

Calculation of Physiologic Dead Space: Comparison of Ventilator Volumetric Capnography to Measurements by Metabolic Analyzer and Volumetric CO₂ Monitor

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BACKGROUND: Calculation of physiologic dead space (dead space divided by tidal volume [V_D/V_T]) using the Enghoff modification of the Bohr equation requires measurement of the partial pressure of mean expired CO₂ (P_{ECO_2}) by exhaled gas collection and analysis, use of a metabolic analyzer, or use of a volumetric CO₂ monitor. The Dräger XL ventilator is equipped with integrated volumetric CO₂ monitoring and calculates minute CO₂ production (\dot{V}_{CO_2}). We calculated P_{ECO_2} and V_D/V_T from ventilator derived volumetric CO₂ measurements of \dot{V}_{CO_2} and compared them to metabolic analyzer and volumetric CO₂ monitor measurements. **METHODS:** A total of 67 measurements in 36 subjects recovering from acute lung injury or ARDS were compared. Thirty-one ventilator derived measurements were compared to measurements using 3 different metabolic analyzers, and 36 ventilator derived measurements were compared to measurements from a volumetric CO₂ monitor. **RESULTS:** There was a strong agreement between ventilator derived measurements and metabolic analyzer or volumetric CO₂ monitor measurements of P_{ECO_2} and V_D/V_T . The correlations, bias, and precision between the ventilator and metabolic analyzer measurements for P_{ECO_2} were $r = 0.97$, $r^2 = 0.93$ ($P < .001$), bias -1.04 mm Hg, and precision ± 1.47 mm Hg. For V_D/V_T the correlations were $r = 0.95$ and $r^2 = 0.91$ ($P < .001$), and the bias and precision were 0.02 ± 0.04 . The correlations between the ventilator and the volumetric CO₂ monitor for P_{ECO_2} were $r = 0.96$ and $r^2 = 0.92$ ($P < .001$), and the bias and precision were -0.19 ± 1.58 mm Hg. The correlations between the ventilator and the volumetric CO₂ monitor for V_D/V_T were $r = 0.97$ and $r^2 = 0.95$ ($P < .001$), and the bias and precision were 0.01 ± 0.03 . **CONCLUSIONS:** P_{ECO_2} , and therefore V_D/V_T , can be accurately calculated directly from the Dräger XL ventilator volumetric capnography measurements without use of a metabolic analyzer or volumetric CO₂ monitor. *Key words:* dead space fraction; metabolic analyzer; volumetric CO₂ monitor; ventilator; volumetric capnography; volumetric capnogram. [Respir Care 2013;58(7):1143–1151. © 2013 Daedalus Enterprises]

Introduction

Dead-space ventilation, the portion of a tidal volume that does not contribute to gas exchange, was first described and calculated by the Bohr equation in 1891,¹ and later by the Enghoff modification of the Bohr equation in

1938.² Physiologic dead-space fraction (dead space divided by tidal volume [V_D/V_T]), as defined by Bohr and Enghoff, is the sum of anatomic or airway dead space ($V_{D\text{-anat}}$) and alveolar dead space ($V_{D\text{-alv}}$) divided by the V_T . The definition of pure dead space is ventilation without perfusion, whereby alveolar gases do not contact blood flowing through the pulmonary capillaries. All conducting airways (anatomical and mechanical dead space), areas of

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pure shunt (pulmonary capillary perfusion with no ventilation), areas of pure dead space, and the presence of gas exchange units with any degree of inequality of ventilation in relation to perfusion, can contribute to the calculated dead-space ventilation.

Assessing V_D/V_T in critically ill patients during mechanical ventilation is important for several reasons.³ The prognostic value of V_D/V_T has been linked to mortality risk in ARDS⁴⁻⁷ and to other important clinical indices. V_D/V_T is known to correlate with the severity of lung injury,⁸⁻¹² can be useful as an indicator of lung recruitment versus overdistention in patients with acute lung injury (ALI) and ARDS,¹³⁻¹⁷ may be helpful as a predictor of successful extubation in pediatric¹⁸ and adult patients,¹⁹ and may be useful in diagnosing and assessing the severity of pulmonary embolism.^{20,21}

