Case 20

Essential Respiratory Calculations: Lung Volumes, Dead Space, and Alveolar Ventilation

This case will guide you through some of the important, basic calculations involving the respiratory system. Use the information provided to answer the questions.

Figure 3–1 shows a record from a person breathing into and out of a spirometer. The volume displaced by the spirometer's bell is recorded on calibrated paper. The person took one normal breath followed by a maximal inhalation, a maximal exhalation, and another normal breath. (The volume remaining in the lungs after maximal expiration is not measurable by spirometry and was determined by other techniques.)

![Spirometry diagram showing a tidal breath, followed by maximal inspiration and maximal expiration.](image)

**TABLE 3-1** Respiratory Values for Case 20

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breathing rate</td>
<td>12 breaths/min</td>
</tr>
<tr>
<td>$P_{aCO_2}$ (arterial $P_{CO_2}$)</td>
<td>40 mm Hg</td>
</tr>
<tr>
<td>$P_{aO_2}$ (arterial $P_{O_2}$)</td>
<td>100 mm Hg</td>
</tr>
<tr>
<td>$P_{ECO_2}$ (expired $P_{CO_2}$)</td>
<td>30 mm Hg</td>
</tr>
<tr>
<td>$P_{h2}$ (humidified $P_{O_2}$)</td>
<td>150 mm Hg</td>
</tr>
<tr>
<td>$P_{hCO_2}$ (inspired $P_{CO_2}$)</td>
<td>0</td>
</tr>
<tr>
<td>$V_{CO_2}$ (rate of $CO_2$ production)</td>
<td>200 mL/min</td>
</tr>
<tr>
<td>$V_{O_2}$ (rate of $O_2$ consumption)</td>
<td>250 mL/min</td>
</tr>
</tbody>
</table>

$P_{CO_2}$ partial pressure of carbon dioxide; $P_{O_2}$ partial pressure of oxygen.
QUESTIONS

1. Using the information provided in Table 3–1 and Figure 3–1, what are the values for tidal volume, inspiratory capacity, expiratory reserve volume, functional residual capacity, vital capacity, and total lung capacity? (Hint: It may be helpful to label the spirometry diagram with the names of the lung volumes and capacities.)

2. What is the name of the volume remaining in the lungs after maximal expiration that is not measurable by spirometry? What other lung volumes or capacities are not measurable by spirometry?

3. What is the meaning of the term "physiologic dead space"? What assumptions are made in calculating the physiologic dead space? What is the volume of the physiologic dead space in this case?

4. What is the value for minute ventilation?

5. What is the value for alveolar ventilation?

6. What is the alveolar ventilation equation? Use this equation to calculate alveolar partial pressure of carbon dioxide ($P_{\text{ACO}_2}$) in this case.

7. What is the value for alveolar partial pressure of oxygen ($P_{\text{AO}_2}$)?
1. Static lung volumes (except for residual volume) are measured by spirometry. They include the tidal volume, inspiratory reserve volume, expiratory reserve volume, and residual volume. Lung capacities include two or more lung volumes. If you began by labeling the lung volumes and capacities, as shown in Figure 3-2 and Table 3-2, then determining the numerical values should be a straightforward exercise.

![Figure 3-2 Spirometry diagram labeled with lung volumes and capacities.](image_url)

<table>
<thead>
<tr>
<th>Table 3-2</th>
<th>Lung Volumes and Capacities in Case 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume</td>
<td>500 ml</td>
</tr>
<tr>
<td>Inspiratory capacity</td>
<td>3500 mL</td>
</tr>
<tr>
<td>Expiratory reserve volume</td>
<td>1000 mL</td>
</tr>
<tr>
<td>Functional residual capacity</td>
<td>2500 mL</td>
</tr>
<tr>
<td>Vital capacity</td>
<td>4500 mL</td>
</tr>
<tr>
<td>Total lung capacity</td>
<td>6000 mL</td>
</tr>
</tbody>
</table>

2. The volume remaining in the lungs after maximal expiration is called the residual volume. This volume is not measurable by spirometry. Therefore, any lung volume or capacity that includes the residual volume is also not measurable by spirometry (i.e., functional residual capacity, total lung capacity).
3. **Physiologic dead space** is the volume of air in the lungs that does not participate in gas exchange (i.e., it is "dead"). Physiologic dead space has two components: (1) anatomic dead space, which is the volume of conducting airways; and (2) functional dead space, which is alveoli that do not participate in gas exchange (i.e., alveoli that are ventilated, but are not perfused by pulmonary capillary blood). By comparing the physiologic dead space with the tidal volume, it is possible to estimate how much ventilation is "wasted."

