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: $\frac{V}{Q} = 1$
- Pulmonary Blood Flow: 5000 mL/min

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Gas Composition in the Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

\[ P_{iO2} = (\text{barometric pressure} - \text{H2O vapor pressure}) \times F_iO2 \]
\[ = (760 - 47) \times 0.21 = 150 \text{ mmHg} \]

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

\[ P_{O2} = 40 \text{ mmHg} \]
\[ P_{CO2} = 45 \text{ mmHg} \]
\[ P_{O2} = 100 \text{ mmHg} \]
\[ P_{CO2} = 40 \text{ mmHg} \]
Alveolar Gas Equation

$$\text{PAO}_2 = (\text{PiO}_2) - (\text{PaCO}_2/R)$$.

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:

$$\text{PAO}_2 = 150 - 40/0.8 = 100 \text{ mmHg}$$
Gas Composition in the Normal Alveolar Space

Trachea: partial pressure of CO2 is approximately 0

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

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).

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

PO2 114

↑ PCO2
↓ PO2

PO2 50

PO2 114

PO2 ?
• 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

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

- % Hemoglobin Saturation
- Oxygen Combined With Hemoglobin
- Dissolved Oxygen
- Oxygen Content (ml/100 ml)

\[ \text{PO}_2 \text{ mmHg} \]
Low V/Q Effect on Oxygenation

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

Normal

Low V/Q

PO2 114

PO2 50

PO2 ?

PO2 ?

↑ PCO2

↓ PO2
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

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

Oxygen Combined With Hemoglobin

Total Oxygen

Oxygen Content (ml/100 ml)

20

16

12

8

4

0

0

20

40

60

80

100

600
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
- 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

Gas Composition
- Mixed Venous Blood
- Normal
- Inspired Air

V/Q
- 0
- 1
- ∞

Dead Space

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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.

PO2 114 mmHg
O2sat 100%

PO2 40 mmHg
O2sat 50%

PO2 49 mmHg
O2sat 75%

Normal

Shunt
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

- \( Q_t \times C_{aO2} = \) total volume of oxygen per time entering systemic arteries
  - \( Q_t = \) total perfusion
  - \( Q_s = \) shunt perfusion
  - \( C_{aO2}, C_{c'O2}, C_{vO2} \) are oxygen contents of arterial, capillary and venous blood
- \( (Q_t-Q_s) \times C_{c'O2} = \) oxygen coming from normally functioning lung units
- \( Q_s \times C_{vO2} = \) oxygen coming from shunt blood flow
Shunt
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: \[(\Pi O_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.