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Simplified bedside calculation of V_D/V_T requires a measurement of the partial pressure of mean expired CO_2 (P_{ECO_2}) and use of the Enghoff modification of the Bohr equation.² The Enghoff equation differs from the original Bohr equation by the substitution of P_{aCO_2} for the partial pressure of mixed alveolar CO_2 (P_{ACO_2}). The Enghoff equation became the standard in clinical practice for calculation of V_D/V_T because P_{ACO_2} has been difficult to accurately measure or estimate at the bedside. The traditional technique of measuring P_{ECO_2} used the Douglas bag method of exhaled gas collection and analysis.²² Technological advancements allow the use of a metabolic analyzer,^{23,24} and, more recently, use of volumetric capnography and a volumetric CO_2 monitor.²⁵

The Dräger XL ventilator (Dräger Medical, Telford, Pennsylvania) is equipped with integrated CO_2 and volume measurement capabilities (volumetric CO_2). We calculated P_{ECO_2} and V_D/V_T directly from the Dräger XL ventilator volumetric CO_2 measurements of \bar{V}_{CO_2} and compared them to metabolic analyzer and volumetric CO_2 monitor measurements of P_{ECO_2} and V_D/V_T .

Methods

A total of 67 measurements were performed in 36 subjects who met the American-European Consensus Conference criteria for ALI or ARDS.²⁶ Measurement were done at varying time periods after ALI or ARDS criteria were met (Table 1). Phase 1 of the study compared 31 ventilator derived measurements in 25 subjects to measurements from 3 different metabolic analyzers: Metascope (Cybermedic, Louisville, Colorado, $n = 9$), Deltatrac (SensorMedics, Yorba Linda, California, $n = 4$), and Vmax Encore (Via-

QUICK LOOK

Current knowledge

Measurement of the ratio of physiologic dead space (V_D) to tidal volume (V_T) with mixed expired carbon dioxide and blood gas analysis can be accomplished with various commercially available monitors. In acute respiratory distress syndrome, higher V_D/V_T is associated with higher mortality.

What this paper contributes to our knowledge

V_D/V_T was accurately measured by volumetric capnography on the Dräger XL ventilator, compared with 3 metabolic analyzers (Metascope, Deltatrac, and Vmax Encore) and the NICO monitor. Volumetric capnography on the Dräger XL ventilator obviates the use of a stand-alone analyzer for measuring V_D/V_T .

sys, Yorba Linda, California, $n = 18$). Use of the various metabolic analyzers was based on functional availability. All metabolic analyzers used were maintained by annual biomedical engineering preventive maintenance and performance verification. In phase 2 of the study, 36 ventilator derived measurements in 11 subjects were compared to the NICO₂ Respiratory Profile Monitor (Philips Healthcare, Andover, Massachusetts).

V_D/V_T measurements were performed when requested by the ICU team. Arterial blood gas samples for P_{aCO_2} determination and V_D/V_T calculation were obtained from arterial catheters. Prior to all measurements, ventilator, metabolic analyzer, and NICO₂ monitor CO_2 and flow sensors were calibrated using the manufacturers' specifications. Following all ventilator circuit disconnections, approximately 30 min was allowed for patient stabilization. Ventilator measurements were done simultaneously during metabolic analyzer and NICO₂ monitor measurements, for comparison. The ventilator circuit was checked for leaks, and patients with active pulmonary air leaks were excluded from the study. The study was approved by the Committee on Human Research at the University of California, San Francisco.

Ventilator Volumetric CO_2 Measurements

The Dräger XL ventilator's mainstream CO_2 sensor was placed between the ventilator circuit and the patient connection. The ventilator expiratory flow sensor positioned at the distal side of the expiratory valve measured exhaled V_T and exhaled minute ventilation (\dot{V}_E). Ventilator volumetric CO_2 measurements were initiated and displayed on

Table 1. Subject Characteristics

| | |
|-------------------------------|-----------------|
| Female/male | 8/28 |
| Age, mean \pm SD y | 49.4 \pm 14.5 |
| ALI/ARDS, mean \pm SD days* | 7.9 \pm 3.8 |
| ALI/ARDS etiology | |
| Pneumonia | 8 |
| Trauma | 17 |
| Burns | 3 |
| Sepsis | 5 |
| Pancreatitis | 3 |

* Number of days after ARDS protocol initiated and study data collected.
ALI = acute lung injury

the ventilator trend data screen. After measured values stabilized and reached a steady state, ventilator trend data for minute CO₂ production (\dot{V}_{CO_2}) and \dot{V}_E were averaged over 5 min. All measurements were reported at body temperature, and pressure, saturated (BTPS).

