Ventilation/Perfusion (V/Q) 1 and 2
Linda Costanzo Ph.D.

OBJECTIVES:
After studying this lecture, the student should understand:

1. Regional variations in ventilation, perfusion, and ventilation/perfusion in the upright lung.
2. The effect of regional variations in ventilation/perfusion on $P_{O_2}$ and $P_{CO_2}$.
3. The patterns of ventilation/perfusion defects, including dead space and shunt, and the effects on alveolar and arterial $P_{O_2}$ and $P_{CO_2}$.
4. How to measure physiological dead space.
5. The physiological shunt, right-to-left shunts, and left-to-right shunts.
6. How to calculate the A-a gradient and how to use the calculated A-a gradient in comparing causes of hypoxemia.
7. How to measure the size of a right-to-left shunt with the shunt equation.
8. Causes and mechanisms of hypoxemia.
9. Causes and mechanisms of hypoxia.

I. OVERVIEW OF V/Q MATCHING

Ventilation/perfusion (V/Q) matching is essential for normal gas exchange in the lungs. For normal gas exchange, alveoli must be in close proximity to pulmonary capillaries -- ventilation must be close to blood flow. The V/Q ratio expresses the matching of ventilation (V in L/min) to perfusion or blood flow (Q in L/min). It is useless if ventilated alveoli are not near perfused capillaries, or if perfused capillaries are not near ventilated alveoli.

For the entire lung, the average normal value of V/Q is 0.8. This means for the whole lung, ventilation (L/min) is 80% of perfusion (L/min). However, V/Q is not uniformly 0.8 throughout the entire normal lung; some regions have higher V/Q and some regions have lower V/Q. An average V/Q of 0.8 results in an arterial $P_{O_2}$ of 100 mm Hg and arterial $P_{CO_2}$ of 40 mm Hg, the normal values.

II. REGIONAL VARIATIONS IN V/Q

In the upright lung, there are regional variations in both ventilation and blood flow. We have already discussed the gravitational effects that cause blood flow to be highest at the base and lowest at the apex. There are also regional variations in
ventilation that occur in the same direction as those for blood flow; thus, ventilation is highest at the base and lowest at the apex. However, and importantly, the variations in blood flow are greater than the variations for ventilation, such that the apex has a higher V/Q and base has a lower V/Q.

Zone 1 has the lowest blood flow, the lowest ventilation, and highest V/Q. Zone 3 has the highest blood flow, the highest ventilation, and the lowest V/Q. Zone 2 is in between.

Figure 5-8. Distribution of ventilation and blood flow down the upright lung (compare Figures 2-7 and 4-7). Note that the ventilation-perfusion ratio decreases down the lung.
These regional variations in V/Q ratio have implications for gas exchange that produce regional variations in $P_{O_2}$ and $P_{CO_2}$.

1. **The higher the V/Q**, the higher the ventilation relative to perfusion, the higher the $P_{A_{O_2}}$ and the lower the $P_{A_{CO_2}}$ (more gas exchange).
2. **The lower the V/Q**, the lower the ventilation relative to perfusion, the lower the $P_{A_{O_2}}$ and the higher the $P_{A_{CO_2}}$ (less gas exchange).

These differences in V/Q are superimposed on the $O_2 - C_{O_2}$ diagram below. Now, instead of a single value for alveolar (arterial) $P_{O_2}$ and $P_{CO_2}$, the range is shown for different regions of the lung. Zone 1, with the lowest blood flow, lowest ventilation, and highest V/Q has the highest $P_{O_2}$ and lowest $P_{CO_2}$. Zone 3, with the highest blood flow, highest ventilation, and lowest V/Q has the lowest $P_{O_2}$ and highest $P_{CO_2}$.
FIGURE 5-25. Effect of regional differences in ventilation/perfusion (V/Q) on Pco₂ and Po₂. Regional differences in Po₂ are much greater than the regional differences in Pco₂.

Figure 3.
III. V/Q DEFECTS

V/Q matching means that ventilation and perfusion are “matched up”, that ventilated alveoli are close to perfused capillaries, which provides for ideal gas exchange. A mismatch of ventilation and perfusion (called V/Q mismatch or V/Q defect) causes a defect in gas exchange. The defect can range from ventilated alveoli that are not perfused (called “dead space”) to perfused capillaries that are not ventilated (called “shunt”), and every possibility in between (high V/low Q = high V/Q; low V/high Q = low V/Q). Any V/Q mismatch implies that inadequate gas exchange will occur.