The volume of the physiologic dead space is estimated with a method based on the P\textsubscript{CO\textsubscript{2}} of expired air (P\textsubscript{ECO\textsubscript{2}}) that applies the following three assumptions. (1) There is no CO\textsubscript{2} in inspired air (i.e., P\textsubscript{ICO\textsubscript{2}} = 0). (2) The physiologic dead space does not participate in gas exchange; therefore, it does not contribute any CO\textsubscript{2} to expired air. (3) All of the CO\textsubscript{2} in expired air comes from the exchange of CO\textsubscript{2} in functioning alveoli.

When discussing physiologic dead space, it is helpful to consider two examples, one in which there is no physiologic dead space and the other in which some degree of physiologic dead space is present. If there is no physiologic dead space, P\textsubscript{ECO\textsubscript{2}} should equal the P\textsubscript{CO\textsubscript{2}} in alveolar air (P\textsubscript{A\textsubscript{CO\textsubscript{2}}}). If there is a physiologic dead space present, then P\textsubscript{ECO\textsubscript{2}} will be "diluted" by air expired from the dead space (air that contains no CO\textsubscript{2}), and P\textsubscript{ECO\textsubscript{2}} will be less than P\textsubscript{A\textsubscript{CO\textsubscript{2}}}.

One problem in comparing the P\textsubscript{CO\textsubscript{2}} of alveolar and expired air is that alveolar air cannot be sampled directly; in other words, we cannot measure P\textsubscript{A\textsubscript{CO\textsubscript{2}}}. This problem can be solved, however, because alveolar gas normally equilibrates with pulmonary capillary blood (which becomes systemic arterial blood). Thus, by measuring arterial P\textsubscript{CO\textsubscript{2}} (P\textsubscript{A\textsubscript{CO\textsubscript{2}}}), we can determine P\textsubscript{A\textsubscript{CO\textsubscript{2}}}.

Using the foregoing assumptions, **physiologic dead space** is calculated as follows:

\[
V_D = V_T \times \frac{P_{A\textsubscript{CO\textsubscript{2}}} - P_{E\textsubscript{CO\textsubscript{2}}}}{P_{A\textsubscript{CO\textsubscript{2}}}}
\]

where

- \(V_D\) = physiologic dead space (mL)
- \(V_T\) = tidal volume (mL)
- \(P_{A\textsubscript{CO\textsubscript{2}}}\) = P\textsubscript{CO\textsubscript{2}} of arterial blood (mm Hg)
- \(P_{E\textsubscript{CO\textsubscript{2}}}\) = P\textsubscript{CO\textsubscript{2}} of expired air (mm Hg)

In words, physiologic dead space is the tidal volume multiplied by a fraction that expresses the dilution of alveolar P\textsubscript{CO\textsubscript{2}} by dead-space air.

We have all of the values we need to calculate the physiologic dead space in this case. Tidal volume was determined from spirometry, and the values for P\textsubscript{A\textsubscript{CO\textsubscript{2}}} and P\textsubscript{E\textsubscript{CO\textsubscript{2}}} are given in the case data.

\[
V_D = V_T \times \frac{P_{A\textsubscript{CO\textsubscript{2}}} - P_{E\textsubscript{CO\textsubscript{2}}}}{P_{A\textsubscript{CO\textsubscript{2}}}}
= 500 \text{ mL} \times \frac{40 \text{ mm Hg} - 30 \text{ mm Hg}}{40 \text{ mm Hg}}
= 500 \text{ mL} \times 0.25
= 125 \text{ mL}
\]

Thus, in the tidal volume of 500 mL, 125 mL occupied the physiologic dead space (i.e., the conducting airways and nonfunctional alveoli). In other words, 125 mL was "wasted" in lung spaces that cannot participate in gas exchange.