The fraction of exhaled CO₂ (F_{ECO_2}) was calculated manually by dividing the ventilator derived \dot{V}_{CO_2} by the \dot{V}_E :

$$F_{\text{ECO}_2} = \dot{V}_{\text{CO}_2} / \dot{V}_E \quad (1)$$

P_{ECO_2} was then calculated by multiplying F_{ECO_2} by the barometric pressure minus water vapor pressure:

$$P_{\text{ECO}_2} = F_{\text{ECO}_2} \times (760 - 47) \quad (2)$$

P_{ECO_2} was then used to calculate V_D/V_T by the Enghoff modification of the Bohr equation:

$$V_D/V_T = (P_{\text{aCO}_2} - P_{\text{ECO}_2}) / P_{\text{aCO}_2} \quad (3)$$

The automated ventilator correction for delivered and measured V_T was used by performing a circuit compliance test at device startup. The automated ventilator correction adjusts the delivered and measured V_T , and therefore the ventilator calculated values for \dot{V}_{CO_2} and \dot{V}_E reflect the adjusted values and eliminate the need for a manual circuit compression volume correction.

Metabolic Analyzer Measurements

The metabolic analyzers were warmed up for 20 min and calibrated per the manufacturers' recommendations. The inspired gases were sampled from the ventilator's inspiratory limb, and the exhaled gases and volumes were measured by directing expiratory gas flow into the metabolic analyzer (Metascope and Deltatrac) or by placement of the metabolic analyzer flow sensor and expired gas

sampling line at the ventilator expired gas outlet (Vmax Encore). After a stable 10-min measurement period, F_{ECO_2} averaged over a 5 min period from the metabolic analyzer was used to calculate P_{ECO_2} , using equation 2 above.

All metabolic analyzer measurements of P_{ECO_2} were corrected for circuit compression volume, as previously described,^{23-25,27-29} whereby the P_{ECO_2} was multiplied by the ratio of the observed V_T divided by the observed V_T minus the calculated compression volume using the following equations:

$$\text{Compression volume} = (\text{peak inspiratory pressure} - \text{PEEP}) \times \text{circuit compliance} \quad (4)$$

$$\text{Corrected } P_{\text{ECO}_2} = P_{\text{ECO}_2} \times (V_T / [V_T - \text{compression volume}]) \quad (5)$$

Ventilator circuit compliance factors of 2.5 and 2.0 mL/cm H₂O were used pre and post a ventilator circuit configuration change that was implemented during the study period. The circuit compliance factor of 2.5 mL/cm H₂O was used for the Metascope and Deltatrac, and 2.0 mL/cm H₂O was used for the Vmax Encore. Circuit compression volume was determined by laboratory testing and confirmed by the ventilator circuit compliance test mentioned above. V_T was derived by dividing the \dot{V}_E by the breathing frequency measured by the metabolic analyzer. The Dräger XL ventilator uses a non-bias-flow triggering method, and therefore additional correction for potential measurement error caused by bias flow was unnecessary.

NICO₂ Monitor Measurements

The NICO₂ monitor combined CO₂/flow sensor was allowed to warm up for 5 min until stable measurements for P_{ECO_2} were obtained. Both the NICO₂ combined sensor and the ventilator mainstream CO₂ sensor were placed between the ventilator circuit and the subject. The NICO₂ sensor and the ventilator CO₂ sensor were placed distal and proximal to each other in random order. In a previous bench study, the distal or proximal position of either sensor did not result in position related bias.³⁰ P_{ECO_2} derived from the ventilator measurements was rounded to the nearest whole number for comparison to the NICO₂ monitor display of P_{ECO_2} .

Since the NICO₂ combined CO₂/flow sensor measures distal to the ventilator Y-piece, the effects of ventilator circuit compression volume and the utilization of a correction factor are unnecessary.

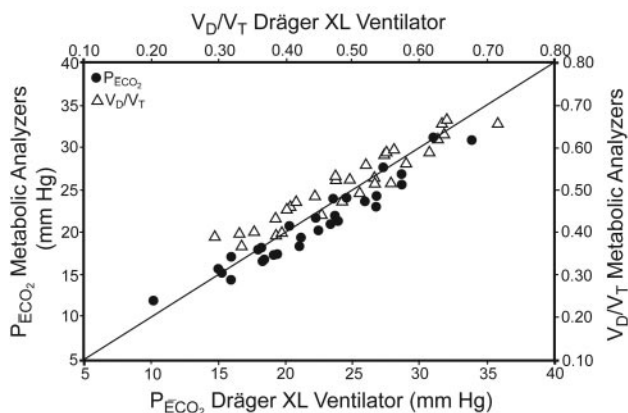


Fig. 1. Correlation of partial pressure of mean expired CO_2 (P_{ECO_2}) and ratio of dead space to tidal volume [V_D/V_T] between the Dräger XL ventilator and 3 different metabolic analyzers, plotted against the line of identity. For P_{ECO_2} , $r = 0.97$ and $r^2 = 0.93$ ($P < .001$). For V_D/V_T , $r = 0.95$ and $r^2 = 0.91$ ($P < .001$).

