Ventilation/Perfusion (V/Q) 1 and 2

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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_{O2} and P_{CO2}.
3. The patterns of ventilation/perfusion defects, including dead space and shunt, and the effects on alveolar and arterial P_{O2} and P_{CO2}.
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_{O2} of 100 mm Hg and arterial P_{CO2} 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.

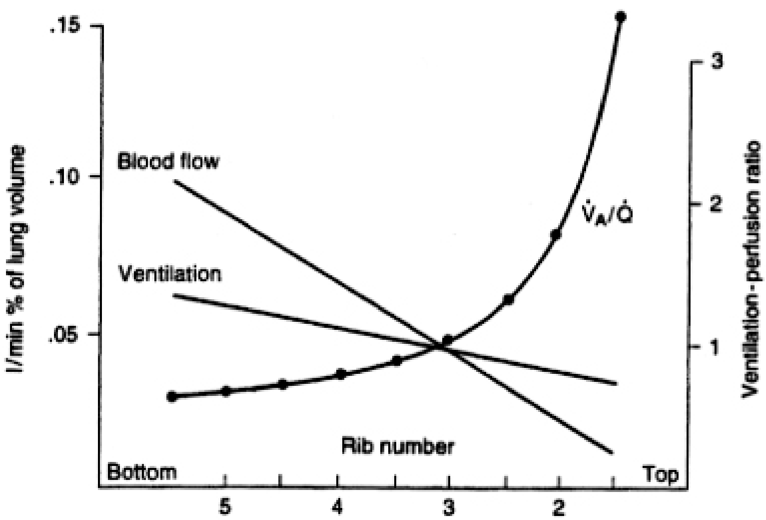
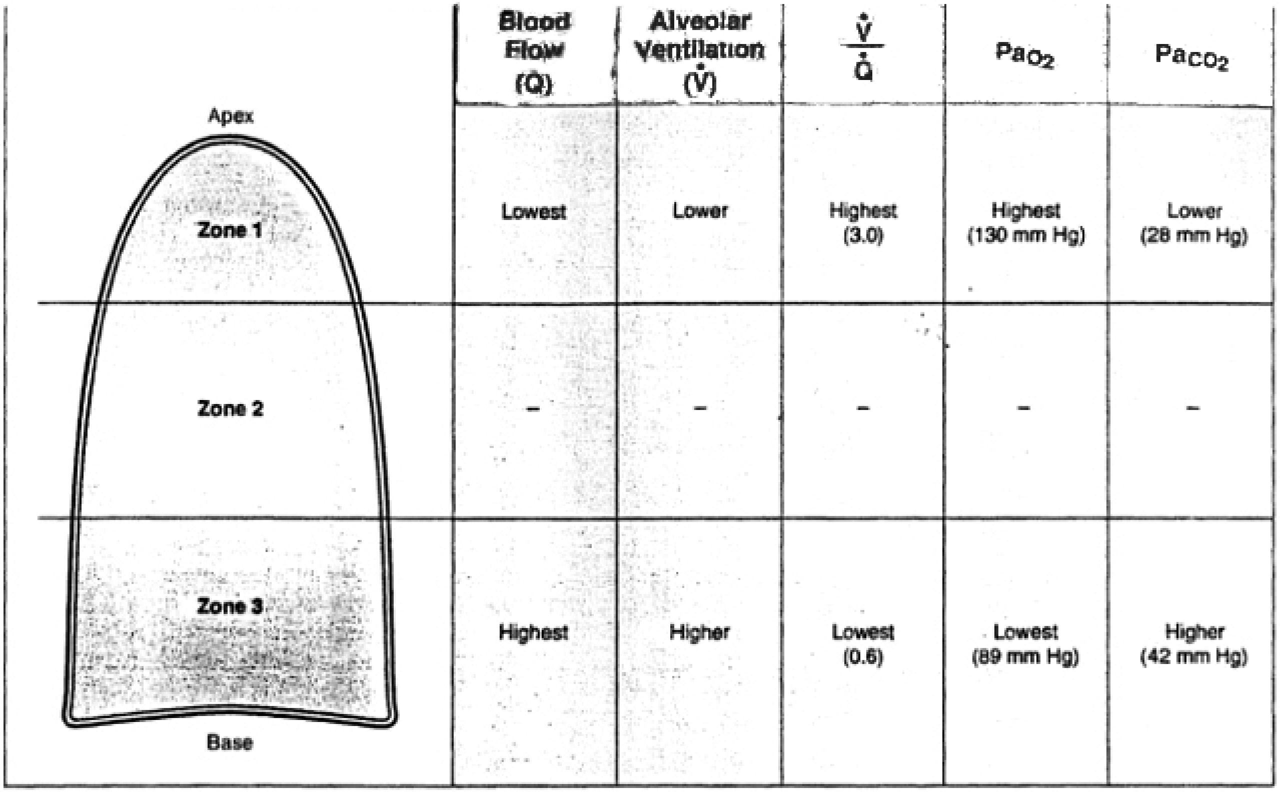


