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M1 - Cardiovascular / Respiratory, Fall 2007

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Ventilation/Perfusion Matching

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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

Ventilation / Perfusion = $\frac{\dot{V}}{\dot{Q}} = 1$

Pulmonary Blood Flow: 5000 mL/min

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Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ PiO_2 = (\text{barometric pressure}-\text{H2O vapor pressure}) \times FiO_2 = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

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 \( \text{CO}_2 \)

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

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

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

In the alveolar space, oxygen diffuses into the blood and CO2 diffuses into the alveolus from the blood.
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).

\[ \text{PaCO2} \approx \frac{VCO2}{VA} \]
Alveolar Hypoventilation

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.

- Normal unit:
  - PO2 114

- Low V/Q unit:
  - PO2 50
  - PCO2 ↑
  - PO2 ↓

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.
\[ CO_2 = (1.3 \times HGB \times \text{Sat}) + (0.003 \times P_O_2) \]

- **Oxyhemoglobin Dissociation Curve**
- **% Hemoglobin Saturation**
- **P_O_2 mmHg**
- **Oxygen Content (ml/100 ml)**
- **Oxygen Combined With Hemoglobin**
- **Dissolved Oxygen**
Low V/Q Effect on Oxygenation

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

- Normal lung unit:
  - PO2: 114
  - PCO2: ↓
  - PO2: ↑

- Low V/Q lung unit:
  - PO2: 50
  - PCO2: ↑
  - PO2: ↓

PO2: ?
Oxyhemoglobin Dissociation Curve and O2 Content

- % Hemoglobin Saturation
- PO₂ mmHg
- Total Oxygen
- Oxygen Combined With Hemoglobin

Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

PO₂ mmHg

Total Oxygen

Oxygen Combined With Hemoglobin

Oxyhemoglobin

Oxyhemoglobin Dissociation Curve and O2 Content

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 20ml/dl

Low V/Q:
- PO2 50 mmHg
- O2sat 80%
- O2 content 16ml/dl
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

\[ \text{PO}_2 \text{ mmHg} \]

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
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**: $P_{O_2} = 150\,\text{mmHg}$, $P_{CO_2} = 0\,\text{mmHg}$
- **Normal**: $P_{O_2} = 100\,\text{mmHg}$, $P_{CO_2} = 40\,\text{mmHg}$

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

V/Q:
- **0**: Dead Space
- **1**: Normal
- **$\infty$**: Shunt

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Effects of V/Q Relationships on Alveolar PO2 and PCO2

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One lung unit has normal ventilation and perfusion, while the other has no ventilation.
Response to Breathing 100% Oxygen

- 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

- $\text{Qt} \times \text{CaO}_2 = \text{total volume of oxygen per time entering systemic arteries}$
  - $\text{Qt} = \text{total perfusion}$
  - $\text{Qs} = \text{shunt perfusion}$
  - $\text{CaO}_2, \text{Cc’O}_2, \text{CvO}_2$ are oxygen contents of arterial, capillary and venous blood

- $(\text{Qt}-\text{Qs}) \times \text{Cc’O}_2 = \text{oxygen coming from normally functioning lung units}$

- $\text{Qs} \times \text{CvO}_2 = \text{oxygen coming from shunt blood flow}$
Shunt

\[ \dot{Q}_t \quad C_{\bar{v}O_2} \]

\[ \dot{Q}_s \]

\[ C_{c'O_2} \]

\[ \dot{Q}_t \quad C_{aO_2} \]
Shunt Equation

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

\[ \frac{\text{Qs}}{\text{Qt}} = \frac{\text{Cc'O2} - \text{CaO2}}{\text{Cc'O2} - \text{CvO2}} \]
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
A-a O2 gradient

- 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 affecting alveolar O2 (PAO2).

- Calculate the PAO2 using the alveolar gas equation, then subtract the arterial 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

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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.