Statistical Analysis

The ventilator derived measurements of \dot{V}_{CO_2} , F_{ECO_2} , P_{ECO_2} , and V_D/V_T were compared to the metabolic analyzer measurements. The P_{ECO_2} and V_D/V_T derived from ventilator measurements were compared to the NICO₂ monitor measurements. The data were compared and analyzed by correlation measured by the Pearson product-moment correlation coefficient (r) and the coefficient of determination (r^2). Bias and precision were assessed by Bland-Altman analysis. Statistical analysis was done using commercially available software (Excel, 14.2.2, Microsoft, Redmond, Washington). Correlation results were considered to be significant when $P < .05$.

Results

There was a strong correlation, agreement, and accuracy between the ventilator derived measurements and the metabolic analyzer or volumetric CO_2 monitor measurements of \dot{V}_{CO_2} , F_{ECO_2} , P_{ECO_2} , and V_D/V_T .

In phase 1 of the study, the correlations between the ventilator derived measurements and the metabolic analyzer measurements for \dot{V}_{CO_2} and F_{ECO_2} were $r = 0.92$ and $r^2 = 0.85$ ($P < .001$), and $r = 0.95$ and $r^2 = 0.91$ ($P < .001$). The bias and precision for \dot{V}_{CO_2} and F_{ECO_2} were 24 ± 31 mL/min and $0.07 \pm 0.23\%$, respectively. The correlations for P_{ECO_2} were $r = 0.97$ and $r^2 = 0.93$ ($P < .001$) (Fig. 1), and the bias and precision were -1.04 ± 1.47 mm Hg (Fig. 2). The correlations for V_D/V_T were $r = 0.95$ and $r^2 = 0.91$ ($P < .001$) (see Fig. 1), and the bias and precision were 0.02 ± 0.04 (Fig. 3). The P value of 2 tailed probability for the Pearson correlation

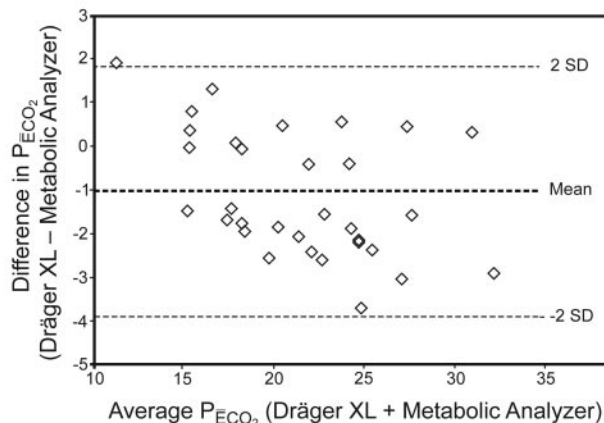


Fig. 2. Bland-Altman plot comparing partial pressure of mean expired CO_2 (P_{ECO_2}) calculated by measurements from the Dräger XL ventilator and 3 different metabolic analyzers. The bias and precision are -1.04 ± 1.47 mm Hg (95% CI -3.91 to 1.84 mm Hg).

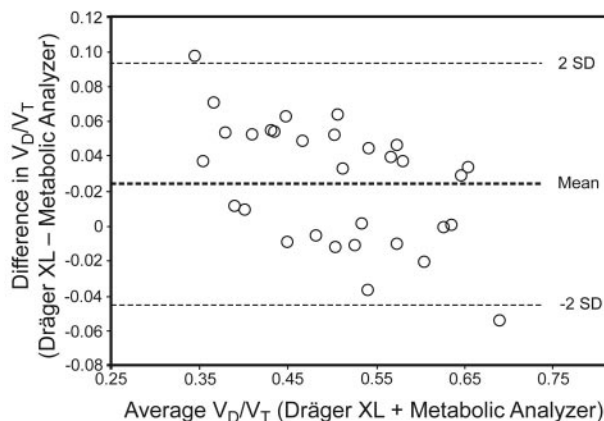


Fig. 3. Bland-Altman plot comparing the ratio of dead space to tidal volume [V_D/V_T], calculated by measurements from the Dräger XL ventilator and 3 different metabolic analyzers. The bias and precision are 0.02 ± 0.04 (95% CI -0.05 to 0.09).

coefficient reached statistical significance for each metabolic analyzer for both P_{ECO_2} and V_D/V_T , except for one where the sample size was very small (DeltaTrac, $n = 4$, V_D/V_T , $P = .09$). Similarly, bias and precision remained within clinically acceptable ranges when individual measurements between the 3 metabolic analyzers were compared to the combined data from all 3 analyzers (Table 2).

