"Murder mystery" for student practice of pulmonary physiology calculations

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Maron, Michael B., and Frank J. Bosso. "Murder mystery" for student practice of pulmonary physiology calculations. Am. J. Physiol. 261 (Adv. Physiol. Educ. 6): S3–S6, 1991.—We have developed an exercise designed to give students practice calculating arterial O2 content, O2 delivery, physiological dead space, dead space and alveolar ventilation, and alveolar partial pressure of O2 and CO2. The exercise is in the form of a "murder mystery" in which students are required to make these calculations to identify the murderer.

physiology education; problem set

IN THE STUDY of pulmonary physiology, there are a number of important calculations that can be made that give insight into how well the lungs are functioning. These include calculations of alveolar partial pressure of O2 (Pao2), arterial O2 content, physiological dead space, and alveolar ventilation. In the relatively short time available for the discussion of each organ system in medical physiology courses, students are often overwhelmed by the number of equations in the pulmonary unit. Although students are given the opportunity to practice doing these calculations in the form of problem sets, there is often a lack of interest in spending the time required to make these a useful exercise. In an attempt to make these problems more interesting, we have developed a "murder mystery" in which students are required to apply basic principles learned in the pulmonary unit to determine the identity of the murderer. To solve the case, students must calculate arterial O2 content, O2 delivery, physiological dead space, dead space ventilation, alveolar ventilation, and alveolar PO2 and partial pressure of CO2 (PCO2). The title of the exercise is "The Case of the Murdered Rapper: A Whodunit Where Basic Principles of Respiratory Physiology Are Brought to Bear Upon the Matter of the Identity of the Murderer." Although the scenario is admittedly farfetched, we have observed that its improbability is the critical ingredient that makes the exercise appealing.

CAST OF CHARACTERS

Davenport Deadspace. The powerful chairman of a large international conglomerate (Environrape, Inc.) that has made billions but whose products have contributed to the defoliation of the Amazon rain forests.

Daphne Deadspace. The lovely and beguiling daughter of Davenport Deadspace. A debutante of the first rank and heiress who is betrothed to Bobby Bronchus, a heavy metal rapper. She sings weekends with the Metropolitan Opera.

Bobby Bronchus. A heavy metal rapper, whose band (Bobby Bronchus and the Bronchial Tubes) are the rage of two continents and discrete sections of a third. Bobby channels much of his rapper earnings into causes advocating the preservation of the environment and is a member of 37 different environmental organizations. He is torn between his love for Daphne and that for the environment.

Victor Ventilation. The Deadspaces’ loyal butler, who has worked for the family for the last 30 years. Generations of Ventilations have worked for generations of Deadspaces.

Aldo Alveolus, PhD. A respiratory physiologist, who early in his career was an advocate of the O2 secretion hypothesis of O2 transfer from air to blood. His research is funded by grants from Environape, Inc.

Madeline Medstudent. A medical student, who is working her way through medical school as a part-time employee of the Acme Detective Service. She has been assigned to solve the murder.

THE MURDER

Bobby Bronchus has volunteered to be a subject in one of Dr. Alveolus’ lung function studies and will have his CO diffusion capacity measured. The amount of CO used in this test is normally very small and poses no threat to life. Someone, however, has switched the gas cylinders, and the new tank now contains a lethal concentration of CO. Dr. Alveolus’ technician administers the test to Bobby, who quickly collapses and dies.

THE INVESTIGATION

Madeline arrives to investigate the death and immediately suspects foul play when she learns that CO has been used. The immediate question is, however, was the CO concentration high enough to kill Bobby or did he die of natural causes? Madeline draws a sample of Bobby’s arterial blood and finds that the hemoglobin concentration is 14.0 g/dl, and the carboxyhemoglobin level is 80%. Madeline then assumes that, at rest, Bobby would have had a cardiac output of ~5 l blood/min, an O2 consumption of ~250 ml O2/min, and an arterial PO2 of ~100 Torr. She quickly uses the Fick principle (see APPENDIX for formulas) to calculate Bobby’s normal arteriovenous O2 content difference at rest and then compares this value with his calculated arterial O2 con-
tent to determine if the amount of CO found in Bobby's blood was enough to prevent normal O₂ delivery. Madeline reasons that the arteriovenous O₂ content difference at resting cardiac output and O₂ consumption reflects the amount of O₂ that must leave the blood to maintain a normal resting metabolism. A finding that Bobby's blood was incapable of carrying even this amount would suggest that Bobby died a hypoxic death. Perform these calculations and fill in the blanks in Table 1 to determine if Bobby died of CO poisoning.

