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Introduction

Flow-controlled ventilation (FCV) is an emerging method of controlled mechanical ventilation characterized by constant, active expiratory flow.[1-3] The inspiratory flow pattern during FCV is similar to volume-controlled ventilation (VCV, Figure 1). During early expiration, gas flow is limited, while during late expiration, flow is expedited. In contrast to passive expiratory flow limitation, the expiratory time during FCV is controlled and generally shorter.[3]

FCV may result in improved CO_2 clearance and a more homogeneous distribution of ventilation.[4-6] Reduced dead space ventilation might explain these observations.

Volumetric capnography (V_{cap}) has been validated for dead space measurements during passive expiration,[7] but its use during active expiration has not been studied.

We assessed the validity of volumetric capnography for the quantification of dead space ventilation during active, constant expiratory flow in a bench test.

Methods

Bohr dead space ventilation ($V_{D\text{-}br}/V_T$) was compared between FCV (Evone, Ventinova) and VCV (Servo-i, Getinge, Sweden) at baseline and for the rate of change with increasing instrumental dead space ($V_{D\text{-}inst}$).

A test lung with a fixed compliance and resistance was connected to a breathing circuit using two conventional tube adapters (Ventinova), a flow sensor (MBMED, Argentina) and an adult CO_2 adapter (Philips, The Netherlands). CO_2 was injected at a constant flow of 100 ml/min via a small indwelling line (EL-FLOW Select, Bronkhorst).

During each ventilatory mode, $V_{D\text{-}inst}$ was augmented in nine steps using catheter mounts (Teleflex, Ireland) and airway adapters (22M-22F connector, Intersurgical). VCV and FCV were provided using dual and single limb breathing circuits respectively. The net volumes of the circuits were determined as the weight of bubble-free water.

At baseline, VCV was set with a respiratory rate (RR) of 20/min, an I:E ratio of 1:2 and a PEEP of 5 cmH_2O. Tidal volumes (TV) were then titrated to an end-tidal CO_2 ($ETCO_2$) of 40mmHg, resulting in volumes of 220 ml. During FCV, settings were adjusted to produce the same tidal volume. This required a peak tracheal pressure of 20 cmH_2O and an end-expiratory tracheal pressure of 5 cmH_2O, with a flow of 15 L/min and an I:E ratio of 1:1.

Volumetric capnography was recorded with the capnostat 5 (Philips). Airway pressure, flow and volume were captured with the FluxMed GrT monitor (MBMED). At each step in each ventilation mode, recordings were sampled at 256 Hz for 120 seconds.

Data were analyzed in R (v4). The primary outcome was the $V_{D\text{-}br}/V_T$, defined as (*alveolar partial pressure of CO_2 – expired partial pressure of CO_2) / alveolar partial pressure of CO_2*.

The median of all breaths at each measurement point was calculated. The interaction between added dead space volume and mode of ventilation was tested with linear

modelling. Assumptions were graphically verified and the threshold for significance was set at 0.05.

Results

The total number of breaths sampled across all levels of dead space was 407 for FCV and 377 for VCV. There were no missing data. The dead space of the breathing circuit at baseline was 37 ml larger with FCV. A linear relation between the added dead space volume and $V_{D\text{-}br}/V_T$ was observed for both FCV and VCV (Figure 2). The corresponding linear model met all assumptions and had an excellent fit (R^2 97%). $V_{D\text{-}br}/V_T$ was 16% higher during FCV ($p<0.001$). There was no interaction between the added dead space volume and mode of ventilation (FCV slope: 0.0028, VCV slope: 0.0032, $p = 0.29$).

Discussion

This test compares $V_{D\text{-}br}/V_T$ during FCV and VCV over a wide range of $V_{D\text{-}inst}$. The parallel linear relationship confirms that increases in $V_{D\text{-}inst}$ can be measured as a synchronous rise in $V_{D\text{-}br}/V_T$ during both FCV and VCV. Therefore, constant, active expiratory flow does not affect $V_{D\text{-}br}/V_T$ readings and conventional volumetric capnography is feasible in this setting.