4. **Minute ventilation** is the tidal volume multiplied by the number of breaths per minute. In this case:

\[
\text{Minute ventilation} = V_T \times \text{breaths/minute}
= 500 \text{ mL} \times 12/\text{min}
= 6000 \text{ mL/minute}
\]
5. Alveolar ventilation ($\dot{V}_A$) is minute ventilation corrected for physiologic dead space, or:

$$\dot{V}_A = (V_T - V_D) \times \text{breaths/min}$$

where

- $\dot{V}_A = \text{alveolar ventilation (mL/min)}$
- $V_T = \text{tidal volume (mL)}$
- $V_D = \text{physiologic dead space (mL)}$

In this case, tidal volume was determined by spirometry (500 mL), and physiologic dead space was calculated in the previous question (125 mL). Thus, alveolar ventilation is:

$$\dot{V}_A = (500\text{ mL} - 125\text{ mL}) \times 12 \text{ breaths/min}$$
$$= 375\text{ mL} \times 12 \text{ breaths/min}$$
$$= 4500\text{ mL/min}$$

6. In considering these questions about alveolar ventilation and alveolar $P_{CO_2}$, perhaps you wondered what alveolar ventilation has to do with alveolar $P_{CO_2}$. The answer is everything! The fundamental relationship in respiratory physiology is an inverse correlation between alveolar ventilation (the volume of air reaching functional alveoli per minute) and alveolar $P_{CO_2}$. If $CO_2$ production is constant, the higher the alveolar ventilation, the more $CO_2$ expired and the lower the alveolar $P_{CO_2}$. Conversely, the lower the alveolar ventilation, the less $CO_2$ expired and the higher the alveolar $P_{CO_2}$. This relationship is expressed by the alveolar ventilation equation:

$$\dot{V}_A = \frac{\dot{V}_{CO_2} \times K}{P_{ACO_2}}$$

Rearranging to solve for $P_{ACO_2}$:

$$P_{ACO_2} = \frac{\dot{V}_{CO_2} \times K}{\dot{V}_A}$$

where

- $P_{ACO_2} = \text{alveolar } P_{CO_2}$
- $\dot{V}_A = \text{alveolar ventilation}$
- $\dot{V}_{CO_2} = \text{rate of } CO_2 \text{ production (mL/min)}$
- $K = \text{constant (863 mm Hg)}$

The constant ($K$) requires a brief explanation. The value for $K$ is 863 mm Hg under conditions of BTPS, when $\dot{V}_A$ and $\dot{V}_{CO_2}$ are expressed in the same units (e.g., mL/min). BTPS refers to body temperature (310 K), ambient pressure (760 mm Hg), and gas saturated with water vapor.

Now, let’s calculate the value for $P_{ACO_2}$. The rate of $CO_2$ production was given (200 mL/min), and alveolar ventilation was calculated in the previous question (4500 mL/min).

$$P_{ACO_2} = \frac{200\text{ mL/min}}{4500\text{ mL/min}} \times 863\text{ mm Hg}$$
$$= 38.4\text{ mm Hg}$$

7. Because we cannot sample alveolar gas, we cannot directly measure $P_{AO_2}$. However, we can use the following approach to estimate its value. $P_{AO_2}$ is determined by the balance between removal of $O_2$ from alveolar gas (to meet the body’s demands for $O_2$) and replenishment of $O_2$ by alveolar ventilation. Therefore, if $O_2$ consumption is constant, alveolar $P_{O_2}$ is determined by alveolar ventilation (just as alveolar $P_{CO_2}$ is determined by alveolar ventilation).

This relationship is expressed by the alveolar gas equation, which incorporates the factors that determine $P_{AO_2}$ [including partial pressure of $O_2$ in inspired air ($P_{O_2}$)], $P_{ACO_2}$ (which reflects alveolar ventilation, as explained earlier), and respiratory quotient ($R$, the ratio of $CO_2$ production to $O_2$ consumption):
\[ \text{PA}_{O_2} = \text{Pi}_{O_2} - \frac{\text{PA}_{CO_2}}{R} \]

where
\[ \text{PA}_{O_2} = \text{alveolar } P_{O_2} \text{ (mm Hg)} \]
\[ \text{Pi}_{O_2} = P_{O_2} \text{ in inspired air (mm Hg)} \]
\[ \text{PA}_{CO_2} = \text{alveolar } P_{CO_2} \text{ (mm Hg)} \]
\[ R = \text{respiratory quotient (ratio of } CO_2 \text{ production to } O_2 \text{ consumption)} \]

In this case, the value for \( \text{Pi}_{O_2} \) (150 mm Hg) was given, the value for \( \text{PA}_{CO_2} \) (38.4 mm Hg) was calculated in the previous question, and the value for respiratory quotient can be calculated as the rate of \( CO_2 \) production (200 mL/min) divided by the rate of \( O_2 \) consumption (250 mL/min), or 0.8.

\[ \text{PA}_{O_2} = 150 \text{ mm Hg} - \frac{38.4 \text{ mm Hg}}{0.8} \]
\[ = 150 \text{ mm Hg} - 48 \text{ mm Hg} \]
\[ = 102 \text{ mm Hg} \]