The Effects of Apparatus Dead Space on \( P_{a\text{CO}_2} \) in Patients Receiving Lung-Protective Ventilation

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BACKGROUND: Lung-protective ventilation using tidal volume (\( V_T \)) of 4–6 mL/kg (predicted body weight) reduces mortality (compared with traditional \( V_T \)) in patients with acute respiratory distress syndrome and acute lung injury. Standardized use of lower \( V_T \) can result in respiratory acidosis and has raised new concerns about the appropriate configuration of the ventilator circuit, especially in regard to the dead space (\( V_D \)) of the apparatus. We hypothesized that, with a patient receiving lung-protective ventilation, the removal of all apparatus dead space from the circuit would reduce \( P_{a\text{CO}_2} \) and allow a reduction in minute ventilation.

METHODS: All the studied patients met the American-European consensus-conference criteria for acute respiratory distress syndrome/acute lung injury, were receiving a lung-protective ventilation strategy, were > 18 years of age, and were hemodynamically stable. We prospectively tested 3 different ventilator-circuit configurations, in random sequence, for 15 min each: (1) standard hygroscopic heat-and-moisture exchanger (HME) with 15-cm flexible tubing, (2) 15-cm flexible tubing only, (3) no HME or flexible tubing. \( V_T \), respiratory rate, positive end-expiratory pressure, and fraction of inspired oxygen were maintained constant throughout the study, and exhaled CO\(_2\) was measured continuously. Physiologic dead space (\( V_D/V_T \)) was calculated using the Enghoff modification of the Bohr equation. RESULTS: Seven patients were studied. Removal of the HME from the circuit significantly decreased \( V_D/V_T \) (by approximately 6%) and \( P_{a\text{CO}_2} \) (by approximately 5 mm Hg). Removal of both the HME and flexible tubing from the circuit reduced \( V_D/V_T \) by an additional 5%, and \( P_{a\text{CO}_2} \) by an additional 6 mm Hg. With both circuit-configuration changes, minute ventilation fell from a mean of 11.51 L/min to 10.35 L/min, and pH increased from 7.30 to 7.38. Carbon-dioxide production did not change significantly. CONCLUSION: In patients receiving lower-\( V_T \) ventilation, removing all the apparatus \( V_D \) from the ventilator circuit reduces \( P_{a\text{CO}_2} \) and increases pH, at a lower minute ventilation. This information will help guide ventilator-circuit configuration for patients receiving lung-protective ventilation.

Key words: acute respiratory distress syndrome, ARDS, dead space, lung-protective ventilation, mechanical ventilation, hypercapnia. [Respir Care 2006;51(10):1140 –1144. © 2006 Daedalus Enterprises]
ARDS/ALI. When $V_T$ is in the 8–12 mL/kg range, apparatus $V_D$ may not be an important factor in determining total ventilatory requirements, but this may not be the case during low-$V_T$ ventilation. In addition, patients with ARDS have severe gas-exchange impairment, including compromised CO$_2$ elimination, which makes normalizing the P$_{aCO_2}$ difficult or impossible in many cases.

We hypothesized that the removal of all apparatus $V_D$ from a ventilator circuit during lung-protective ventilation would reduce P$_{aCO_2}$, increase pH, and allow a reduction in minute ventilation ($V_E$).

**Methods**

The study was conducted between September 28, 2004, and January 18, 2005, at Harborview Medical Center, which is a level-one trauma, burn, and acute-care hospital in Seattle, Washington. Patients who met the study criteria were identified during respiratory-care shift report by the study authors. Patients were selected who met the American-European consensus-conference criteria for ARDS/ALI, were > 18 years of age, were on lung-protective ventilation protocol ($V_T$ of 4–6 mL/kg predicted body weight), and were hemodynamically stable. The patients were managed according to a local protocol that is based on the ARDS Network protocol for lung-protective ventilation. The University of Washington investigational review board approved the study, and informed consent was obtained from each patient’s legal next of kin prior to any data collection. Patients were studied nonconsecutively.