Figure 5-8. Distribution of ventilation and blood flow down the upright lung (compare Figures 2-7 and 4-7). Note that the ventilation-perfusion ratio decreases down the lung.

Figure 1.



	Blood Flow ($\dot{Q}$)	Alveolar Ventilation ($\dot{V}$)	$\frac{\dot{V}}{\dot{Q}}$	Pa_{O_2}	Pa_{CO_2}
Apex Zone 1	Lowest	Lower	Highest (3.0)	Highest (130 mm Hg)	Lower (28 mm Hg)
Zone 2	–	–	–	–	–
Zone 3 Base	Highest	Higher	Lowest (0.6)	Lowest (89 mm Hg)	Higher (42 mm Hg)

FIGURE 5–24. Variation in ventilation/perfusion ($\dot{V}/\dot{Q}$) in the three zones of the lung. The effects of regional differences in $\dot{V}/\dot{Q}$ on Pa_{O_2} and Pa_{CO_2} also are shown.

Figure 2.

These regional variations in V/Q ratio have implications for gas exchange that produce regional variations in P_{O2} and P_{CO2}.

1. **The higher the V/Q**, the higher the ventilation relative to perfusion, the higher the Pa_{O2} and the lower the Pa_{CO2} (more gas exchange).
2. **The lower the V/Q**, the lower the ventilation relative to perfusion, the lower the Pa_{O2} and the higher the Pa_{CO2} (less gas exchange).

These differences in V/Q are superimposed on the O_2 - C_{O2} diagram below. Now, instead of a single value for alveolar (arterial) P_{O2} and P_{CO2}, 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_{O2} and lowest P_{CO2}. Zone 3, with the highest blood flow, highest ventilation, and lowest V/Q has the lowest P_{O2} and highest P_{CO2}.