In phase 2 of the study, the correlations, between the ventilator and the volumetric CO_2 monitor measurements for P_{ECO_2} were $r = 0.96$ and $r^2 = 0.92$ ($P < .001$) (Fig. 4), and the bias and precision were -0.19 ± 1.58 mm Hg (Fig. 5), and for V_D/V_T the correlations were $r = 0.97$ and $r^2 = 0.95$ ($P < .001$) (see Fig. 4), and the bias and precision were 0.01 ± 0.03 (Fig. 6).

Table 2. Correlation, Bias, and Precision Between Individual Metabolic Analyzers, Compared to the Combined Data From All 3 Analyzers

| | Correlation Coefficient r | Coefficient of Determination r^2 | P | Bias | Precision |
|-------------------------------|--------------------------------|---------------------------------------|--------|-------|-----------|
| Combined data ($n = 31$) | | | | | |
| V_D/V_T | 0.95 | 0.91 | < .001 | 0.02 | 0.04 |
| P_{ECO_2} | 0.97 | 0.93 | < .001 | -1.04 | 1.47 |
| Metascope ($n = 9$) | | | | | |
| V_D/V_T | 0.98 | 0.96 | < .001 | 0.01 | 0.02 |
| P_{ECO_2} | 0.98 | 0.97 | < .001 | -1.39 | 0.91 |
| Deltatrac ($n = 4$) | | | | | |
| V_D/V_T | 0.91 | 0.82 | .09 | 0.01 | 0.03 |
| P_{ECO_2} | 0.96 | 0.93 | .04 | -0.84 | 1.69 |
| Vmax ($n = 18$) | | | | | |
| V_D/V_T | 0.97 | 0.94 | < .001 | 0.04 | 0.04 |
| P_{ECO_2} | 0.98 | 0.95 | < .001 | -1.50 | 1.49 |

V_D/V_T = ratio of dead space to tidal volume
 P_{ECO_2} = partial pressure of mean expired CO_2

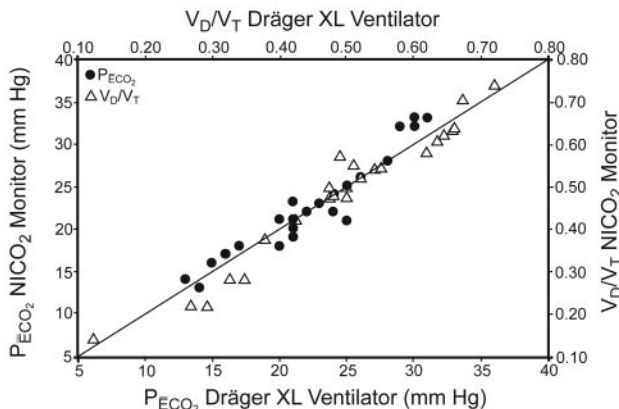


Fig. 4. Correlation of partial pressure of mean expired CO_2 (P_{ECO_2}) and ratio of dead space to tidal volume [V_D/V_T] between the Dräger XL ventilator and the NICO₂ volumetric CO_2 monitor, plotted against the line of identity. For P_{ECO_2} , $r = 0.96$ and $r^2 = 0.92$ ($P < .001$). For V_D/V_T , $r = 0.97$ and $r^2 = 0.95$ ($P < .001$).

Discussion

The results of this study confirm that P_{ECO_2} , and therefore V_D/V_T , using the Enghoff equation can be accurately calculated directly from the Dräger XL ventilator's volumetric capnography measurements, without use of a metabolic analyzer or volumetric CO_2 monitor. In a recent study, use of volumetric capnography calculations of V_D/V_T from the Dräger XL ventilator were shown to be a predic-