The question now becomes, “whodunit?” Madeline quickly learns that all of the characters have motives to commit the murder. Davenport has learned that Bobby has found out about the rape of the Amazon rain forests and will soon be going public with the information. Davenport thus sees a long prison sentence ahead and the evaporation of the pretentious life-style that he has come to love. Daphne has several motives. First, she loves her father and cannot bear to see him suffer. Second, she too has come to enjoy the life-style made possible by her father’s ill-gotten riches and would not be able to continue her voice lessons without this support. Finally, she has recently learned that Bobby has been having an affair with the Bronchial Tube’s female drummer, Helen Hemoglobin. Victor, the butler, has motive in that his loyalty for the Deadspace family could drive him to commit any manner of heinous wrongdoing to protect the Deadspace family. Finally, Dr. Alveolus stands to lose his research support if Environrape, Inc., experiences financial difficulties.

Madeline further learns that the CO cylinder could only have been switched between 2:00 and 2:45 P.M. on the preceding Saturday. All of the suspects were attending a lawn party at the Deadspace mansion at that time and all have alibis except for this 45-min period. None of the suspects can establish exactly where they were during this time. Madeline realizes that the murderer would have had to run from the mansion to the lab (a distance of ~1 mile), exchange the cylinder, and then run back to the mansion during this period. Madeline figures that the murderer would have to complete each leg of the run in ~10 min. She does a quick mental calculation and concludes that the murderer would be required to deliver ~2,300 ml O₂/min to the working muscles to accomplish this feat in the allotted time. As a first step, she has arterial blood samples drawn from each of the suspects and also has their maximal cardiac outputs determined on a treadmill. She uses this data to calculate each individual’s O₂ content and maximal O₂ delivery rate and is quickly able to eliminate one of the suspects. Perform these calculations and tabulate them in Table 2 to determine which suspect Madeline is able to eliminate.

Back at school, Madeline attends an exercise physiology lecture and learns that few individuals are able to maintain their maximal rate of O₂ delivery for very long. Thinking about this, she reasons that none of the suspects would be able to maintain an O₂ delivery rate >75% of maximum. A lightening-quick series of calculations immediately eliminates another suspect. Perform these calculations and enter the results in Table 3 to find out who is eliminated.

A few days later, Madeline returns to the scene of the crime to search for further clues. She interviews the cleaning crew and learns that they saw no one in the lab when they cleaned between 2:10 and 2:35 P.M. Obviously, the murderer had hidden in the lab during this interval. All of the obvious places to hide, however, are filled with an underwater weighing pool, a large tank built into the ground that is used to weigh subjects underwater for the determination of body fat content. By the pool, she finds a large piece of plastic tubing of the type used for plumbing. It is clear that the murderer had used the tubing as a snorkel while hiding from the cleaning crew in the underwater weighing pool.

Madeline determines the volume of the tubing by water displacement to be 135 ml. “This means that the murderer’s dead space ventilation increased while hiding in the tank,” Madeline concludes. “This will have important implications for O₂ and CO₂ homeostasis. Perhaps the murder can be solved on this basis.”

Madeline observes that the tubing is equipped with a pneumotach (a device that measures airflow) and has cable connections to an analog-to-digital converter attached to Dr. Alveolus’ computer. The tubing is obviously a home-made device for studies of dead space. Madeline

### Table 1. Calculations to determine CO poisoning

| Arteriovenous oxygen content difference | 5.0 ml O₂/dl |
| Arterial oxygen content in presence of 80% carboxyhemoglobin | 4.2 ml O₂/dl |

Underlined values are those to be calculated.

### Table 2. Arterial O₂ content and maximal O₂ delivery rate values

<table>
<thead>
<tr>
<th>Suspects</th>
<th>[Hb]</th>
<th>Pao₂</th>
<th>Sat.</th>
<th>Q₀</th>
<th>Cao₂</th>
<th>Max Del.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davenport</td>
<td>15</td>
<td>97</td>
<td>98</td>
<td>20</td>
<td>20.72</td>
<td>4144</td>
</tr>
<tr>
<td>Daphne</td>
<td>12</td>
<td>95</td>
<td>97</td>
<td>16</td>
<td>16.46</td>
<td>2634</td>
</tr>
<tr>
<td>Victor</td>
<td>8</td>
<td>98</td>
<td>98</td>
<td>30</td>
<td>11.19</td>
<td>3357</td>
</tr>
<tr>
<td>Aldo</td>
<td>8</td>
<td>70</td>
<td>90</td>
<td>12</td>
<td>10.22</td>
<td>1226</td>
</tr>
</tbody>
</table>

[Hb], arterial hemoglobin concentration; Pao₂, arterial partial pressure of O₂; Sat, arterial HbO₂ saturation; Q₀, maximal cardiac output; Cao₂, arterial O₂ content; Max Del, maximal rate of O₂ delivery. Bold values are those given; underlined values are those to be calculated.