The baseline $V_{D\text{-}br}/V_T$ of 0.4 during VCV (Figure 2) may be partly attributed to the dead space of the two conventional tube adapters, the flow sensor and the CO_2 adapter. During FCV, $V_{D\text{-}br}/V_T$ was 16% higher at baseline and throughout the range of increasing $V_{D\text{-}inst}$. In contrast with VCV, which uses a conventional breathing circuit, FCV uses a single-limb circuit. The $V_{D\text{-}inst}$ was 37 ml larger in the single-limb compared with the dual limb circuit. This represents 17% of the titrated tidal volumes (220 ml). The differences in $V_{D\text{-}br}/V_T$ between FCV and VCV may thus be attributed to the difference in dead space of the breathing circuits.

Despite matching of ventilator settings, tidal volumes differed slightly between modes. This does not invalidate the analysis, however, as in Bohr's equation dead space is normalized to tidal volume.

Limitations

The increased CO_2 clearance observed during FCV may arise through a reduction of physiological dead space ($V_{D\text{-}phys}$). This bench test simulated changes in dead space through $V_{D\text{-}inst}$ and did not aim to report on the effects of FCV on $V_{D\text{-}phys}$.

More breaths were sampled during FCV, because we matched tidal volume, but not respiratory rate. I:E ratio was maintained at 1:2 during VCV, but 1:1 during FCV, according to the manufacturer's recommendations. During analysis, however, ventilatory modes were compared using the median $V_{D\text{-}br}/V_T$ at each level of added dead space.

Validating Enghoff dead space as well as alveolar dead space and airway dead space volumes was not feasible in this bench test as the arterial partial pressure of CO_2 could not be simulated.

Conclusion

Bohr dead space measured with volumetric capnography quantifies changes in instrumental dead spaces equally during VCV and FCV. Volumetric capnography may thus be used to measure dead space during active expiratory flow. Differences in breathing circuit dead space should be accounted for when comparing absolute values of dead space.

References

1. Schmidt J, Wenzel C, Mahn M, Spassov S, Cristina Schmitz H, Borgmann S, et al. Improved lung recruitment and oxygenation during mandatory ventilation with a new expiratory ventilation assistance device: A controlled interventional trial in healthy pigs. Eur J Anaesthesiol 2018;35(10):736-744.
2. Barnes T, Enk D. Ventilation for low dissipated energy achieved using flow control during both inspiration and expiration. Trends in Anaesthesia and Critical Care 2019;24:5 - 12.
3. Bialka S, Palaczynski P, Szuldrzynski K, Wichary P, Kowalski D, van der Hoorn JWA, et al. Flow-controlled ventilation - a new and promising method of ventilation presented with a review of the literature. Anaesthesiol Intensive Ther 2022.
4. Van Dessel ED, De Meyer GR, Morrison SG, Jorens PG, Schepens T. Flow-controlled ventilation in moderate acute respiratory distress syndrome due to COVID-19: an open-label repeated-measures controlled trial. Intensive Care Med Exp 2022;10(1):19.
5. Weber J, Schmidt J, Straka L, Wirth S, Schumann S. Flow-controlled ventilation improves gas exchange in lung-healthy patients- a randomized interventional cross-over study. Acta Anaesthesiol Scand 2019.
6. Weber J, Straka L, Borgmann S, Schmidt J, Wirth S, Schumann S. Flow-controlled ventilation (FCV) improves regional ventilation in obese patients - a randomized controlled crossover trial. BMC Anesthesiol 2020;20(1):24.
7. Verscheure S, Massion PB, Verschuren F, Damas P, Magder S. Volumetric capnography: lessons from the past and current clinical applications. Crit Care 2016;20(1):184.

Figure legends

Figure 1 – Pressure, flow and volume tracings during pressure, volume and flow-controlled ventilation on a test lung. Ventilator settings between modes were matched for tidal volume and respiratory rate. The I:E ratio was 1:1 in FCV and 1:2 in PCV and VCV. The dashed red line indicates a tidal volume of 500 ml. FCV is characterized by the constant, active expiratory flow.

FCV: flow-controlled ventilation, I:E ratio: ratio of inspiratory to expiratory time, PCV: pressure-controlled ventilation, VCV: volume-controlled ventilation

Figure 2 – Relation between the added dead space volume and Bohr dead space measured with volumetric capnography per ventilation mode.

The secondary x-axis indicates the number of catheter mounts (S) and/or airway adapters (A). Boxplots at each level of dead space indicate the spread of repeated breaths over 120 seconds. A linear regression was fitted per ventilation mode, with the respective equations presented top left. The grey shade of the regression line is the standard error.

FCV: flow-controlled ventilation, VCV: volume-controlled ventilation

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