Figure 4.
**A. Dead Space**

Dead space is the volume of the airways and the lungs that does not participate in gas exchange. The **anatomic dead space** is the volume of the conducting airways; they cannot possibly participate in gas exchange because they have no alveoli. The **physiologic dead space**, includes the anatomic dead space plus functional dead space in alveoli (alveoli that are ventilated but not perfused). In normal persons, the physiologic dead space is nearly equal to the anatomic dead space. However, in lung diseases in which a V/Q defect develops, the physiologic dead space increases.

So...one extreme of V/Q mismatch is called dead space. It refers to alveoli that are ventilated, but not perfused. No O\(_2\) or CO\(_2\) can be exchanged with air entering these alveoli because there is no blood flow to pick up O\(_2\) or to release CO\(_2\). In regions of the lung where there is dead space, **alveolar P\(_{O_2}\) and P\(_{CO_2}\) approach their values in inspired air.**
Physiologic dead space is calculated by Bohr’s equation, which assumes that (1) all of the CO\(_2\) in expired air comes from functional alveoli (alveoli that are perfused); (2) that inspired air has no CO\(_2\), and (3) that alveolar and arterial P\(_{CO2}\) are equal.

\[
VD = VT \times \frac{Pa_{CO2}-PE_{CO2}}{Pa_{CO2}}
\]

VD is physiologic dead space (ml), VT is tidal volume, \(Pa_{CO2}\) is the P\(_{CO2}\) of arterial blood, and \(PE_{CO2}\) is the P\(_{CO2}\) of expired air.

1. If there is no dead space, then \(PE_{CO2}\) equals \(Pa_{CO2}\) (same as \(Pa_{CO2}\)), and VD comes out to be zero in the calculation (see that?).
2. If dead space is the whole tidal volume then \(PE_{CO2}\) is zero and VD equals VT in the calculation. (That would be really bad, the person would be dead.)

B. Shunts

Shunts occur when a portion of the pulmonary blood flow bypasses the alveoli; gas exchange cannot occur in shunted blood, i.e., the P\(_O2\) and P\(_{CO2}\) of shunted blood equals their values in mixed venous blood.

1. Physiologic shunt. Normally, a small portion (2%) of the pulmonary blood flow bypasses the alveoli (a portion of bronchial blood flow drains into the pulmonary veins and a portion of coronary blood flow drains directly into the left ventricle via the Thebesian veins). Thus, a small physiologic shunt is always present and causes Pa\(_O2\) to be slightly less than PA\(_O2\), a difference we usually ignore.
2. Right-to-left cardiac shunts. Defects in the intraventricular septum can result in as much as 50% of the cardiac output being routed from the right ventricle to the left ventricle without going to the lungs for gas exchange. In cardiac right-to-left shunts, there is always hypoxemia (decreased arterial P\(_O2\)) -- shunted blood is not oxygenated in the lungs and dilutes the non-shunted (normal) blood that is oxygenated.

More common are left-to-right cardiac shunts, which do not cause hypoxemia. When blood is shunted from the left heart to the right heart, there is a decrease in cardiac output of the left heart and an increase in cardiac output of the right heart, but no “problem” with oxygenation. A portion of the oxygenated blood from the left heart is recycled to the lungs, raising P\(_O2\) on the right side of the heart.
3. **Intrapulmonary shunts.** Blood can also be shunted within the lungs, such that a portion of the pulmonary blood flow perfuses lung regions that are not ventilated (regions where \( V/Q = 0 \)); there can be no gas exchange in that blood and there is **always hypoxemia.** For example, if a large bronchiole is occluded, all of the blood perfusing that region becomes a shunt. For another example, in adult respiratory distress syndrome (ARDS), certain cytokines released by the lung cause local vasoconstriction and re-route blood to regions that are not ventilated. Don’t forget — a shunt is an extreme of \( V/Q \) defect in which \( V \) is zero, \( Q \) is some value, and \( V/Q \) is zero.

![Diagram of intrapulmonary shunts](image)

**Figure 6.**

4. **“A - a gradient”**

The presence of a shunt can be detected by calculating the so-called A- a gradient. “A” stands for alveolar \( P_{O_2} \) \( (P_{A_{O_2}}) \) and “a” stands for arterial \( P_{O_2} \) \( (P_{a_{O_2}}) \). You must know this lingo!! *Alveolar \( P_{O_2} \), or “A”, is calculated with the alveolar gas equation. Arterial \( P_{O_2} \), or “a”, is measured in the arterial blood gases.*

\[
\text{A - a gradient} = P_{A_{O_2}} - P_{a_{O_2}}
\]

(Substituting \( P_{A_{O_2}} \) from the alveolar gas equation)

\[
\text{A - a gradient} = (P_{O_2} - P_{A_{CO_2}}) - P_{a_{O_2}}
\]

Normally, the A - a gradient is small (nearly zero). The small normal A -a gradient reflects the small physiologic shunt that bypasses the lungs and is not oxygenated.
The **A-a gradient is increased** when there is a shunt (either right-to-left cardiac shunt or intrapulmonary shunt). A larger-than-normal portion of the pulmonary blood flow is not oxygenated; the \( P_{O2} \) of this shunted blood remains at the value for mixed venous blood, i.e., 40 mm Hg, and dilutes the overall \( P_{O2} \) of the blood leaving the lungs.