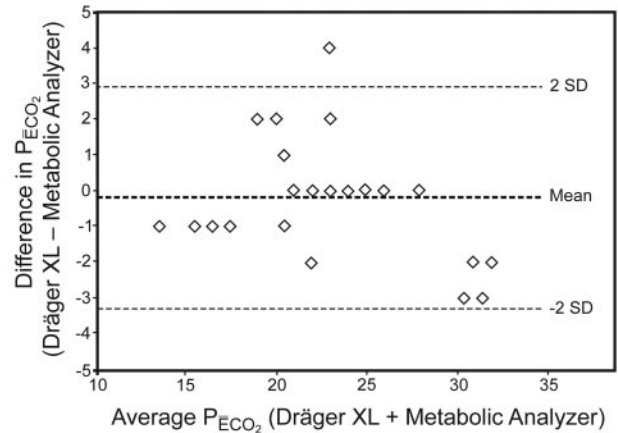


Fig. 5. Bland-Altman plot comparing partial pressure of mean expired CO_2 (P_{ECO_2}) calculated by measurements from the Dräger XL ventilator and the NICO₂ volumetric CO_2 monitor. The bias and precision are -0.19 ± 1.58 mm Hg (95% CI -3.30 to 2.91 mm Hg).

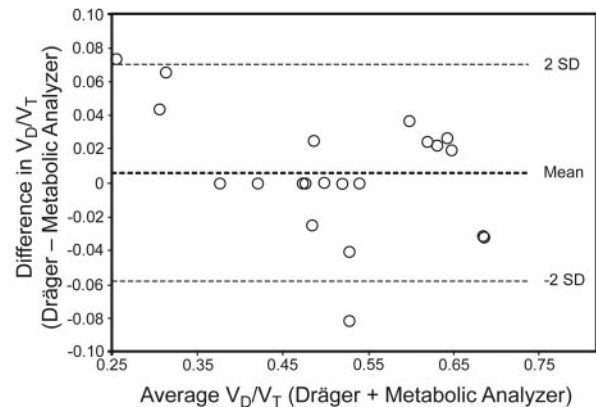


Fig. 6. Bland-Altman plot comparing the ratio of dead space to tidal volume [V_D/V_T] calculated by measurements from the Dräger XL ventilator and the NICO₂ volumetric CO_2 monitor. The bias and precision are 0.01 ± 0.03 (95% CI 0.01 – 0.03).

tor of extubation success.¹⁹ However, to our knowledge the results of our study are the first to validate the accuracy of the Dräger XL measurements of V_D/V_T against previously accepted methods.

These findings have several important implications. This simplified approach to V_D/V_T measurement will improve availability, allow early and repeated measurements, and will increase the utilization of V_D/V_T for prognostic, diagnostic, and disease severity monitoring in the critical care setting. V_D/V_T has been shown to be predictive of the mortality risk in patients with ARDS in both the early and intermediate phases of the disease progression in single center or small cohort studies.^{4–8} Patients with $V_D/V_T \geq 0.57$ were found to have higher mortality, with a 45% increase in the odds of dying for every 0.05 increase

Table 3. Correlation, Bias, and Precision From Studies That Compared Different Methods for Calculating the Ratio of Dead Space to Tidal Volume Using the Enghoff Equation

| | Correlation r | Bias | Precision | Study |
|---|------------------|-------|-----------|-------------------------|
| Metabolic analyzer vs Dräger XL | 0.95 | 0.02 | 0.04 | Present study |
| NICO ₂ monitor vs Dräger XL | 0.97 | 0.01 | 0.03 | Present study |
| Douglas bag vs metabolic analyzer | 0.92 | 0.01 | 0.03 | MacKinnon ²³ |
| Douglas bag vs metabolic analyzer | 0.99 | -0.02 | 0.01 | Lum ²⁴ |
| Metabolic analyzer vs NICO ₂ monitor | 0.94 | 0.02 | 0.05 | Kallet ²⁵ |

in dead-space fraction.⁵ V_D/V_T is also known to be a marker of the severity of lung injury.⁹⁻¹³ Serial monitoring of V_D/V_T over the duration and course of ALI/ARDS can be useful as a means to assess the need and effects of supportive therapeutic strategies and interventions.^{12,13} V_D/V_T measurements in patients with ALI/ARDS have been found to be useful for titrating PEEP and optimizing cardiopulmonary function,¹⁴⁻¹⁶ and may be useful as a tool to monitor lung recruitment versus overdistention.¹⁷ Assessment of V_D/V_T may also be used to predict successful extubation in pediatric¹⁸ and adult patients.¹⁹ $V_D/V_T \leq 0.50$ and ≥ 0.65 in infants and children were found to be predictive of extubation success or failure,¹⁸ whereas in adult patients the V_D/V_T cutoff value that offered the best sensitivity and specificity for predicting extubation failure was 0.58.¹⁹ V_D/V_T , in addition to other clinical assessments and diagnostic tests, has also been used in diagnosing and assessing the severity of pulmonary embolism.^{20,21} The culmination of the broad clinical value of V_D/V_T assessments in the critical care setting support the integration of this measurement into routine clinical practice.