At the time of the study, the patients were not undergoing any procedures and were reasonably calm and synchronous with the ventilator (Servo 300, Siemens/Maquet, Bridgewater, New Jersey). A respiratory monitor (CO$_2$SMO Plus 8100, Novametrix Medical Systems, Wallingford, Connecticut) was connected at the circuit Y-piece (CO2SMO Plus 8100, Novametrix Medical Systems, Wallingford, Connecticut) was connected at the circuit Y-piece to measure exhaled CO$_2$ (volumetric capnography). The device was warmed and calibrated. Three ventilator-circuit configurations were tested:

1. Standard hygroscopic HME (Humid-Vent Filter Light, Hudson RCI, Research Triangle Park, North Carolina) with an approximately 15-cm piece of flexible tubing (Tube-Flex, Puritan Bennett, Pleasanton, California)
2. Flexible tubing (approximately 15 cm) only
3. No HME or flexible tubing

The order of configuration was randomized for each patient, and the baseline configuration was the setup the patient had at the time of the study.

After 15 min on one of the circuit configurations, an arterial blood sample was drawn from an indwelling catheter, and, from the patient’s exhaled gas we measured end-tidal carbon dioxide, mixed expired carbon dioxide, and carbon-dioxide production. Blood pressure, heart rate, and respiratory rate were monitored. $V_T$, set respiratory rate, positive end-expiratory pressure, and fraction of inspired oxygen were maintained constant throughout the study period. Then the circuit was changed to the next configuration and, after 15 min elapsed, the data gathering was repeated with that circuit configuration.

The data were analyzed using spreadsheet software (Excel, Microsoft, Redmond, Washington) and graphing software (Prism, GraphPad Software, San Diego, California). Physiologic $V_D/(V_D/V_T)$ was calculated using the Enghoff modification of the Bohr equation:

$$V_D/V_T = (P_{aCO_2} - P_{eCO_2})/P_{aCO_2}$$

in which $P_{eCO_2}$ is the mixed expired pressure of carbon dioxide.

The data are presented as mean ± standard deviation. Differences between conditions were compared using a paired $t$ test with the Bonferoni correction for multiple comparisons. Differences were considered significant when $p < 0.05$. Linear regression was performed to determine the correlation coefficient between the fraction of apparatus $V_D$ (normalized to the maximum [HME + flexible tubing]) and the mean of measured variables, with linearity confirmed with the runs test.

**Results**

Seven patients were enrolled in the study (Table 1). The volume of the HME was 60 mL, and that of the flexible tubing was 55 mL, for a total maximum apparatus $V_D$ of 115 mL. Removal of the HME from the circuit decreased $V_D/V_T$ by approximately 6% ($p = 0.01$) and decreased P$_{aCO_2}$ by 5 mm Hg ($p = 0.007$) (Fig. 1). Removing both the HME and the flexible tubing decreased $V_D/V_T$ by an additional 5% ($p = 0.007$) and decreased P$_{aCO_2}$ by an additional 6 mm Hg ($p = 0.03$). Removing both the HME and the flexible tubing allowed for a $V_E$ decrease, from a mean of 11.51 L/min to 10.35 L/min ($p = 0.02$) and increased pH from 7.30 to 7.38 ($p = 0.005$) (Fig. 2). The relationships between apparatus $V_D$ and $V_D/V_T$ and $V_E$ were linear, with correlation coefficients of 0.99 and 0.94, respectively. With removal of apparatus $V_D$ there was a trend toward increased carbon-dioxide production, but there were no significant changes in mean arterial pressure, P$_{aO_2}$, or heart rate (Table 2).

