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

- Respiratory Rate: 15/min
- Total Ventilation: 7500 mL/min
- Tidal Volume: 500 mL
- Anatomic Dead Space: 150 mL
- Alveolar Ventilation: 5250 mL/min
- Alveolar Gas Volume: 3000 mL
- Volume of Blood in Pulmonary Capillaries: 70 mL
- Pulmonary Blood Flow: 5000 mL/min

\[
\frac{V}{Q} = 1
\]
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.
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:**
  – \( \text{PACO}_2 \) rises
  – \( \text{PAO}_2 \) falls until there is no gradient for diffusion into the blood

• **Hypoventilation:**
  – Inadequate ventilation for perfusion
  – \( \text{PACO}_2 \) rises
  – \( \text{PAO}_2 \) 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.

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

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 phase:
  - PO2 114
  - Normal V/Q

- Low V/Q phase:
  - PO2 50
  - ↑ PCO2, ↓ PO2

PO2 question mark in the low V/Q area.
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

CO2 = (1.3 \times \text{HGB} \times \text{Sat}) + (0.003 \times \text{PO2})

- Oxygen Combined With Hemoglobin
- Dissolved Oxygen

% Hemoglobin Saturation

PO_2 \text{ 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

PO2 50

PO2 ?

↑ PCO2

↓ PO2

Normal

Low V/Q
Oxyhemoglobin Dissociation Curve and O2 Content

- Total Oxygen
- Oxygen Combined With Hemoglobin

% Hemoglobin Saturation vs. 
\( P_{O_2} \) 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**
- PO2 114 mmHg
- O2sat 100%
- O2 content 20ml/dl

**Low V/Q**
- PO2 50 mmHg
- O2sat 80%
- O2 content 16ml/dl
Oxyhemoglobin Dissociation Curve and O2 Content

% Hemoglobin Saturation vs. \( P_O_2 \) mmHg

Total Oxygen

Oxygen Combined With Hemoglobin

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 V/Q:
  - PO2 114 mmHg
  - O2sat 100%
  - O2 content 20ml/dl

- Low V/Q:
  - PO2 50 mmHg
  - O2sat 80%
  - O2 content 16ml/dl


PO2 60mmHg
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

[Diagram showing the effect of changing V/Q ratio on Alveolar PO2 and PCO2 with different PO2 and PCO2 values.

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

Diagram showing the relationship between alveolar PO2 and PCO2, illustrating the impact of V/Q mismatch with different lung conditions:

- **Mixed Venous Blood**
- **Normal**
- **Inspired Air**

The graph plots PO2 (mmHg) on the x-axis and PCO2 (mmHg) on the y-axis, highlighting the differences in oxygen and carbon dioxide levels under various V/Q conditions.
One lung unit has normal ventilation and perfusion, while the
has no ventilation.

- Normal:
  - PO2 114 mmHg
  - O2sat 100%

- Shunt:
  - 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.
- \( \text{PaO}_2 \) 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
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: 
  \[ \left( \text{PiO}_2 \right) - \frac{\text{PaCO}_2}{R} - \text{PaO}_2 \]

- 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.