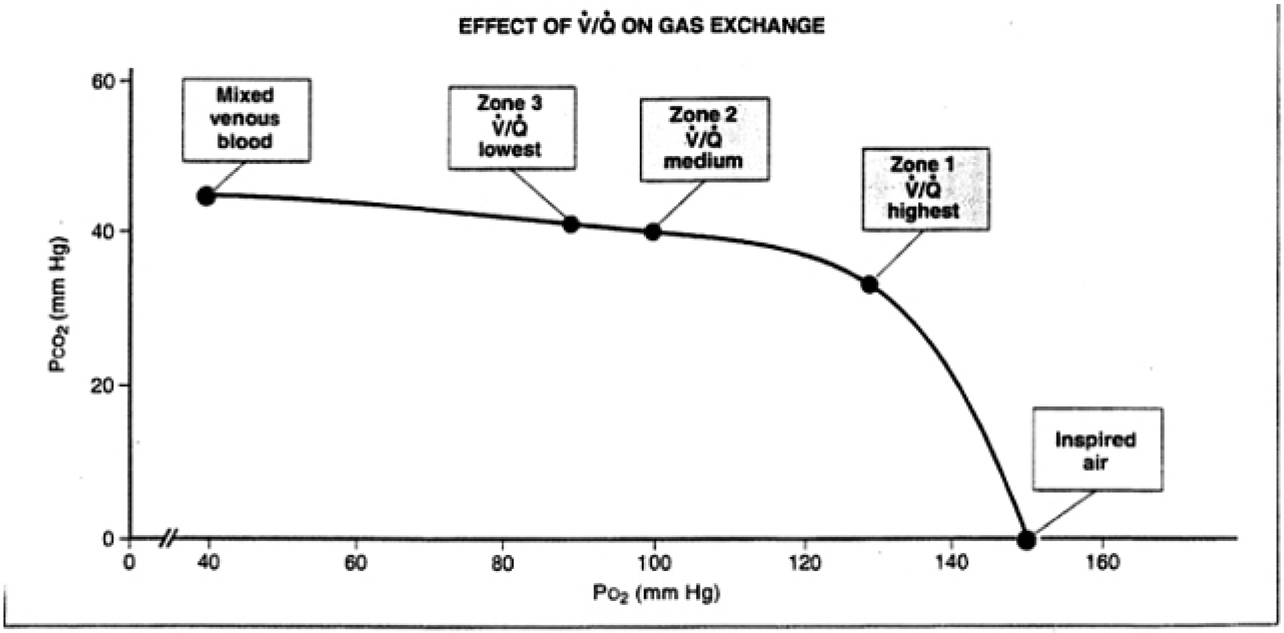


FIGURE 5–25. Effect of regional differences in ventilation/perfusion ($\dot{V}/\dot{Q}$) on P_{CO_2} and P_{O_2}. Regional differences in P_{O_2} are much greater than the regional differences in P_{CO_2}.

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.

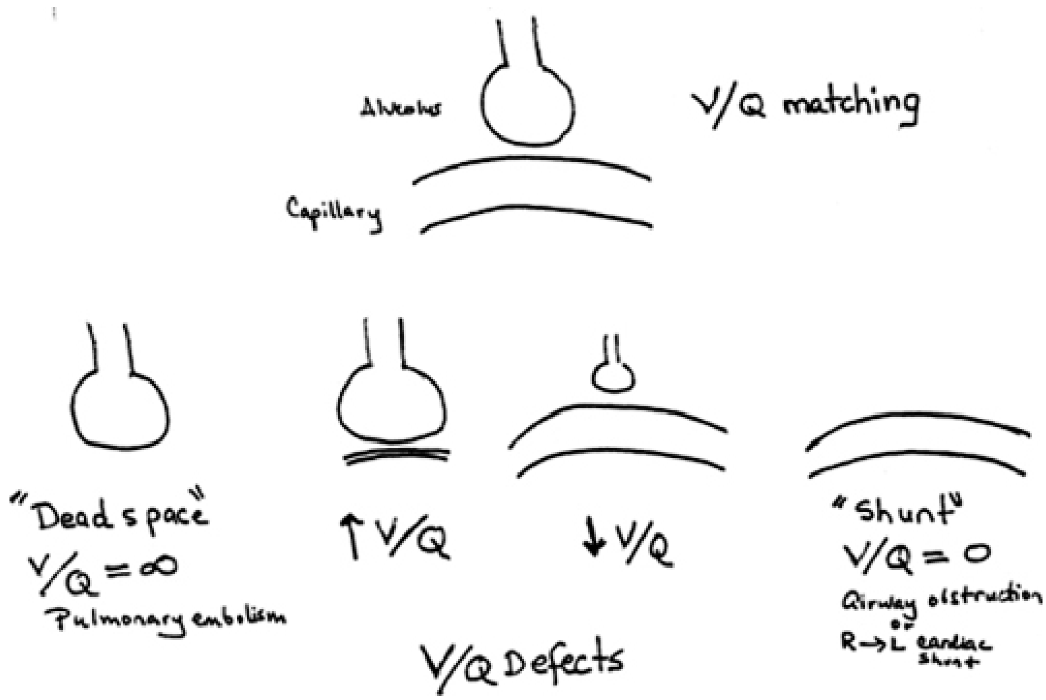
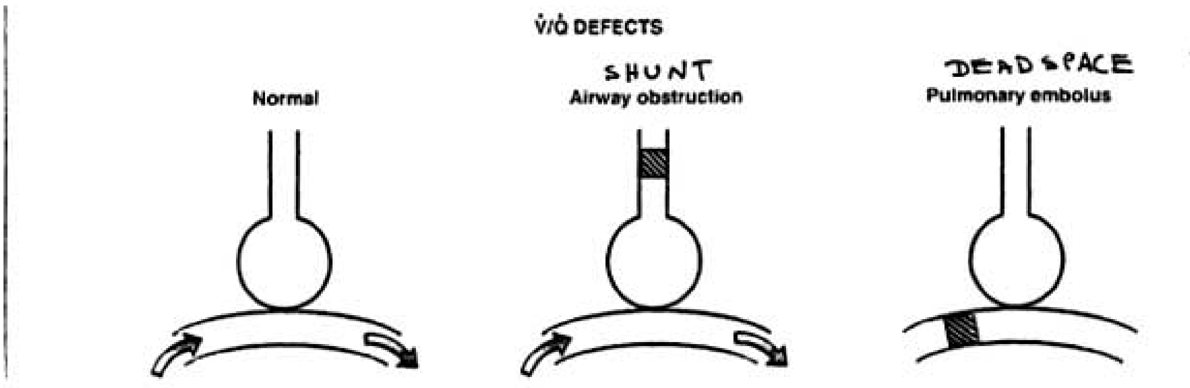