**Treatment with 100% \( O_2 \) tests for a shunt.** When a person with a shunt (and therefore an increased A-a gradient) breathes 100% \( O_2 \), their A-a gradient will remain increased. Although the high \( O_2 \) treatment will raise the \( P_{O2} \) of the non-shunted blood, the \( P_{O2} \) of the shunted blood remains at the value for mixed venous blood; thus, overall \( P_{A02} \) remains lower than \( PA_{O2} \), i.e., increased A-a gradient. The “quick and dirty” wisdom you will hear is that a shunt is not “treatable” with 100% \( O_2 \). This wisdom is superficial. Correctly speaking, the A-a gradient and \( O_2 \) delivery are not correctable. The overall \( P_{O2} \) of arterial blood will be somewhat increased by giving 100% \( O_2 \), but the extent of increase arterial \( P_{O2} \) depends on the size of the shunt.

5. **The shunt equation**

The shunt equation calculates the fraction of total pulmonary blood flow (\( Q_T \)) that is shunted (\( Q_s \)). It is based upon the principle of conservation of mass for \( O_2 \). (Suggestion: use this equation in combination with the previous picture of a shunt.)

\[
\frac{Q_s}{Q_T} = \frac{O_2 \text{ content of non-shunted blood} - \text{arterial } O_2 \text{ content}}{O_2 \text{ content of non-shunted blood} - \text{venous } O_2 \text{ content}}
\]

- a. \( Q_s \) is blood flow through the shunt
- b. \( Q_T \) is total pulmonary blood flow, or cardiac output
- c. \( O_2 \) content of non-shunted blood is calculated based on equilibration of that blood with alveolar gas, i.e., \( P_{O2} = 100 \text{ mm Hg} \)
- d. Arterial \( O_2 \) content is calculated based on the measured arterial \( P_{O2} \)
- e. Venous \( O_2 \) content is calculated based on the measured venous \( P_{O2} \)
IV. HYPOXEMIA

Hypoxemia is a **decrease in arterial \( P_O2 \)**. As we have repeatedly emphasized, normally \( O_2 \) equilibrates across the alveolar-pulmonary capillary barrier and arterial \( P_O2 \) equals alveolar \( P_O2 \), which is 100 mm Hg at sea level. Logically, then, a decrease in arterial \( P_O2 \) is seen if (1) there is a defect in \( O_2 \) exchange in the lungs or (2) the alveolar \( P_O2 \) is decreased (e.g., decreased barometric pressure). Each of the following scenarios causes a decrease in arterial \( P_O2 \).

<table>
<thead>
<tr>
<th>Causes of Hypoxemia</th>
<th>( Pa_O2 )</th>
<th>A - a gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Altitude</td>
<td>Decreased</td>
<td>Normal</td>
</tr>
<tr>
<td>Hypoventilation</td>
<td>Decreased</td>
<td>Normal</td>
</tr>
<tr>
<td>Diffusion Defect (e.g., fibrosis, pulmonary edema)</td>
<td>Decreased</td>
<td>Increased</td>
</tr>
<tr>
<td>V/Q Defect</td>
<td>Decreased</td>
<td>Increased</td>
</tr>
<tr>
<td>Shunt (V/Q = 0)</td>
<td>Decreased</td>
<td>Increased</td>
</tr>
</tbody>
</table>

**High altitude** causes hypoxemia because barometric pressure and \( Pa_O2 \) are decreased; assuming perfect \( O_2 \) equilibration, \( Pa_O2 \) will have the same (lower) value as \( Pa_O2 \). A - a gradient is normal (near zero) because \( Pa_O2 \) is equal to \( PaO2 \), both are lower than normal.

**V/Q defect always causes hypoxemia.** You might wonder why this is “always” true. Why can’t regions of high V/Q compensate for the regions of low V/Q so that the final \( P_O2 \) of blood leaving the lungs is relatively normal. Good idea ☹️, but things don’t work that way. Although high V/Q regions will raise their blood to a super high value of \( P_O2 \), the blood flow to those regions is relatively small. Thus, that blood has a small quantitative effect on the \( P_O2 \) of the total blood leaving the lungs. (The low V/Q regions where \( P_O2 \) is low will have the greatest effect because they have highest blood flow.)

