M1 - Cardiovascular / Respiratory, Fall 2007

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Objectives

- To recognize the importance of matching ventilation and perfusion
- To explain the consequences of mismatched ventilation and perfusion
- To define shunt and dead space physiology
- To be able to determine the alveolar pO$_2$
- To be able to determine the A-a O$_2$ gradient and understand the implications of an increased gradient
- To explain and understand the consequences of regional differences in ventilation and perfusion due to effects of gravity
Ventilation and Perfusion at the Level of the Whole Lung

- Tidal Volume: 500 mL
- Anatomic Dead Space: 150 mL
- Alveolar Gas Volume: 3000 mL
- Volume of Blood in Pulmonary Capillaries: 70 mL
- Respiratory Rate: 15 min
- Total Ventilation: 7500 mL/min
- Alveolar Ventilation: 5250 mL/min

\[
\frac{\text{Ventilation}}{\text{Perfusion}} = \frac{V}{Q} = 1
\]

Pulmonary Blood Flow: 5000 mL/min

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Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ \text{PiO}_2 = (\text{barometric pressure- H2O vapor pressure}) \times \text{FiO}_2 = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

In the alveolar space, oxygen diffuses into the blood and CO2 diffuses into the alveolus from the blood.
Alveolar Gas Equation

\[ \text{PAO}_2 = (\text{PiO}_2) - (\text{PaCO}_2/R). \]

\( \text{PaCO}_2 \) approximates \( \text{PACO}_2 \) due to the rapid diffusion of \( \text{CO}_2 \)

\( R = \text{Respiratory Quotient (VCO2/V02)} = 0.8 \)

In a normal individual breathing room air:

\[ \text{PAO}_2 = 150 - 40/0.8 = 100 \text{ mmHg} \]
Gas Composition in the Normal Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ \text{PiO}_2 = (\text{barometric pressure-H}_2\text{O vapor pressure}) \times \text{FiO}_2 \]
\[ = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

In the alveolar space, oxygen diffuses into the blood and CO2 diffuses into the alveolus from the blood.
Consequences of Inadequate Ventilation

- Apnea:
  - PACO2 rises
  - PAO2 falls until there is no gradient for diffusion into the blood

- Hypoventilation:
  - Inadequate ventilation for perfusion
  - PACO2 rises
  - PAO2 falls, but diffusion continues
How Can We Tell if Alveolar Ventilation is Adequate?
PaCO2 and Alveolar Ventilation

• PaCO2 is:
  – directly related to CO2 production (tissue metabolism).
  – Inversely related to alveolar ventilation.

• Increased PaCO2 (hypercarbia) is always a reflection of inadequate alveolar ventilation (VA).

\[ \text{PaCO2} \approx \frac{VCO2}{VA} \]
Suppose a patient hypoventilates, so that the PCO2 rises to 80 mmHg. We can estimate the PAO2 based on the alveolar gas equation.

\[ \text{PAO2} = 150 - \frac{80}{0.8} = 50 \text{ mmHg} \]

Thus even with perfectly efficient lungs, the PaO2 would be 50, and the patient would be severely hypoxemic. Therefore, hypoventilation results in hypoxemia.
V/Q Matching

• 300 million alveoli.

• Different alveoli may have widely differing amounts of ventilation and of perfusion.

• Key for normal gas exchange is to have matching of ventilation and perfusion for each alveolar unit
  – Alveoli with increased perfusion also have increased ventilation
  – Alveoli with decreased perfusion also have decreased ventilation
  – V/Q ratio = 1.0
Two Lungs, Not One

• Suppose the left lung is ventilated but not perfused (dead space).

• Suppose the right lung is perfused but not ventilated (shunt).

• Total V/Q = 1, but there is no gas exchange (V/Q must be matched at level of alveolar unit).
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

↑ PCO2  
↓ PO2

PO2 114

PO2 50

PO2 ?
Mixing Blood

- What is the PO2 of a mixture of two volumes of blood with different initial PO2?
- Determined by interaction of oxygen with hemoglobin.
  - the partition of oxygen between plasma (and thus the pO2) and bound to hemoglobin is determined by the oxyhemoglobin dissociation curve.
Oxyhemoglobin Dissociation Curve

CO₂ = (1.3 x HGB x Sat) + (.003 x PO₂)

% Hemoglobin Saturation

Oxygen Combined With Hemoglobin

Dissolved Oxygen

Oxygen Content (ml/100 ml)

P_O₂ mmHg
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

- Normal: PO2 114
- Low V/Q: PO2 50
- PO2 ?

