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 \( pO_2 \)
  – 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
- Ventilation/Perfusion ratio: $\frac{V}{Q} = 1$

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Gas Composition in the 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.
Alveolar Gas Equation

$$PAO_2 = (PiO_2) - (PaCO_2/R).$$

$PaCO_2$ approximates $PACO_2$ due to the rapid diffusion of $CO_2$

$R = Respiratory Quotient \ (VCO2/V02) = 0.8$

In a normal individual breathing room air:

$$PAO_2 = 150 - 40/0.8 = 100 \ mmHg$$
Gas Composition in the Normal Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

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

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).

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

↑ 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

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

- Oxygen Combined With Hemoglobin
- Dissolved Oxygen

% Hemoglobin Saturation

\( \text{PO}_2 \) mmHg

Oxygen Content (ml/100 ml)

0 20 40 60 80 100

0 100
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

PO2: 50

PO2: ?

Normal

Low V/Q
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation vs. P_{O2} (mmHg)

- Total Oxygen
- Oxygen Combined With Hemoglobin

Oxygen Combined With Hemoglobin

O2 Content (ml/100 ml) vs. 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 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

Total Oxygen

Oxygen Combined With Hemoglobin
PO2 50 mmHg
O2sat 80%
O2 content 16ml/dl

PO2 60mmHg

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

Low V/Q Effect on Oxygenation

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

Normal

Low V/Q
• 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

**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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Shunt Physiology

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

- PO2: 114 mmHg, O2sat: 100%
- PO2: 40 mmHg, O2sat: 50%
- 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

\[ \dot{Q}_t \quad C_{\bar{v}O_2} \quad \dot{Q}_s \quad C_{c'O_2} \quad C_{aO_2} \quad \dot{Q}_t \]
Shunt Equation

\[ Q_t \times C_{aO2} = [(Q_t - Q_s) \times C_{cO2}] + [Q_s \times C_{vO2}] \]

\[ \frac{Q_s}{Q_t} = \frac{C_{c'O2} - C_{aO2}}{C_{c'O2} - C_{vO2}} \]
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

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: 
\[
(PiO_2) - (PaCO_2/R) - PaO2.
\]

• 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
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.