V. HYPOXIA

\( O_2 \) delivery to the tissues is determined by **blood flow** and the **\( O_2 \) content** of that blood. In terms of the whole organism, blood flow can be considered to be cardiac output. \( O_2 \) content of the blood is the sum of dissolved \( O_2 \) and \( O_2 \)-hemoglobin.

\[
O_2 \text{ delivery} = \text{Cardiac output} \times \frac{O_2 \text{ content of blood}}{\text{(blood flow)}}
\]

\[
= \text{Cardiac output} \times (\text{Dissolved } O_2 + O_2 \text{-hemoglobin})
\]
Dissolved O₂ is the PaO₂ times the solubility of O₂. O₂-hemoglobin is determined by the concentration of hemoglobin, the O₂-binding capacity of that hemoglobin, and % saturation (which is determined by PaO₂).

Hypoxia is **decreased O₂ delivery to the tissues**, which can be caused by decreased cardiac output (blood flow) and/or decreased O₂ content of blood.

A. **Causes of hypoxia**

1. Anemia (decreased hemoglobin concentration)
2. Decreased cardiac output
3. Hypoxemia (decreased PaO₂, decreased % saturation of Hb)...any of the causes of hypoxemia produces hypoxia
4. CO poisoning (decreased O₂-binding capacity of hemoglobin)
5. CN poisoning (uncoupler of oxidative phosphorylation)

VI. **PRACTICE QUESTIONS**

1. Use the following information to answer the questions.

<table>
<thead>
<tr>
<th>Breath frequency</th>
<th>12/minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume</td>
<td>500 ml</td>
</tr>
<tr>
<td>PaCO₂</td>
<td>40 mmHg</td>
</tr>
<tr>
<td>PaO₂</td>
<td>100 mmHg</td>
</tr>
<tr>
<td>PeCO₂</td>
<td>30 mmHg</td>
</tr>
<tr>
<td>P1O₂</td>
<td>150 mmHg</td>
</tr>
<tr>
<td>P1CO₂</td>
<td>0</td>
</tr>
<tr>
<td>VCO₂</td>
<td>200 ml/minute</td>
</tr>
<tr>
<td>VO₂</td>
<td>250 ml/minute</td>
</tr>
</tbody>
</table>

What is the volume of the physiologic dead space?
What is the value for minute ventilation?

What is the value for alveolar ventilation?

What is alveolar $P_{CO2}$ ($PA_{CO2}$)?

What is the value for alveolar $P_{O2}$ ($PA_{O2}$)?

2. Ventilation to the apex of the lung is 0.8 L/minute and ventilation to the base of the lung is 2.2 L/minute. Blood flow to the apex is 0.4 L/minute and blood flow to the base is 3.2 L/minute. What is the V/Q ratio at the apex and the base of the lung, and what effect would you expect any differences to have on $P_{O2}$ and $P_{CO2}$ in those regions?

3. A person with asthma has the following arterial blood gases while breathing room air. What is his $A-a$ gradient, and what does the value represent? Why is the $Pa_{CO2}$ decreased from normal?

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>7.48 (Normal, 7.4)</td>
</tr>
<tr>
<td>$Pa_{O2}$</td>
<td>55 mm Hg (Normal, 100 mm Hg)</td>
</tr>
<tr>
<td>$Pa_{CO2}$</td>
<td>32 mm Hg (Normal, 40 mm Hg)</td>
</tr>
<tr>
<td>R</td>
<td>0.8</td>
</tr>
</tbody>
</table>

4. The following information was obtained in a person with a pulmonary disease.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$PA_{O2}$</td>
<td>100 mm Hg</td>
</tr>
<tr>
<td>$Pa_{O2}$</td>
<td>70 mm Hg</td>
</tr>
<tr>
<td>$PV_{O2}$</td>
<td>30 mm Hg</td>
</tr>
<tr>
<td>Cardiac output</td>
<td>5.2 L/min</td>
</tr>
<tr>
<td>Hemoglobin</td>
<td>15 g/100 ml</td>
</tr>
<tr>
<td>$O_2$-binding capacity</td>
<td>1.34 ml O$_2$/g hemoglobin</td>
</tr>
</tbody>
</table>

What is the magnitude of the intrapulmonary shunt in L/min?
5. If the V/Q ratio of a lung region decreases, the alveoli in that region will have a:

A. Higher $P_{O2}$ and higher $P_{CO2}$.
B. Lower $P_{O2}$ and lower $P_{CO2}$.
C. Higher $P_{O2}$ and lower $P_{CO2}$.
D. Lower $P_{O2}$ and higher $P_{CO2}$.
E. Lower $P_{O2}$ and unchanged $P_{CO2}$.