Figure 4.



	Normal	Airway obstruction	Pulmonary embolus
$\dot{V}/\dot{Q}$	0.8	0	∞
P_{AO_2}	100	—	150
P_{ACO_2}	40	—	0
P_{aO_2}	100	40	-
P_{aCO_2}	40	46	-

FIGURE 5-26. Effect of ventilation/perfusion ($\dot{V}/\dot{Q}$) defects on gas exchange in the lungs. With airway obstruction, the composition of systemic arterial blood approaches that of mixed venous blood. With pulmonary embolus, the composition of alveolar air approaches that of inspired air.

Figure 5.

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_{O2} and P_{CO2} 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.

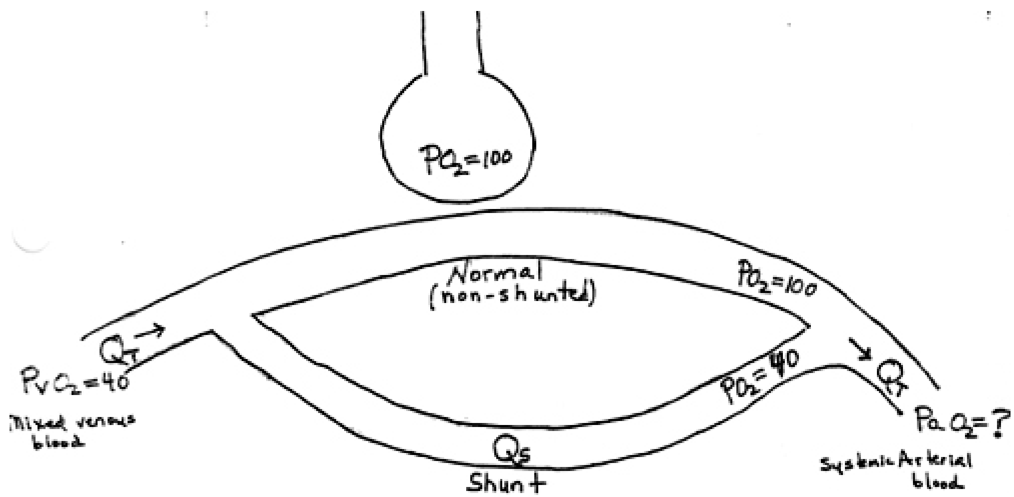


Figure 6.

