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Ventilation/Perfusion Matching

M1 – Cardiovascular/Respiratory Sequence

Thomas Sisson, MD

Fall 2008
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
- Total ventilation: 7500 ml/min
- Anatomic dead space: 150 ml
- Frequency: 15/min
- Alveolar ventilation: 5250 ml/min
- Pulmonary capillary blood: 70 ml
- Pulmonary blood flow: 5000 ml/min

\[ \frac{5250}{7500} \approx 1 \]
Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

PiO2 = (barometric pressure - H2O vapor pressure) x FiO2
= (760 – 47) x 0.21 = 150 mmHg

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

PvO2 = 40
PvCO2 = 45

PAO2 = ?
PACO2 = ?

PaO2 = 100
PaCO2 = 40

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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

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

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

\[
\begin{align*}
\text{PAO}_2 &= 100 \text{ mmHg} \\
\text{PACO}_2 &= 40 \text{ mmHg}
\end{align*}
\]

\[
\begin{align*}
\text{PvO}_2 &= 40 \\
\text{PvCO}_2 &= 45
\end{align*}
\]

\[
\begin{align*}
\text{PO}_2 &= 100 \\
\text{PCO}_2 &= 40
\end{align*}
\]
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.

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

• Increased PaCO2 (hypercarbia) is always a reflection of inadequate alveolar ventilation (VA).
Suppose a patient hypoventilates, so that the PCO2 rises to 80 mmHg. We can estimate the PAO2 based on the alveolar gas equation.

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

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
- Low V/Q

PO2 114
PO2 50
PO2 ?

PCO2 ↑
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

\[ CO_2 = (1.3 \times \text{HGB} \times \text{Sat}) + (0.003 \times \text{PO}_2) \]

- **% Hemoglobin Saturation**
- **PO\(_2\)** in mmHg
- **Oxygen Content (ml/100 ml)**

- **Oxygen Combined With Hemoglobin**
- **Dissolved Oxygen**

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Low V/Q Effect on Oxygenation

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

PO2 114

PO2 50

PO2 ?

PCO2

PO2

↑

↓

Normal

Low V/Q
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation vs. PO₂ (mmHg)

- Total Oxygen
- Oxygen Combined With Hemoglobin

Oxygen Content (ml/100 ml)

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**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
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

Oxygen Content (ml/100 ml)

PO2 (mmHg)

Total Oxygen

Oxygen Combined With Hemoglobin

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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

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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

Dead Space

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 unit:
  - PO2 114 mmHg
  - O2sat 100%

- Shunt unit:
  - PO2 49 mmHg
  - O2sat 75%

- Normal + Shunt unit:
  - PO2 40 mmHg
  - O2sat 50%
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

- $Qt \times CaO_2 = \text{total volume of oxygen per time entering systemic arteries}$
  - $Qt = \text{total perfusion}$
  - $Qs = \text{shunt perfusion}$
  - $CaO_2, Cc'O_2, CvO_2$ are oxygen contents of arterial, capillary and venous blood
- $(Qt-Qs) \times Cc'O_2 = \text{oxygen coming from normally functioning lung units}$
- $Qs \times CvO_2 = \text{oxygen coming from shunt blood flow}$
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 effecting alveolar O2 (PAO2).

• Calculate the PAO2 using the alveolar gas equation, then subtract the arterial PaO2: 
\[ \text{PAO2} = \left( \Pi O_2 \right) - \left( \frac{\text{PaCO}_2}{R} \right) - \text{PaO2} \]

• 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.
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