The following information applies to Questions 6 and 7:

- $F_{I_{O2}}$: 0.5
- $P_{B}$: 760 mm Hg
- $P_{A_{O2}}$: 50 mm Hg
- $P_{A_{CO2}}$: 30 mm Hg
- Respiratory exchange quotient: 0.8
- Solubility of $O_2$ in blood: 0.003 ml $O_2/100$ ml blood/mm Hg
- Solubility of $CO_2$ in blood: 0.07 ml $CO_2/100$ ml blood/mm Hg

6. The patient’s A - a gradient is closest to:

A. Zero
B. 20 mm Hg
C. 60 mm Hg
D. 270 mm Hg
E. 280 mm Hg

7. If all values remain identical except that $F_{I_{O2}}$ is lowered to 0.21, the A - a gradient will be:

A. Increased
B. Decreased
C. Unchanged

8. Pulmonary capillary blood from which lung unit has the lowest $P_{O2}$?

A. $V = 2$ L/min; $Q = 0.2$ L/min
B. $V = 2$ L/min; $Q = 2$ L/min
C. $V = 0.2$ L/min; $Q = 2$ L/min
D. $V = 0$; $Q = 2$ L/min
9. A patient with a right-to-left cardiac shunt who is breathing room air at sea level has the following values:

- $P_{A\text{O}_2}$: 100 mm Hg
- $P_{a\text{O}_2}$: 50 mm Hg
- $P_{v\text{O}_2}$: 30 mm Hg
- Cardiac output: 5 L/min
- O$_2$-binding capacity of blood: 20.1 ml O$_2$/100 ml blood
- Solubility of O$_2$ in blood: 0.003 ml O$_2$/100 ml blood

What percentage of the cardiac output is the shunt?

A. Zero  
B. 38%  
C. 50%  
D. 62%  
E. 100%

10. Which person is expected to have an increased A-a gradient?

A. Left-to-right cardiac shunt  
B. Hypoventilation  
C. High altitude  
D. Pulmonary fibrosis

11. Which cause of hypoxia is corrected best with supplemental O$_2$?

A. High altitude  
B. Right-to-left intrapulmonary shunt  
C. Right-to-left cardiac shunt  
D. Anemia  
E. Decreased cardiac output

12. Compared to the apex of the lung, at the base of the lung:

A. Blood flow is lowest  
B. Ventilation is lowest  
C. V/Q is highest  
D. Alveolar $P_{\text{CO}_2}$ is highest  
E. Alveolar $P_{\text{O}_2}$ is highest
13. Given the following values, calculate alveolar ventilation:

\[
\begin{align*}
\text{Tidal volume} & = 450 \text{ ml} \\
\text{Breaths/minute} & = 14/\text{minute} \\
\text{Arterial} P_{CO_2} & = 45 \text{ mm Hg} \\
\text{Arterial} P_{O_2} & = 55 \text{ mm Hg} \\
\text{Alveolar} P_{CO_2} & = 100 \text{ mm Hg} \\
\text{Expired} P_{CO_2} & = 25 \text{ mm Hg} \\
\text{Cardiac output} & = 5.0 \text{ L/minute}
\end{align*}
\]

A. 6.3 L/min \\
B. 4.8 L/min \\
C. 3.5 L/min \\
D. 2.5 L/min \\
E. 2.0 L/min

14. Using the values given for Question 13, what fraction of each tidal volume is physiologic dead space, and how does this value compare to normal?

A. 0.06; decreased \\
B. 0.3; decreased \\
C. 0.3; normal \\
D. 0.44; decreased \\
E. 0.44; increased

15. Using the information given for Question 13, what is the average value for V/Q in this person?

A. 1.3 \\
B. 1.3 L \\
C. 0.7 \\
D. 0.7 L \\
E. 0.8 L
EXPLANATIONS

1. What is the volume of the physiologic dead space?

\[
VD = VT \times \frac{PaCO_2 - PeCO_2}{PaCO_2}
\]

\[
= 500 \text{ ml} \times \frac{40 \text{ mm Hg} - 30 \text{ mm Hg}}{40 \text{ mm Hg}}
\]

\[
= 500 \text{ ml} \times 0.25
\]

\[
= 125 \text{ ml}
\]

What is the value for minute ventilation?

\[
\text{Minute ventilation} = VT \times \text{breaths/minute}
\]

\[
= 500 \text{ ml} \times 12/\text{minute}
\]

\[
= 6000 \text{ ml/minute}
\]

