{time} \)
Time Constant

• Assume healthy infant
  – Resistance 30 cm H$_2$O/L
  – Compliance 0.004 L/ cm H$_2$O

1 TC = 0.12 sec
5TC = 0.6 sec
Thus, inspiratory or expiratory phase needs to be 0.6 sec (assuming phases are equivalent)
Time Constants

\[ TC_1 = R \times 2C_2 \]
\[ TC_2 = R \times C_2 \]

\[ TC_1 = R_1 \times C_1 \]
\[ TC_2 = R^4 \times C_1 \]
\[ TC_2 = (TC_1)^4 \]
Time Constants

• Normal TC = 0.12-0.15 sec
  – TC = 63% emptying
  – 2 TC = 84% emptying
  – 3 TC = 95 % emptying

• RDS
  – TC ≈ 0.05 sec
Summary

• Think about flow through pipes
• Hypoxia can come from VQ mismatch or shunt
• Need adequate time for gas exchange to take place from the mouth to the alveoli