Additionally, use of a separate standalone device for V_D/V_T measurements, with the associated acquisition and supply costs and staff utilization time, may become unnecessary. Elimination of a metabolic analyzer or volumetric CO₂ monitor simplifies the determination of V_D/V_T . Ventilator derived volumetric CO₂ measurement makes physiologic dead-space fraction more accessible in clinical practice, as ventilator manufacturers incorporate volumetric CO₂ monitoring capabilities into newer ventilator platforms.³¹ The calculations performed for this study were done manually, using ventilator derived measurements, but could easily be incorporated as an automated feature by ventilator software modification. Methods for estimating V_D/V_T by predictive equations have been described using the arterial to end-tidal CO₂ difference^{32,33} and estimation of \bar{V}_{CO_2} .³⁴ The increasing availability of volumetric capnography make the use of predictive equations unnecessary.

The results of this study are consistent with prior data that confirm the accuracy of different methods of calculating V_D/V_T (Table 3). Similar correlation and accuracy

of the exhaled gas collection method using a Douglas bag versus a metabolic analyzer,^{23,24} a metabolic analyzer versus a volumetric CO₂ monitor,²⁵ and ventilator based volumetric capnography versus a metabolic analyzer and a volumetric CO₂ monitor are now demonstrated.

Limitations of this study include a relatively small sample size in each study phase, and the use of 3 different metabolic analyzers in phase 1. Also, the ventilator circuit configuration, and therefore the circuit compression volume, were changed during the study. Despite these factors, the resiliency of the ventilator derived data in relation to the correlation, bias and precision between measurements remained consistent. Although the number of individual measurements between the 3 metabolic analyzers used varied markedly, the agreement of correlation, bias, and precision remained consistent between individual metabolic analyzers, when compared to the combined data from all 3 analyzers (see Table 2). Additionally, the change in ventilator circuit configuration and compression volume did not significantly alter the correlation and agreement of the measurements (see Table 2).

V_D/V_T calculated by the original Bohr equation has been recognized as “true dead space” or the balance between effective and ineffective ventilation. The Bohr dead-space equation relies on the calculation or estimation of P_{aCO_2} from mixed alveolar gas. P_{aCO_2} is affected by the dilution of CO₂ from the alveolar side of the alveolar-capillary membrane before the effects of shunt and venous admixture on P_{aCO_2} . Bohr dead space is affected by areas of high ventilation to perfusion matching, such as alveolar overdistention by excessive PEEP and/or V_T , pulmonary vascular occlusion, and pulmonary hypoperfusion secondary to hypovolemia.³⁵ The Enghoff equation, on the other hand, relies on the P_{aCO_2} of arterial blood and is thus an index of “true dead space” plus the effects of elevated P_{aCO_2} from global gas exchange inefficiency and shunt (Fig. 7). Elevated P_{aCO_2} can result from all causes of low ventilation/perfusion matching and shunt, such as atelectasis, pneumonia, COPD, and asthma. Furthermore, P_{aCO_2} can rise when an increase in metabolic rate and CO₂ production are not accompanied by an increase in CO₂ excretion. Changes