What is the value for alveolar ventilation?

\[
VA = (500 \text{ ml} - 125 \text{ ml}) \times 12 \text{ breaths/minute}
\]

\[
= 375 \text{ ml} \times 12 \text{ breaths/minute}
\]

\[
= 4500 \text{ ml/minute}
\]

What is alveolar \( P_{CO_2} \) (\( PaCO_2 \))?  

\[
PaCO_2 = \frac{VCO_2 \times K}{VA}
\]

\[
K = \text{constant (863 mm Hg)}
\]

\[
PaCO_2 = \frac{200 \text{ ml/min} \times 863 \text{ mm Hg}}{4500 \text{ ml/min}}
\]

\[
= 38.4 \text{ mm Hg}
\]
What is the value for alveolar \( P_{O_2} \) (\( P_{A_O2} \))?

\[
P_{A_O2} = P_{I_O2} - \frac{P_{A_CO2}}{R}
\]

\[
P_{A_O2} = 150 \text{ mm Hg} - 38.4 \text{ mm Hg} \\
= 150 \text{ mm Hg} - 48 \text{ mm Hg} \\
= 102 \text{ mm Hg}
\]

2. 

<table>
<thead>
<tr>
<th>( V )</th>
<th>( Q )</th>
<th>( V/Q )</th>
<th>Expected ( P_{O_2} )</th>
<th>Expected ( P_{CO_2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apex</td>
<td>0.8</td>
<td>0.4</td>
<td>2.0</td>
<td>Higher</td>
</tr>
<tr>
<td>Base</td>
<td>2.2</td>
<td>3.2</td>
<td>0.7</td>
<td>Lower</td>
</tr>
</tbody>
</table>

3. The **A-a gradient** represents the difference between alveolar \( P_{O_2} \) (\( P_{A_O2} \) or “\( A \)”) and arterial \( P_{O_2} \) (\( P_{a_O2} \) or “\( a \)”). The A-a gradient tells us whether \( O_2 \) is equilibrating normally between alveolar gas and pulmonary capillary blood. For example, the normal A-a gradient is close to zero because \( O_2 \) equilibrates almost perfectly — \( P_{A_O2} \) and \( P_{a_O2} \) are equal, or nearly equal. However, if there is a mismatch of ventilation and perfusion (i.e., a V/Q defect), then \( P_{a_O2} \) will be less than \( P_{A_O2} \), and A-a will be greater than zero. The greater the disturbance in \( O_2 \) exchange, the larger the A-a gradient.

*The A-a gradient is determined by measuring “\( a \)” (the \( P_{O_2} \) of arterial blood, \( P_{a_O2} \)) and calculating “\( A \)” (the \( P_{O_2} \) of alveolar gas, \( P_{A_O2} \)) with the alveolar gas equation.* Therefore, at 4 P.M.,
Compared to a normal person, the A-a gradient is greatly increased; O₂ could not fully equilibrate between alveolar gas and pulmonary capillary blood because of a V/Q defect (specifically, a decreased V/Q ratio).

The PaCO₂ is decreased below normal because the person is hyperventilating secondary to hypoxemia. (PaO₂ < 60 mm Hg stimulates the peripheral chemoreceptors.) Hyperventilation drives off “extra” CO₂ and decreases the PaCO₂.

4. Steps:

\[
O₂-binding \ capacity \ of \ blood = \text{hemoglobin concentration} \times O₂-binding \ capacity \\
= 15 \text{ g/100 ml blood} \times 1.34 \text{ ml O₂/g hemoglobin} \\
= 20.1 \text{ ml O₂/100 ml blood}
\]

Determine % saturation that corresponds to the various values of P_O₂

100 mm Hg corresponds to 100% saturation
70 mm Hg corresponds to 90% saturation
30 mm Hg corresponds to 60% saturation

Calculate the O₂ content of arterial blood, venous blood, and non-shunted blood. (Remember, non-shunted blood should have the same P_O₂ as alveolar gas.)

