M1 - Cardiovascular / Respiratory, Fall 2007

Abrams, G.; Sisson, T.; Jacobson, P.

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Ventilation/Perfusion Matching

Thomas H. Sisson, M.D.
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 pO₂
  – To be able to determine the A-a O₂ 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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Trachea: partial pressure of CO2 is approximately 0

\[ P_{iO2} = (\text{barometric pressure} - \text{H2O vapor pressure}) \times FiO2 \]
\[ = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

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

\[ PAO_2 = (PiO_2) - (PaCO_2/R). \]

\( PaCO_2 \) approximates \( PACO_2 \) due to the rapid diffusion of \( CO_2 \)

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

In a normal individual breathing room air:

\[ PAO_2 = 150 - 40/0.8 = 100 \text{ mmHg} \]
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).

\[
PaCO2 \approx \frac{VCO2}{VA}
\]
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).
One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

- **Normal** unit:
  - $PO_2 = 114$

- **Low V/Q** unit:
  - $PCO_2$ increased
  - $PO_2$ decreased
  - $PO_2 = 50$
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

\[ CO_2 = (1.3 \times HGB \times Sat) + (0.003 \times PO_2) \]

- 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 ventilation and perfusion:
  - PO2 114
  - PO2 50

- Inadequate ventilation:
  - PCO2 ↑
  - PO2 ↓
  - PO2 50
  - PO2 114

PO2 ?
Oxyhemoglobin Dissociation Curve and O2 Content

![Graph showing oxygen content and hemoglobin saturation](image)

- **% Hemoglobin Saturation**
- **PO₂ (mmHg)**
- **Oxygen Combined With Hemoglobin**
- **Total Oxygen**

- **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
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation

Total Oxygen

Oxygen Combined With Hemoglobin

PO2 (mmHg)

Oxygen Content (ml/100 ml)
One lung unit has normal ventilation and perfusion, while the other has inadequate ventilation.

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

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

PO2 60 mmHg

Normal

Low V/Q
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.

![Graph showing CO2 content vs. PCO2](image-url)
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

∞

$P_{O_2} = 150 \text{mmHg}$
$P_{CO_2} = 0 \text{mmHg}$

$P_{O_2} = 150 \text{mmHg}$
$P_{CO_2} = 0 \text{mmHg}$

$P_{O_2} = 40 \text{mmHg}$
$P_{CO_2} = 45 \text{mmHg}$

$P_{O_2} = 100 \text{mmHg}$
$P_{CO_2} = 40 \text{mmHg}$

$P_{O_2} = 150 \text{mmHg}$
$P_{CO_2} = 0 \text{mmHg}$

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Effects of V/Q Relationships on Alveolar PO2 and PCO2
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%
- **Shunt**: 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

\[ \dot{Q}_t \quad C_{\nabla O_2} \quad \dot{Q}_s \quad C_{c' O_2} \quad \dot{Q}_t \quad C_{a O_2} \]

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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

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

• 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.