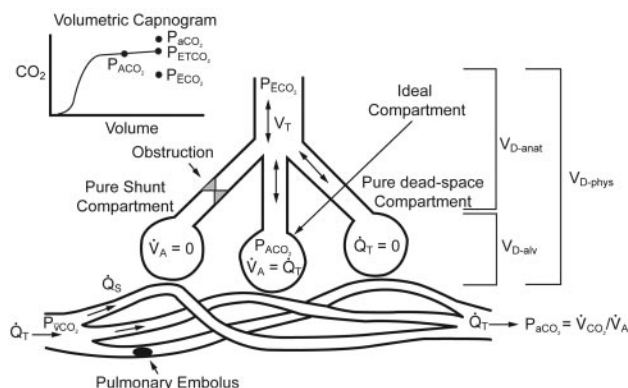


Fig. 7. The 3 compartment lung model described by Riley^{36,37} represents gas exchange in the lung in regards to the matching of alveolar ventilation (\dot{V}_A) and perfusion (\dot{Q}_T), shunt (\dot{Q}_S), and dead space (V_D). The ideal compartment represents areas of perfect \dot{V}_A to \dot{Q}_T matching. The pure shunt compartment represents areas of perfusion without ventilation. The pure dead-space compartment represents areas of ventilation with no perfusion. The sum of the regions of alveolar dead space (V_{D-alv}) and anatomic dead space (V_{D-anat}) equal the physiologic dead space (V_{D-phys}). Dead space fraction is equal to V_{D-phys} divided by tidal volume (V_T). Also shown are the partial pressure of arterial carbon dioxide (P_{aCO_2}), the partial pressure of venous carbon dioxide (P_{vCO_2}), the relationship between P_{aCO_2} and minute CO_2 production (\dot{V}_{CO_2}) and \dot{V}_A , the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}), the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}), and the partial pressure of mean expired carbon dioxide (P_{ECO_2}) in relation to the model and the volumetric capnogram. (From references 35 and 38, with permission.)

in P_{aCO_2} are determined by the relationship between \dot{V}_{CO_2} and minute alveolar ventilation (\dot{V}_A) whereby:

$$P_{aCO_2} = \dot{V}_{CO_2} / \dot{V}_A$$

If \dot{V}_{CO_2} increases without a proportional rise in \dot{V}_A , CO_2 production exceeds CO_2 excretion and P_{aCO_2} increases. Therefore the Enghoff dead-space equation can overestimate V_D/V_T in the presence of shunt and regions of low ventilation/perfusion ratio (Fig. 8).

Use of volumetric capnography to determine P_{ACO_2} for Bohr dead-space calculation has been demonstrated³⁹ and validated in an animal model of lung injury.⁴⁰ P_{ACO_2} measured at the mid-point of phase III of the expired volume capnogram was compared to the P_{ACO_2} mathematically derived using the multiple inert gas elimination technique (MIGET). There was a close linear correlation between the 2 methods for calculating P_{ACO_2} ($r = 0.99$, $P < .001$) and Bohr dead space ($r = 0.96$, $P < .001$). The mean P_{ACO_2} and Bohr dead space from volumetric capnography were similar to the calculations obtained by MIGET, with a mean bias of -0.10 mm Hg (95% CI -2.18 to 1.98 mm Hg) and 10 mL (95% CI -44 to 64 mL), respectively. Given

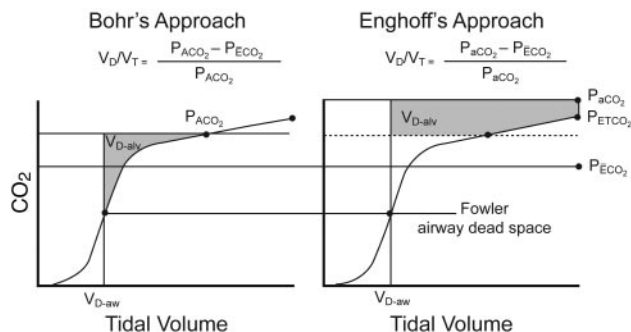


Fig. 8. Graphical representation of physiologic dead space fraction determined by volumetric capnography, using the approaches of Bohr and Enghoff, which shows how use of the Enghoff equation can overestimate alveolar dead space (V_{D-alv}) (shaded areas) by substitution of the partial pressure of arterial carbon dioxide (P_{aCO_2}) for the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}), determined by identifying the mid-point of phase III of the expired volumetric capnogram.^{39,40} Also shown are the airway or anatomical dead space (V_{D-aw}), determined by the Fowler method identified at the mid-point of phase II of the expired volumetric capnogram,⁴¹ the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}), and the partial pressure of mean expired carbon dioxide (P_{ECO_2}) in relation to the volumetric capnogram. (From reference 35, with permission.)

these findings, it has been suggested that simultaneous assessment of Bohr and Enghoff dead space using volumetric capnography may provide useful complementary information in regard to recognizing the effects of shunt and ventilation/perfusion inequality versus “true dead space” or wasted ventilation in critically ill patients with elevated V_D/V_T .³⁵ Furthermore, using volumetric capnography to determine Bohr dead space could be monitored continuously and would not require periodic arterial blood sampling to measure P_{aCO_2} .³⁵

Conclusions

This study confirms that P_{ECO_2} and V_D/V_T using the Enghoff equation can be accurately calculated directly from the Dräger XL ventilator's volumetric capnography measurements, without use of a metabolic analyzer or volumetric CO_2 monitor.

Future study of the use and development of ventilator based techniques for volumetric capnography measurements of V_D/V_T should continue to confirm and validate measurement correlation and accuracy. Investigation of the meaningful use of continuous Bohr V_D/V_T monitoring and simultaneous measurement of Bohr and Enghoff V_D/V_T using volumetric capnography should also be pursued.

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