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
- **Pulmonary Blood Flow**: 5000 mL/min

\[ \text{Ventilation} \div \text{Perfusion} = \frac{V}{Q} = 1 \]
Gas Composition in the 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.
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

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

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).

\[ \text{PaCO2} \approx \frac{V_{CO2}}{VA} \]
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.

PO2: 114

PO2: 50

PO2: 114

PO2: 50

PO2: ?

↑ PCO2

↓ PO2

Normal

Low V/Q
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

\[ CO_2 = (1.3 \times HGB \times Sat) + (0.003 \times P_O^2) \]

- Oxygen Combined With Hemoglobin
- Dissolved Oxygen

% Hemoglobin Saturation

\( P_O^2 \) 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.

Normal

Low V/Q

PO2 114

PO2 50

PO2 ?

PO2 ?

↑ PCO2

↓ PO2

↓ PO2
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

% Hemoglobin Saturation vs. 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.

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

PO2 50 mmHg
O2sat 80%
O2 content 16ml/dl
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

Oxygen Content (ml/100 ml)

Total Oxygen

Oxygen Combined With Hemoglobin

P$_{O_2}$ (mmHg)

0 20 40 60 80 100

0 20 40 60 80 100 120 160

20 40 60 80

0 4 8 12

0 600
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 mmHg
  - O2sat: 100%
  - O2 content: 20 ml/dl

- Low V/Q lung unit:
  - 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

Dead Space

Gas Composition
- Mixed Venous Blood
- Normal
- Inspired Air

V/Q
- 0
- 1
- ∞
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.

- Normal:
  - PO2: 114 mmHg
  - O2sat: 100%

- Shunt:
  - PO2: 40 mmHg
  - O2sat: 50%

- Other:
  - PO2: 49 mmHg
  - O2sat: 75%
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

- $Qt \times CaO2 = \text{total volume of oxygen per time entering systemic arteries}$
  - $Qt = \text{total perfusion}$
  - $Qs = \text{shunt perfusion}$
  - $CaO2, Cc’O2, CvO2$ 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 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 shunt:
  – 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: \( (P_{iO_2}) - (P_{CO_2}/R) \) – 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
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.