O₂ content of arterial blood
Dissolved \( O_2 \) + \( O_2 \) hemoglobin

\[ = 70 \text{ mm Hg} \times 0.003 \text{ ml} \frac{O_2}{100 \text{ ml/mm Hg}} + 20.1 \text{ ml} \frac{O_2}{100 \text{ ml}} \times 0.9 \]

\[ = 0.21 \text{ vol} \% + 18.1 \text{ vol} \% \]

\[ = 18.3 \text{ vol} \% \]

**O₂ content of venous blood**

\[ = \text{Dissolved } O_2 + O_2\text{-hemoglobin} \]

\[ = 30 \text{ mm Hg} \times 0.003 \text{ ml} \frac{O_2}{100 \text{ ml/mm Hg}} + 20.1 \text{ ml} \frac{O_2}{100 \text{ ml}} \times 0.6 \]

\[ = 0.09 \text{ vol} \% + 12.1 \text{ vol} \% \]

\[ = 12.2 \text{ vol} \% \]

**O₂ content of non-shunted blood**

\[ = \text{Dissolved } O_2 + O_2\text{-hemoglobin} \]

\[ = 100 \text{ mm Hg} \times 0.003 \text{ ml} \frac{O_2}{100 \text{ ml/mm Hg}} + 20.1 \text{ ml} \frac{O_2}{100 \text{ ml}} \times 1.0 \]

\[ = 0.3 \text{ vol} \% + 20.1 \text{ vol} \% \]

\[ = 20.4 \text{ vol} \% \]

**Next step: calculate the shunt fraction as:**

\[ Q_S = \frac{O_2 \text{ content of non-shunted blood - arterial } O_2 \text{ content}}{O_2 \text{ content of non-shunted blood - venous } O_2 \text{ content}} \]

\[ = \frac{20.4 \text{ vol} \% - 18.3 \text{ vol} \%}{20.4 \text{ vol} \% - 12.2 \text{ vol} \%} \]

\[ = \frac{2.1 \text{ vol} \%}{8.2 \text{ vol} \%} \]

\[ = 0.26, \text{ or } 26\% \]

**Last step! Calculate the volume, in L/min, of the shunt (Qₜ)**

\[ Q_S = 0.26 \times \text{cardiac output} \]

\[ = 0.26 \times 5.2 \text{ L/min} \]

\[ = 1.35 \text{ L/min} \]
5. **Answer = D.** Begin by drawing a lung and labeling the apex and base with respect to blood flow, ventilation, \( P_{O_2} \), and \( P_{CO_2} \). You can probably use it for other questions, so do it right the first time. Base has highest blood flow and highest ventilation. Blood flow is relatively higher than ventilation at the base, so \( V/Q \) is lowest at the base and highest at the apex. \( V/Q \) determines \( P_{O_2} \) and \( P_{CO_2} \). The higher the ventilation relative to perfusion, the higher the \( P_{O_2} \) and the lower the \( P_{CO_2} \) (that's what ventilation does...it adds \( O_2 \) and takes away \( CO_2 \), right?) If \( V/Q \) is decreased, less \( O_2 \) is brought in, less \( CO_2 \) is taken away. Ok, so you didn’t really need to draw the lung for this question.

6. **Answer = D, 270 mm Hg.** This question requires that you first calculate \( PA_{O_2} \) with the alveolar gas equation. Then, the \( A - a \) gradient is calculated as the difference between this calculated “\( A \)” and the measured “\( a \)” You’ll need to know the alveolar gas equation for the exam. “\( A = PA_{O_2} = PI_{O_2} - PA_{CO_2}/R \). \( PI_{O_2} \) is calculated from barometric pressure corrected for water vapor times the \( F_{I_{O_2}} \). \( PA_{CO_2} \) is assumed to be the same as \( PA_{CO_2} \) (given). \( R \) is respiratory exchange ratio or respiratory quotient, which is 0.8. “\( A = PA_{O_2} = (760 - 47) x 0.5 - 30/0.8 = 319 \) mm Hg. Finally, \( A - a = 319 \) mm Hg - 50 mm Hg = 269 mm Hg. The solubilities are extraneous information.

7. **Answer = B.** You can calculate a new value of “\( A \)” at an \( F_{I_{O_2}} \) of 0.21. However, you needn’t go to all that trouble. If everything else is the same, \( PI_{O_2} \) at an \( F_{I_{O_2}} \) of 0.21 is lower than it is at an \( F_{I_{O_2}} \) of 0.5. Thus, the calculated value of “\( A \)” will also be lower. Thus, the \( A - a \) gradient will be decreased.

8. **Answer = D.** \( P_{O_2} \) of pulmonary capillary blood is lowest in the region where ventilation is lowest relative to perfusion. Among the choices, where \( V = 0 \), which is called a shunt.