↑ PCO2
↓ PO2

PO2 50
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

% Hemoglobin Saturation

PO2 mmHg

Oxygen Content (ml/100 ml)
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

PO₂ mmHg

Total Oxygen

Oxygen Combined With Hemoglobin

Oxygen Content (ml/100 ml)
Low V/Q Effect on Oxygenation

One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

Normal

PO2 114 mmHg
O2sat 100%
O2 content 20 ml/dl

Low V/Q

PO2 50 mmHg
O2sat 80%
O2 content 16 ml/dl

PO2 60 mmHg
PCO2 in V/Q Mismatch

- Increased ventilation can compensate for low V/Q units.
  - Shape of CO2 curve
- Total ventilation (VE) must increase for this compensation.
Extremes of V/Q Inequality

• **Shunt**
  – Perfusion of lung units without ventilation
    • Unoxygenated blood enters the systemic circulation
    • V/Q = 0

• **Dead space**
  – Ventilation of lung units without perfusion
    • Gas enters and leaves lung units without contacting blood
    • Wasted ventilation
    • V/Q is infinite
Effect of Changing V/Q Ratio on Alveolar PO2 and PCO2

- **Shunt**
  - \( P_{O_2} = 40 \text{mmHg} \)
  - \( P_{CO_2} = 45 \text{mmHg} \)

- **Dead Space**
  - \( P_{O_2} = 150 \text{mmHg} \)
  - \( P_{CO_2} = 0 \text{mmHg} \)

**Gas Composition**
- Mixed Venous Blood
- Normal
- Inspired Air

**V/Q**
- 0
- 1
- \( \infty \)

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Effects of V/Q Relationships on Alveolar PO2 and PCO2
Shunt Physiology

One lung unit has normal ventilation and perfusion, while the other has no ventilation.

- Normal lung unit: PO2 114 mmHg, O2sat 100%
- Shunt lung unit: PO2 49 mmHg, O2sat 75%
• Alveolar hypoventilation or V/Q mismatch responds to 100% oxygen breathing.

• Nitrogen will be washed out of low ventilation lung units over time.

• PaO2 will rise to > 550 mmHg.

• Limited response to oxygen in shunt.

• Use this characteristic to diagnose shunt.
Shunt Calculation

- $Qt \times CaO2 = \text{total volume of oxygen per time entering systemic arteries}$
  - $Qt = \text{total perfusion}$
  - $Qs = \text{shunt perfusion}$
  - $CaO2, Cc’O2, CvO2$ are oxygen contents of arterial, capillary and venous blood

- $(Qt-Qs) \times Cc’O2 = \text{oxygen coming from normally functioning lung units}$

- $Qs \times CvO2 = \text{oxygen coming from shunt blood flow}$
Shunt

\[
\begin{align*}
\dot{Q}_t & \quad C_{\overline{v}O_2} \\
\dot{Q}_s & \\
C_{c'O_2} & \\
C_{aO_2} & \quad \dot{Q}_t
\end{align*}
\]
Shunt Equation

\[ Qt \times CaO2 = [(Qt - Qs) \times CcO2] + [Qs \times CvO2] \]

\[ \frac{Qs}{Qt} = \frac{Cc'O2 - CaO2}{Cc'O2 - CvO2} \]
Causes of Shunt

- **Physiologic shunts:**
  - Bronchial veins, pleural veins

- **Pathologic shunts:**
  - Intracardiac
  - Intrapulmonary
    - Vascular malformations
    - Unventilated or collapsed alveoli
Detecting V/Q Mismatching and Shunt

• Radiotracer assessments of regional ventilation and perfusion.

• Multiple inert gas elimination.
  – Takes advantage of the fact that rate of elimination of a gas at any given V/Q ratio varies with its solubility.

• A-aO2 Gradient.
V/Q Relationships

Multiple Inert Gas Elimination

In a totally efficient lung unit with matched V/Q, alveolar and capillary PO2 would be equal.

Admixture of venous blood (or of blood from low V/Q lung units) will decrease the arterial PaO2, without effecting alveolar O2 (PAO2).

Calculate the PAO2 using the alveolar gas equation, then subtract the arterial PaO2: 

\[ \text{PAO2} = (\text{PiO}_2) - (\text{PaCO}_2/R) - \text{PaO2} \]

The A-a O2 gradient (or difference) is < 10-15 mmHg in normal subjects

- Why is it not 0?
Apical and Basilar Alveoli in the Upright Posture

- Elastic recoil of the individual alveoli is similar throughout the normal lung.

- At end expiration (FRC) apical alveoli see more negative pressure and are larger than basilar alveoli.

- During inspiration, basilar alveoli undergo larger volume increase than apical alveoli.

- Thus at rest there is more ventilation at the base than the apex.

- Also More Perfusion to Lung Bases Due to Gravity.
Effects of Gravity on Ventilation and Perfusion

Effects of Gravity on Ventilation and Perfusion Matching
Causes of Abnormal Oxygenation

- Hypoventilation
- V/Q mismatch
- Shunt
- Diffusion block
Key Concepts:

- Ventilation and Perfusion must be matched at the alveolar capillary level.

- V/Q ratios close to 1.0 result in alveolar PO2 close to 100 mmHg and PCO2 close to 40 mmHg.

- V/Q greater than 1.0 increase PO2 and Decrease PCO2. V/Q less than 1.0 decrease PO2 and Increase PCO2.

- Shunt and Dead Space are Extremes of V/Q mismatching.

- A-a Gradient of 10-15 Results from gravitational effects on V/Q and Physiologic Shunt.