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_{O2} (P_{AO2}) and "a" stands for arterial P_{O2} (P_{aO2}). You must know this lingo!! *Alveolar P_{O2}, or "A", is calculated with the alveolar gas equation. Arterial P_{O2}, or "a", is measured in the arterial blood gases.*

$$\text{A - a gradient} = P_{AO2} - P_{aO2}$$

(Substituting P_{AO2} from the alveolar gas equation)

$$\text{A - a gradient} = \left(P_{IO2} - \frac{P_{ACO2}}{R}\right) - P_{aO2}$$

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 Pa_{O2} 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. Qs 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., $P_{O2} = 100$ 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}.

Causes of Hypoxemia	**Pa_{O2}**	**A - a gradient**
High Altitude	Decreased	Normal
Hypoventilation	Decreased	Normal
Diffusion Defect (e.g., fibrosis, pulmonary edema)	Decreased	Increased
V/Q Defect	Decreased	Increased
Shunt (V/Q = 0)	Decreased	Increased

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 PA_{O2}, 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.

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

$$= \text{Cardiac output} \times (\text{Dissolved } O_2 + O_2 \text{ hemoglobin})$$

Dissolved O_2 is the Pa_{O2} times the solubility of O_2. O_2-hemoglobin is determined by the concentration of hemoglobin, the O_2-binding capacity of that hemoglobin, and % saturation (which is determined by Pa_{O2}).

Hypoxia is **decreased O_2 delivery to the tissues**, which can be caused by decreased cardiac output (blood flow) and/or decreased O_2 content of blood.

A. **Causes of hypoxia**

1. Anemia (decreased hemoglobin concentration)
2. Decreased cardiac output
3. Hypoxemia (decreased Pa_{O2}, decreased % saturation of Hb)...any of the causes of hypoxemia produces hypoxia
4. CO poisoning (decreased O_2-binding capacity of hemoglobin)
5. CN poisoning (uncoupler of oxidative phosphorylation)

VI. PRACTICE QUESTIONS

1. Use the following information to answer the questions.

Breathing frequency	12/minute
Tidal volume	500 ml
Pa_{CO2}	40 mm Hg
Pa_{O2}	100 mm Hg
PE_{CO2}	30 mm Hg
PI_{O2}	150 mm Hg
PI_{CO2}	0
V_{CO2}	200 ml/minute
V_{O2}	250 ml/minute

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?

pH	7.48 (Nomal, 7.4)
Pa_{O2}	55 mm Hg (Nomal, 100 mm Hg)
Pa_{CO2}	32 mm Hg (Nomal, 40 mm Hg)
R	0.8

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

PA_{O2}	100 mm Hg
Pa_{O2}	70 mm Hg
Pv_{O2}	30 mm Hg
Cardiac output	5.2 L/min
Hemoglobin	15 g/100 ml
O_2-binding capacity	1.34 ml O_2/g hemoglobin

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_{IO_2}	0.5
P_B	760 mm Hg
Pa_{O_2}	50 mm Hg
Pa_{CO_2}	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_{IO2} 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_{AO_2}	100 mm Hg
Pa_{O_2}	50 mm Hg
$P\bar{v}_{O_2}$	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_{CO2} is highest
E. Alveolar P_{O2} is highest

13. Given the following values, calculate alveolar ventilation:

Tidal volume	=	450 ml
Breaths/minute	=	14/minute
Arterial P_{CO2}	=	45 mm Hg
Arterial P_{O2}	=	55 mm Hg
Alveolar P_{O2}	=	100 mm Hg
Expired P_{CO2}	=	25 mm Hg
Cardiac output	=	5.0 L/minute