9. **Answer = B.** This is a straight shunt calculation. On the exam, you will be given the equation, but you must understand how to apply it ♦. Non-shunted blood is assumed to equilibrate normally with alveolar gas; thus, non-shunted (normal) blood has the same \( P_{O_2} \) as alveolar gas, 100 mm Hg. Shunted blood has the same \( P_{O_2} \) as mixed venous blood, 30 mm Hg. Arterial blood has a measured \( P_{O_2} \) of 50 mm Hg. First calculate the \( O_2 \) content of each kind of blood: non-shunted (normal), mixed venous, and systemic arterial. On the exam, you will be given the % saturation that corresponds to each \( P_{O_2} \). You are given the \( O_2 \) binding capacity of blood (always measured at 100% saturation!!) as 20.1 ml \( O_2 /100 \) ml blood. Set up a table with all the calculated values, thus:

<table>
<thead>
<tr>
<th></th>
<th>( P_{O_2} )</th>
<th>% sat</th>
<th>Dissolved ( O_2 )</th>
<th>Bound ( O_2 )</th>
<th>Total ( O_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-shunted (normal) blood</td>
<td>100</td>
<td>100</td>
<td>0.3</td>
<td>20.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Arterial blood</td>
<td>50</td>
<td>85</td>
<td>0.15</td>
<td>17.1</td>
<td>17.3</td>
</tr>
<tr>
<td>Mixed venous blood</td>
<td>30</td>
<td>60</td>
<td>0.09</td>
<td>12.1</td>
<td>12.2</td>
</tr>
</tbody>
</table>
** Units for $P_{O2}$ are mm Hg, for % saturation are %, and for $O_2$ content are vol %.

\[ Q_8 = \frac{20.4 - 17.3}{20.4 - 12.2} = \frac{3.1}{8.2} = 0.38, \text{ or } 38\% \]

Final comment, if the shunt was zero percent of the cardiac output, the arterial $P_{O2}$ would have been equal to alveolar $P_{O2}$. If the shunt was 100% of the cardiac output, arterial $P_{O2}$ would have been equal to mixed venous $P_{O2}$. Final, final comment. The way the question was asked, you didn’t need the value for cardiac output.

10. Answer = D. An $A-a$ gradient is present when systemic arterial blood is not equilibrated with alveolar gas (with respect to $P_{O2}$). The more impaired the $O_2$ equilibration, the larger the $A-a$ gradient. Left-to-right cardiac shunts involve routing already-oxygenated, equilibrated (arterialized) blood from the left heart back to the right heart and the lungs. Persons with hypoventilation have decreased alveolar $P_{O2}$; arterial blood equilibrates with that lower alveolar $P_{O2}$ and $A-a$ gradient is small or zero. Persons at high altitude have decreased alveolar $P_{O2}$ because inspired air has a lower $P_{O2}$ at lower barometric pressure; arterial blood equilibrates and $A-a$ gradient is small or zero. In fibrosis, the diffusion process for $O_2$ is impaired; arterial blood cannot equilibrate with alveolar gas and $A-a$ is increased.

11. Answer = A. Hypoxia at high altitude is correctable by breathing supplemental $O_2$; the whole, entire cause of high altitude hypoxia is breathing air with a low $P_{O2}$. The hypoxia in right-to-left intrapulmonary or cardiac shunt is not correctable b/c shunted blood always has the same $P_{O2}$ and $O_2$ content as mixed venous blood. The non-shunted (normal) blood can have its $P_{O2}$ raised by supplemental $O_2$, but once that blood’s hemoglobin is 100% saturated, the additional $O_2$ only adds to the dissolved $O_2$, which does little to raise $O_2$ content of the blood. Hypoxia persists. Hypoxia due to anemia is due to decreased hemoglobin concentration; once that hemoglobin is fully saturated, giving supplemental $O_2$ only increases the dissolved $O_2$, which helps very little. Hypoxia due to decreased cardiac output is a blood flow delivery problem; supplemental $O_2$ only increases the dissolved $O_2$.

12. Answer = D. Find that lung picture you drew for Question 5. Base has highest blood flow, highest ventilation, lowest $V/Q$, thus highest $P_{CO2}$ (expires less $CO_2$).
13. Answer = C. First calculate dead space, then calculate alveolar ventilation. Several values were listed that you don’t need for the calculations, so be careful!

\[ V_D = VT \times \frac{P_{aCO_2} - P_{E_{CO_2}}}{P_{aCO_2}} \]

\[ = 450 \text{ ml} \times \frac{45 \text{ mm Hg} - 25 \text{ mm Hg}}{45 \text{ mm Hg}} \]

\[ = 200 \text{ ml} \]

Alveolar ventilation \[= (VT - VD) \times \text{breaths/minute} \]

\[= (450 \text{ ml} - 200 \text{ ml}) \times 14/\text{minute} \]

\[= 3500 \text{ ml/minute, or 3.5 L/minute} \]

14. Answer = E

15. Answer = A. The V in V/Q is total ventilation. V/Q has no units..