These data eliminate Aldo as the suspect.

### Table 3. Maximal and 75% maximal O₂ delivery rate values

<table>
<thead>
<tr>
<th>Suspect</th>
<th>Maximum Delivery, ml O₂/min</th>
<th>75% Maximum, ml O₂/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davenport</td>
<td>4,144</td>
<td>3,108</td>
</tr>
<tr>
<td>Daphne</td>
<td>2,634</td>
<td>1,976</td>
</tr>
<tr>
<td>Victor</td>
<td>3,357</td>
<td>2,518</td>
</tr>
<tr>
<td>Aldo</td>
<td>1,226</td>
<td>900</td>
</tr>
</tbody>
</table>

Note: remember Madeline has calculated that an oxygen delivery of 2,300 ml/min is required to make the run in time. Underlined values are those to be calculated.

These data eliminate Daphne as a suspect.
turns on the computer and learns that the system was on during the time of the murder and that there are actual recordings of ventilation during the time the murderer was using the tubing as a snorkel. The records indicate that the total minute ventilation of the murderer while breathing through the tubing was 6,450 ml/min. Madeline realizes that all she has to do is to find which suspect would have a total ventilation of 6,450 ml/min while breathing through the tubing at the bottom of the pool. This individual would have to be the murderer.

The most direct approach to solving this problem would be to measure the total ventilation of each suspect breathing through the tubing. Madeline is concerned, however, that the murderer would quickly understand what she is up to and would hyperventilate or hypoventilate during the test to change ventilation. Dejected, she continues to search through the computer records and finds experimental data for all of the suspects from a study on dead space conducted by Dr. Alveolus. “Eureka!” she shouts. Madeline has found mixed expiratory PCO₂, arterial PCO₂, tidal volume, total ventilation, and respiratory rate data under baseline conditions for each subject. Her strategy is now immediately clear. She reasons that she can use this information to calculate each suspect’s normal alveolar ventilation and that this value should be similar (if the individual is to maintain O₂ and CO₂ homeostasis) under conditions of snorkel breathing. All she has to do is to add the total dead space ventilation (physiological + snorkel deadspace) to this value to obtain the total ventilation. Perform the calculations indicated in Table 4 to determine the identity of the murderer.

It is clear now that _______ is the murderer. Impressed and frustrated by Madeline’s relentless logic, he cries, “Curses, done in by a medical student with a sound knowledge of respiratory physiology!” Before leaving the crime scene and turning her attention to biochemistry.