Four of the studied patients were receiving $V_T$ of 6 mL/kg, whereas the other 3 patients were receiving 4 mL/kg. Reductions in $V_D/V_T$ and P$_{aCO_2}$ occurred in both groups, although the effects tended to be larger among the patients receiving 4 mL/kg. For example, comparing the maximum and minimum apparatus $V_D$, P$_{aCO_2}$ fell from 68 ± 10 mm Hg to 51.7 ± 8.4 mm Hg in patients who received $V_T$ of 4 mL/kg, whereas P$_{aCO_2}$ fell from 59.5 ± 14.5 mm Hg to...
ARDS/ALI is characterized by severe ventilation-perfusion mismatch, due to increased pulmonary vascular permeability and alveolar injury, leading to alveolar flooding, disruption of the hypoxic vasoconstriction response, and shunting due to collapsed alveolar units. The result is severe compromise of pulmonary gas exchange, with resulting hypoxemia and hypercapnia, which is frequently resistant to conventional oxygen therapy and mechanical ventilatory support. The gas-exchange abnormality can be further demonstrated by an increase in the Enghoff modification of the Bohr VD/Vt (physiologic VD/Vt). The increased VD/Vt is believed to be due primarily to areas of shunt and low alveolar ventilation-perfusion rather than areas of high alveolar ventilation-perfusion, but the net result remains impaired CO2 elimination, with consequent hypercapnia and respiratory acidosis, despite increased intensity of ventilatory support.
In patients who received low V\textsubscript{T} as part of a lung-protective strategy, the apparatus V\textsubscript{D} of the ventilator circuit may also contribute to impaired CO\textsubscript{2} elimination and hypercapnia. For example, the HME used in our study had a V\textsubscript{D} of 60 mL and the flexible tubing had a V\textsubscript{D} of 55 mL. The baseline apparatus V\textsubscript{D} was 15 mL for the CO\textsubscript{2} monitor and inline suction catheter, whereas the V\textsubscript{T} ranged from 270 mL to 465 mL, with a mean of 337 ± 80 mL. The apparatus V\textsubscript{D} with both the HME and the flexible tubing accounted for 40.3 ± 8.5% of the V\textsubscript{T}, and the apparatus V\textsubscript{D} of the flexible tubing alone accounted for 21.7 ± 4.6% of V\textsubscript{T}. The baseline apparatus V\textsubscript{D} accounted for 4.6 ± 1.0%. Indeed, we found that removal of the HME and flexible tubing from the ventilator circuit reduced V\textsubscript{D}/V\textsubscript{T}, which significantly reduced P\textsubscript{aCO\textsubscript{2}} at a lower total V\textsubscript{E}. Removal of apparatus V\textsubscript{D} was also associated with a clinically relevant increase in arterial-blood pH.

Patients on lung-protective ventilation with impaired CO\textsubscript{2} elimination may benefit from the removal of all possible apparatus V\textsubscript{D}, for 3 reasons. First, removal of apparatus V\textsubscript{D} reduces hypercapnia and increases arterial-blood pH. Second, a reduction in ventilatory demand, with an associated decrease in V\textsubscript{E}, may decrease air trapping and intrinsic positive end-expiratory pressure, with consequent reduced intrathoracic pressure, improved hemodynamics, and lower intracranial pressure. The latter is supported by observations of the effects of HMEs on ventilatory mechanics in spontaneously breathing patients. Intrinsic positive end-expiratory pressure, with consequent reduced intrathoracic pressure, improved hemodynamics, and lower intracranial pressure. The latter is supported by observations of the effects of HMEs on ventilatory mechanics in spontaneously breathing patients. Third, the improved CO\textsubscript{2} elimination may allow reducing V\textsubscript{T} or respiratory rate, which may reduce gas trapping and ventilator-induced lung injury.

There is ongoing debate regarding the harm or benefits of hypercapnia on gas exchange and lung injury. Experimental models suggest that inhalation of CO\textsubscript{2} to induce hypercapnic acidosis improves P\textsubscript{aO\textsubscript{2}} in animals with normal lungs. Inhaled CO\textsubscript{2} attenuated lung injury in experimental models. In contrast, inducing hypercapnia by reducing V\textsubscript{E} increased lung injury in rabbits treated with lipopolysaccharide. In addition, the benefits of therapeutic or passive hypercapnia on gas exchange or lung injury have not been reproduced in patients with severe lung injury. A recent retrospective analysis of data from the original ARDS Network lung-protective-ventilation trial found that hypercapnia did not affect mortality in patients ventilated with low V\textsubscript{T} (6 mL/kg) but was associated with a mortality reduction in the high-V\textsubscript{T} group. Similar to other investigators, we found no P\textsubscript{aO\textsubscript{2}} effect from manipulation of apparatus V\textsubscript{D} and the associated changes in P\textsubscript{aCO\textsubscript{2}}. Thus it would be premature to recommend hypercapnic acidosis as a protective or therapeutic strategy in patients with ARDS and ALI, particularly when induced by a reduction in V\textsubscript{E}.