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?

$$V_D = V_T \times \frac{Pa_{CO_2} - P_{E_{CO_2}}}{Pa_{CO_2}}$$

$$= 500\ ml \times \frac{40\ mm\ Hg - 30\ mm\ Hg}{40\ mm\ Hg}$$

$$= 500\ ml \times 0.25$$

$$= 125\ ml$$

What is the value for minute ventilation?

$$\text{Minute ventilation} = V_T \times \text{breaths/minute}$$
$$= 500\ ml \times 12/\text{minute}$$
$$= 6000\ ml/\text{minute}$$

What is the value for alveolar ventilation?

$$V_A = (500\ ml - 125\ ml) \times 12\ \text{breaths/minute}$$
$$= 375\ ml \times 12\ \text{breaths/minute}$$
$$= 4500\ ml/\text{minute}$$

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

$$P_{A_{CO_2}} = \frac{VCO_2 \times K}{V_A}$$

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

$$P_{A_{CO_2}} = \frac{200\ ml/min}{4500\ ml/min} \times 863\ mm\ Hg$$
$$= 38.4\ mm\ Hg$$

What is the value for alveolar P_{O2} (P_{AO2})?

$$P_{AO2} = P_{IO2} - \frac{P_{ACO2}}{R}$$

$$P_{AO2} = 150 \text{ mm Hg} - \frac{38.4 \text{ mm Hg}}{0.8}$$

$$= 150 \text{ mm Hg} - 48 \text{ mm Hg}$$

$$= 102 \text{ mm Hg}$$

2.

	V	*Q*	*V/Q*	*Expected P_{O2}*	*Expected P_{CO2}*
Apex	*0.8*	*0.4*	*2.0*	*Higher*	*Lower*
Base	*2.2*	*3.2*	*0.7*	*Lower*	*Higher*

3. The **A-a gradient** represents the difference between alveolar P_{O2} (P_{AO2} or "A") and arterial P_{O2} (Pa_{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_{AO2} and Pa_{O2} are equal, or nearly equal. However, if there is a mismatch of ventilation and perfusion (i.e., a V/Q defect), then Pa_{O2} will be less than P_{AO2}, 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_{O2} of arterial blood, Pa_{O2}) and calculating "A" (the P_{O2} of alveolar gas, PAO2) with the ***alveolar gas equation****. Therefore, at 4 P.M.,*

$$\text{"a"} = Pa_{O_2} = 55 \text{ mm Hg}$$

$$\text{"A"} = P_{A_{O_2}} = P_{I_{O_2}} - \frac{P_{A_{CO_2}}}{R}$$

$$= (P_B - P_{H_2O}) \times F_{I_{O_2}} - \frac{P_{A_{CO_2}}}{R}$$

$$= (760 \text{ mm Hg} - 47 \text{ mm Hg}) \times 0.21 - \frac{32 \text{ mm Hg}}{0.8}$$

$$= 150 \text{ mm Hg} - \frac{32 \text{ mm Hg}}{0.8}$$

$$= 150 \text{ mm Hg} - 40 \text{ mm Hg}$$

$$= 110 \text{ mm Hg}$$

$$A - a = 110 \text{ mm Hg} - 55 \text{ mm Hg}$$

$$= 55 \text{ mm Hg}$$

Compared to a normal person, the A-a gradient is greatly increased; O_2 could not fully equilibrate between alveolar gas and pulmonary capillary blood because of a **V/Q defect** *(specifically, a decreased V/Q ratio).*

The Pa_{CO2} is decreased below normal because the person is hyperventilating secondary to hypoxemia. ($Pa_{O2} < 60$ mm Hg stimulates the peripheral chemoreceptors.) Hyperventilation drives off "extra" CO_2 and decreases the Pa_{CO2}.