### TABLE 4. Ventilatory calculations

<table>
<thead>
<tr>
<th>Control conditions</th>
<th>Davenport</th>
<th>Daphne</th>
<th>Victor</th>
<th>Aldo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed expired Pco₂, Torr</td>
<td>27</td>
<td>29</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td>Arterial (= alveolar) Pco₂, Torr</td>
<td>40</td>
<td>39</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>Tidal volume, ml</td>
<td>510</td>
<td>450</td>
<td>487</td>
<td>400</td>
</tr>
<tr>
<td>Physiological dead space, ml</td>
<td>166</td>
<td>115</td>
<td>200</td>
<td>168</td>
</tr>
<tr>
<td>Total ventilation, ml/min</td>
<td>5,100</td>
<td>5,400</td>
<td>5,844</td>
<td>6,000</td>
</tr>
<tr>
<td>Respiratory rate, breaths/ min</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Dead space ventilation, ml/min</td>
<td>1,660</td>
<td>1,380</td>
<td>2,400</td>
<td>2,590</td>
</tr>
<tr>
<td>Alveolar ventilation, ml/min</td>
<td>3,440</td>
<td>4,020</td>
<td>3,444</td>
<td>3,480</td>
</tr>
<tr>
<td>Added dead space (note respiratory rate remains constant)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snorkel + physiological dead space, ml</td>
<td>301</td>
<td>250</td>
<td>335</td>
<td>303</td>
</tr>
<tr>
<td>Dead space ventilation, ml/min</td>
<td>3,010</td>
<td>3,000</td>
<td>4,020</td>
<td>4,545</td>
</tr>
<tr>
<td>Total ventilation, ml/min</td>
<td>6,450</td>
<td>7,020</td>
<td>7,464</td>
<td>8,025</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Davenport</th>
<th>Daphne</th>
<th>Victor</th>
<th>Aldo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total ventilation under control conditions, ml/min</td>
<td>5,100</td>
<td>5,400</td>
<td>5,844</td>
</tr>
<tr>
<td>Dead space ventilation with added dead space, ml/min</td>
<td>3,010</td>
<td>3,000</td>
<td>4,020</td>
</tr>
<tr>
<td>Alveolar ventilation, ml/min</td>
<td>2,090</td>
<td>2,400</td>
<td>1,824</td>
</tr>
<tr>
<td>Alveolar Pco₂, Torr</td>
<td>65.8</td>
<td>65.3</td>
<td>75.5</td>
</tr>
<tr>
<td>Alveolar Pox, Torr</td>
<td>62.8</td>
<td>63.4</td>
<td>50.7</td>
</tr>
</tbody>
</table>

Bold values are those given; underlined values are those to be calculated.

Madeline decides to perform another series of calculations for relaxation. She knows from her pulmonary physiology lectures that to maintain CO₂ and O₂ homeostasis during snorkel breathing, one must maintain alveolar ventilation by increasing total ventilation. Madeline wonders what each of the suspect’s alveolar Pox and Pco₂ would be if ventilation were not increased. Help Madeline unwind by performing the calculations indicated in Table 5.

### APPENDIX

**Symbols, constants, and equations are from West (1).**

**Environmental Conditions and Constants**

- Barometric pressure (Pb) = 140 Torr
- Water vapor pressure (Pv) = 47 Torr at 37°C
- Hemoglobin (Hb)-O₂ combining capacity = 1.39 ml O₂/g Hb
- O₂ solubility coefficient = 0.003 ml O₂/dl blood °° Torr⁻¹
- Inspired O₂ fraction (Fio₂) = 0.2093
- Respiratory exchange ratio (R) = 0.8

**Equations (in Order of Use)**

1. Arteriovenous O₂ content difference (A-VO₂) (Fick equation)

\[
A-VO₂ = \frac{\dot{V}O₂}{Q} \quad (A1)
\]

where \(\dot{Q}\) is cardiac output and \(\dot{V}O₂\) is the rate of O₂ consumption.

2. Hbo₂ = (Hb)(HbO₂ combining capacity)(S/100) \quad (A2)

3. dissolved O₂ = (Pox)(O₂ solubility coefficient) \quad (A3)

4. total O₂ content of blood = Hbo₂ + dissolved O₂ \quad (A4)

where Hbo₂ is O₂ content of blood combined with Hb and S is percent Hb saturation with O₂.

5. O₂ delivery rate = CaO₂Q \quad (A5)

where CaO₂ is arterial O₂ content.

6. Dead space volume (Vd) [assuming equivalency of alveolar Pco₂ (Paco₂) and arterial Pco₂ (Poa) is]

\[
V_d = V_T \left( \frac{Paco₂ - Pco₂}{Paco₂} \right) \quad (A6)
\]
where $V_t$ is tidal volume and $P_{ECO_2}$ is expired $PO_2$.

Dead space ventilation ($V_D$) is

$$
V_D = V_0 f
$$

where $f$ is respiratory rate.

Total minute ventilation ($V_t$) is

$$
V_t = V_E + V_D
$$

where $V_A$ is alveolar ventilation.

Alveolar ventilation is

$$
V_A = V_E - V_D
$$

The alveolar ventilation equation is

$$
A = (VCO_2/PA CO_2)(K)
$$

where $VCO_2$ is rate of CO$_2$ production and $K$ is a constant.

Assuming constancy of $VCO_2$ and equivalency of $PA CO_2$ and $PA CO_2$ gives

$$
V_A PA CO_2 = K
$$

Alveolar $PO_2$ ($PA O_2$) is

$$
PA O_2 = (P_B - PHo)(P_{IO_2}) - (PA CO_2/R)
$$

(A12)

(note: for simplicity, a small correction factor normally added to the right side of the equation has been omitted).

REFERENCES