When Does Apparatus Dead Space Matter?

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BACKGROUND

• Physiologic dead space can be defined as any volume in the airway, lungs or breathing circuit with bidirectional gas flow but no gas exchange.

• Physiologic dead space reduces the effectiveness of mechanical ventilation because minute ventilation delivered to dead space does not result in oxygen delivery or carbon dioxide elimination.

• In the intubated patient, total physiologic dead space is the sum of the dead space contributed by the breathing circuit apparatus, the airways and poorly perfused alveoli where no gas exchange occurs.

• For circle breathing circuits any components distal to the y-piece increase the apparatus dead space.

• Apparatus added to the breathing circuit will increase dead space and cause either an increased arterial CO2 (PaCO2) or the need to increase minute ventilation to avoid hypercarbia.

• Carbon dioxide (CO2) is highly diffusible and therefore it can be assumed that PACO2=PaCO2 due to a negligible PCO2 gradient between blood and alveolar space.

• Small children are especially vulnerable to the impact of apparatus added to the breathing circuit since even small increases in apparatus dead space can significantly increase \(V_t/V_e\).

OBJECTIVE

• Develop a mathematical model to estimate when the relationship between patient size and apparatus dead space has a significant effect on CO2 elimination as determined by resulting hypercapnia and/or the need to increase respiratory rate to avoid hypercarbia.

METHODS

Measurement of Apparatus Dead Space

• The volumes of circuit filters and connectors at our institution were obtained from the manufacturer package insert or by measuring the volume of displaced water and are shown below in Figure 1.

Modeling the Effects of Apparatus Dead Space on PACO2 and Respiratory Rate

• The relationship of fraction of alveolar CO2 (\(\text{FACO}_2\)) to PaCO2, metabolic minute production of CO2 in mL/minute and alveolar ventilation (VA) in mL/minute can be estimated by the following equation:

\[
\text{FACO}_2 = \frac{\text{CO}_2\text{production} \times \text{VA}}{\text{PaCO}_2 \times \text{VA}}
\] (1)

• Alveolar ventilation is the difference between minute ventilation and dead space ventilation:

\[
\text{VA} = \text{V}_{t} - \text{V}_{d} = \text{F}_{t} \times (\text{V}_{d}/\text{VA})
\] (2)

• \(\text{VCO}_2\) can be estimated using Brody’s equation4, where weight is in kg:

\[
\text{VCO}_2 = 8 \times \text{wt}^{0.34}
\] (4)

• The alveolar CO2 partial pressure at sea level (PACO2) in mmHg is found by multiplying \(\text{FACO}_2\) by the difference of atmospheric pressure and partial pressure of water vapor:

\[
\text{PACO}_2 = \text{FACO}_2 \times (713 - 8 \times \text{wt})/8
\] (5)

• Substituting Equation 4 and Equation 5 into Equation 3 yields Equation 6, thus allowing for the modeling of PACO2 as apparatus dead space increases:

\[
\text{PACO}_2 = \frac{713 \times \text{wt}^{0.34} \times \text{VA}}{(\text{V}_{d} \times \text{VA})}
\] (6)

• For the model, initial conditions were set assuming a \(V_t\) of 8mL/kg, an initial apparatus dead space of 0mL and \(V_t\) of one third of \(V_t\). \(V_d\) was increased to simulate apparatus dead space and the impact on PACO2 was calculated.

• Alternatively, rearranging Equation 6 to solve for respiratory rate (f) required to maintain a given PaCO2 of 40mmHg yields Equation 7, thus allowing for the modeling of respiratory rate required as apparatus dead space increases:

\[
f = \frac{713 \times \text{wt}^{3/4} \times \text{VA}}{8 \times \text{VA}^{3/4}}
\] (7)

• The relationship of 1 to changes in dead space were calculated starting with \(V_t = 8\text{mL/kg}\) and \(V_d\) one third of \(V_t\). \(V_d\) was increased to simulate the increase in apparatus dead space.

RESULTS

• Seemingly small increases in apparatus dead space can substantially increase PACO2, and/or the respiratory rate required to maintain a normal PaCO2 of 40mmHg.

• PACO2 increased exponentially with increasing apparatus dead space. For smaller patients the PACO2 increased rapidly for small changes in \(V_d\) (Figure 2).

• Respiratory rate required to maintain PACO2=40mmHg also increased exponentially with increasing dead space. Again the impact was greater as the patient size decreased. (Figure 3)

CONCLUSIONS

• Although these data are based on a model, the change in PACO2 and ventilator requirements would be expected to be qualitatively similar for patients of comparable size.

• Increasing apparatus dead space volume can lead to exponential increases in PACO2 or respiratory rate required to maintain normal PaCO2.

• The impact of increased dead space on PACO2 diminishes as patient size increases, but these data suggest it can be significant up to 20 kg or more.

• Individual patients may respond differently to changes in dead space although the model results should provide a qualitative relationship and estimate of clinical results.

• Clinical studies clearly indicate the impact of dead space changes on PaCO2 and ventilatory demands.

• Since an increased \(V_d\) will increase the tidal to arterial CO2 gradient, hypercarbia may go unrecognized if capnography is relied upon to monitor ventilation7.

• Modern approaches to lung protective ventilation dictate that tidal volume and ventilator cycles be limited to minimize the risk of ventilator induced lung injury9. When using a lung protective ventilation strategy, apparatus dead space must be carefully managed to avoid unnecessary hypercarbia or excessive minute ventilation5.

REFERENCES