Two other studies have examined the effects of apparatus V\textsubscript{D} on ventilation in ARDS. Prin et al\textsuperscript{20} studied 11 patients with ARDS. In that study the HME, which had an apparatus V\textsubscript{D} of 100 mL, was removed when P\textsubscript{aCO\textsubscript{2}} exceeded 55 mm Hg. That study found a pH increase, from 7.20 ± 0.08 to 7.26 ± 0.06 (p < 0.005) and P\textsubscript{aCO\textsubscript{2}} reduction from 67 ± 9 mm Hg to 56 ± 6 mm Hg (p < 0.003).\textsuperscript{20} In another study Prat et al\textsuperscript{21} studied the effects of various-size apparatus V\textsubscript{D}, ranging from 120 mL to 0 mL. They found a pH increase, from 7.18 ± 0.08 to 7.28 ± 0.08 (p < 0.05), and P\textsubscript{aCO\textsubscript{2}} reduction, from 80.3 ± 20 mm Hg to 63.6 ± 13 mm Hg (p < 0.05).

Our study differs from the latter 2 studies in a couple of ways. First, we did not modify the patients’ ability to control their ventilation. Prin et al\textsuperscript{20} administered cisatracurium during the study procedure, and Prat et al\textsuperscript{21} maintained their patients’ sedation level to achieve a Ramsey score of 6, resulting in a fixed V\textsubscript{E} in both studies. In our study the patients were able to adjust V\textsubscript{E} with the changes in apparatus V\textsubscript{D}, and V\textsubscript{D} removal significantly reduced V\textsubscript{E}, which may reduce air trapping and allow reduction in the intensity of ventilation. We found pH and P\textsubscript{aCO\textsubscript{2}} improvements comparable to the previous studies, despite the fact that we reduced the V\textsubscript{E}. Second, the V\textsubscript{T} in our study (5.3 ± 1 mL/kg) was lower than in the studies by Prin et al (7.6 ± 0.6 mL/kg) and Prat et al (6.9 ± 1.8 mL/kg).

**Table 2. Effect of Circuit Configuration on Gas Exchange and Vital Signs**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Flexible Tubing and HME</th>
<th>Flexible Tubing Only</th>
<th>No Flexible Tubing or HME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterial pressure (mm Hg)</td>
<td>85 ± 12</td>
<td>81 ± 16</td>
<td>80 ± 13</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>104 ± 21</td>
<td>101 ± 20</td>
<td>95 ± 20</td>
</tr>
<tr>
<td>P\textsubscript{aO\textsubscript{2}} (mm Hg)</td>
<td>77 ± 17</td>
<td>80 ± 23</td>
<td>81 ± 23</td>
</tr>
<tr>
<td>V\textsubscript{CO\textsubscript{2}} (mL/min)</td>
<td>147 ± 56</td>
<td>172 ± 59</td>
<td>175 ± 51</td>
</tr>
<tr>
<td>f (breaths/min)</td>
<td>35.4 ± 6.6†</td>
<td>34.3 ± 6.8†</td>
<td>31.9 ± 6.3‡</td>
</tr>
</tbody>
</table>

\*Values are mean ± SD  
†p < 0.05 versus no flexible tubing, no HME  
‡p < 0.05 versus flexible tubing and HME  
HME = heat-and-moisture exchanger  
V\textsubscript{CO\textsubscript{2}} = carbon dioxide production
The routine removal of apparatus VD from the ventilator circuit during lung-protective ventilation has some theoretical disadvantages. The absence of the flexible tubing can increase tension on the ventilator circuit and potentially increase the risk of inadvertent extubation. Removing the HME from the circuit necessitates the use of a more costly active heated humidifier device. However, for patients with severe gas-exchange abnormalities and associated hypercapnia and respiratory acidosis, removal of apparatus VD offers an important clinical benefit and should be routinely considered.

**Conclusion**

In patients with ARDS or ALI receiving lung-protective ventilation, removing all possible apparatus VD reduces $P_{a\text{CO}_2}$ and increases pH, at a lower V˙E. We recommend a circuit with the minimum possible apparatus VD for adults, and practice guidelines that trigger removal of VD from the circuit.

**REFERENCES**