4. *Steps:*

O_2-binding capacity of blood = hemoglobin concentration x O_2-binding capacity
= 15 g/100 ml blood x 1.34 ml O_2/g hemoglobin
= 20.1 ml O_2/100 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 O_2 content of arterial blood, venous blood, and non-shunted blood. (Remember, non-shunted blood should have the same P_{O2} as alveolar gas.)

O_2 content of arterial blood

$= Dissolved\ O_2 + O_2\ hemoglobin$

$= 70\ mm\ Hg \times 0.003\ ml\ O_2/100\ ml/mm\ Hg + 20.1\ ml\ O_2/100\ ml \times 0.9$
$= 0.21\ vol\ \% + 18.1\ vol\ \%$

$= 18.3\ vol\ \%$

O_2 content of venous blood

$= Dissolved\ O_2 + O_2\text{-}hemoglobin$
$= 30\ mm\ Hg \times 0.003\ ml\ O_2/100\ ml/mm\ Hg + 20.1\ ml\ O_2/100\ ml \times 0.6$
$= 0.09\ vol\ \% + 12.1\ vol\%$
$= 12.2\ vol\ \%$

O_2 content of non-shunted blood

$= Dissolved\ O_2 + O_2\text{-}hemoglobin$
$= 100\ mm\ Hg \times 0.003\ ml\ O_2/100\ ml/mm\ Hg + 20.1\ ml\ O_2/100\ ml \times 1.0$
$= 0.3\ vol\ \% + 20.1\ vol\ \%$
$= 20.4\ vol\ \%$

Next step: calculate the shunt fraction as:

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

$$= \frac{20.4\ vol\ \% - 18.3\ vol\ \%}{20.4\ vol\ \% - 12.2\ vol\ \%}$$

$$= \frac{2.1\ vol\ \%}{8.2\ vol\ \%}$$

$= 0.26$, or 26%

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

$Q_S = 0.26 \times$ cardiac output
$= 0.26 \times 5.2$ L/min
$= 1.35$ L/min

5. *Answer = D. Begin by drawing a lung and labeling the apex and base with respect to blood flow, ventilation, P_{O2}, and P_{CO2}. 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_{O2} and P_{CO2}. The higher the ventilation relative to perfusion, the higher the P_{O2} and the lower the P_{CO2} (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_{O2} 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_{O2} = PI_{O2} - PA_{CO2}/R. PI_{O2} is calculated from barometric pressure corrected for water vapor times the FI_{O2} . PA_{CO2} is assumed to be the same as Pa_{CO2} (given). R is respiratory exchange ratio or respiratory quotient, which is 0.8. "A" = PA_{O2} = (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 FI_{O2} of 0.21. However, you needn't go to all that trouble. If everything else is the same, PI_{O2} at an FI_{O2} of 0.21 is lower than it is at an FI_{O2} 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_{O2} 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_{O2} as alveolar gas, 100 mm Hg. Shunted blood has the same P_{O2} as mixed venous blood, 30 mm Hg. Arterial blood has a measured P_{O2} 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_{O2}. 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:*

	P_{O2}	% sat	Dissolved O_2	Bound O_2	Total O_2
Non-shunted (normal) blood	100	100	0.3	20.1	20.4
Arterial blood	50	85	0.15	17.1	17.3
Mixed venous blood	30	60	0.09	12.1	12.2

*** Units for P_{O2} are mm Hg, for % saturation are %, and for O_2 content are vol %.*

$$\frac{Qs}{Qt} = \frac{20.4 - 17.3}{20.4 - 12.2}$$

$$= \frac{3.1}{8.2}$$

$$= 0.38, \text{ or } 38\%$$

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!*

$$V_D = V_T \times \frac{Pa_{CO2} - PE_{CO2}}{PaCO2}$$

$$= 450\ ml \times \frac{45\ mm\ Hg - 25\ mm\ Hg}{45\ mm\ Hg}$$

$$= 200\ ml$$

Alveolar ventilation $= (V_T - V_D) \times$ *breaths/minute*

$= (450\ ml - 200\ ml) \times 14/minute$

= 3500 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..*