A New Equal Area Method to Calculate and Represent Physiologic, Anatomical, and Alveolar Dead Spaces


**Background:** Physiologic dead space is usually estimated by the Bohr-Enghoff equation or the Fletcher method. Alveolar dead space is calculated as the difference between anatomical dead space estimated by the Fowler equal area method and physiologic dead space. This study introduces a graphical method that uses similar principles for measuring and displaying anatomical, physiologic, and alveolar dead spaces.

**Methods:** A new graphical equal area method for estimating physiologic dead space is derived. Physiologic dead spaces of 1,200 carbon dioxide expirograms obtained from 10 ventilated patients were calculated by the Bohr-Enghoff equation, the Fletcher area method, and the new graphical equal area method and were compared by Bland-Altman analysis. Dead space was varied by varying tidal volume, end-expiratory pressure, inspiratory-to-expiratory ratio, and inspiratory hold in each patient.

**Results:** The new graphical equal area method for calculating physiologic dead space is shown analytically to be identical to the Bohr-Enghoff calculation. The mean difference (limits of agreement) between the physiologic dead spaces calculated by the new equal area method and Bohr-Enghoff equation was −0.07 ml (−1.27 to 1.13 ml). The mean difference between new equal area method and the Fletcher area method was −0.09 ml (−1.52 to 1.34 ml).

**Conclusions:** The authors' equal area method for calculating, displaying, and visualizing physiologic dead space is easy to understand and yields the same results as the classic Bohr-Enghoff equation and Fletcher area method. All three dead spaces—physiologic, anatomical, and alveolar—together with their relations to expired volume, can be displayed conveniently on the x-axis of a carbon dioxide expirogram.

QUANTIFICATION of physiologic dead space (VDphys) provides important insight regarding the efficiency of ventilation and its relation to pulmonary perfusion. Respiratory dead space measurement has found wide applications in respiratory physiology, clinical anesthesia, and critical care medicine. It has been used in the diagnosis of pulmonary embolism and as a predictor of lung volume during controlled ventilation. A physiologic dead space to tidal volume ratio higher than 0.6 was associated with a 1.5-fold increase in mortality rate in infants with congenital diaphragmatic hernia. In a prospective study of adults with acute respiratory distress syndrome, patients who died showed a significantly higher mean dead space fraction compared with survivors (0.63 vs. 0.54, respectively; P < 0.05). Coss-Bu et al. found similar results in critically ill children with lung injury. Routine monitoring of dead space to tidal volume ratio in pediatric patients has been demonstrated to permit earlier extubation and to reduce unexpected extubation failures.

The lack of a simple, practical method for the calculation of dead space components simultaneously has hindered the clinical application of dead space measurement. The total respiratory dead space can be partitioned into two parts: the anatomical dead space (airway, serial, or Fowler dead space, VDana), and alveolar or parallel dead space (VDalv). Because alveolar dead space cannot be measured directly, it is commonly estimated by subtracting the anatomical dead space from the physiologic dead space.

Anatomical dead space is usually calculated by a simple equal area graphical method developed by Fowler. A graphical method for calculating and representing anatomical, physiologic, and alveolar dead space was reported by Fletcher et al., in which the dead spaces are represented by areas of trapezoids.

The calculation of alveolar and physiologic dead spaces by a graphical method similar to the Fowler equal area method and the representation of dead spaces on a linear scale would provide better physiologic insight and clinical representation than the Bohr-Enghoff or Fletcher methods, which are apparently unrelated to the Fowler method.

In this article, we propose a new method, similar to the Fowler equal area method, for calculating and representing physiologic space, and demonstrate its relation to the classic Bohr-Enghoff equation. Our method facilitates simple visual comparison of anatomical, alveolar, and physiologic dead spaces on a linear scale.

**Materials and Methods**

**Physiologic Dead Space**

Physiologic dead space is usually calculated by the Bohr equation, modified by Enghoff:

\[
VD_{physBE} = VT \left(1 - \frac{F_{\text{E}CO_2}}{F_{\text{CO}_2}}\right).
\]
Fig. 1. Expired carbon dioxide fractional concentration as a function of expired volume. Line rb is fitted to phase III of the carbon dioxide expirogram by a linear regression method. Line rb is perpendicular to the x-axis such that areas Aqnb and Anrm are equal. Line ik is perpendicular to the x-axis such that areas Aqjk and Aichj are equal. All the calculated dead spaces and dead space fractions are shown in the diagram. CO2 = carbon dioxide; Faco2 = arterial carbon dioxide fraction; FeCO2 = end-tidal carbon dioxide fraction; Vdalv = alveolar dead space; Vdpree = physiologic dead space; VT = tidal volume; VDanat = anatomical dead space.

where VDphysBE is physiologic dead space calculated by the Bohr-Enghoff equation, FeCO2 is mixed expired concentration of carbon dioxide, Faco2 is the carbon dioxide fraction of a gas in equilibrium with arterial blood, and VT is tidal volume. Arterial and mixed expired carbon dioxide partial pressures can also be used in this equation instead of Faco2 and FeCO2.

In our new equal area method, which is similar to that of Fowler, a vertical line ik intersects the expirogram at j such that areas Aqjk and Aichj are equal (fig. 1). Then,

\[ V_{\text{DphysEA}} = ok, \]

where VDphysEA is physiologic dead space calculated by the new equal area method and ok is the distance between the origin and the point k. VDphysEA may be shown to equal VDphysBE.

Equation 1 can be interpreted graphically as follows (fig. 1). The mean expired carbon dioxide fraction is given by

\[ \text{FeCO2} = \frac{A_{\text{ahd}}}{VT}, \]  

where Aahd is the area under the expirogram, which is the total expired carbon dioxide (VCO2). Substituting equation 2 into 1,

\[ V_{\text{DphysBE}} = VT \left( 1 - \frac{A_{\text{ahd}}}{\text{Faco2VT}} \right). \]  

However,

\[ A_{\text{ahd}} = A_{\text{qjk}} + A_{\text{phdk}} = A_{\text{ichj}} + A_{\text{phdk}} = A_{\text{icdk}}. \]  

Substituting equation 4 into 3 yields

\[ V_{\text{DphysBE}} = VT \left( 1 - \frac{A_{\text{icdk}}}{\text{Faco2VT}} \right). \]  

Area Aicdk can be expressed as

\[ A_{\text{icdk}} = \text{Faco2 kd} = \text{Faco2 (VT - ok)}. \]  

Substituting equation 6 into equation 5 and simplifying yields

\[ V_{\text{DphysBE}} = ok = V_{\text{DphysEA}}. \]  

It is thus demonstrated that the vertical line that makes area Aqjk equal to area Aichj intersects the x-axis at a point (k) that represents the physiologic dead space.

**Anatomical Dead Space**

In the Fowler equal area method (fig. 1), line mb is fitted to phase III of the expirogram and extrapolated to r. The vertical line rb intersects the expirogram and the x-axis at points n and b respectively, making areas Aorm and Aqnb equal. The point b on the expired volume axis is the anatomical dead space.

**Alveolar Dead Space**

In figure 1, the difference between physiologic dead space (ok) and anatomical dead space (ob) is bk, which therefore represents alveolar dead space, Vdalv. Hence anatomical, physiologic, and alveolar dead spaces are calculated by similar equal areas principles and displayed graphically on the same x-axis.

**Fletcher Graphical Method and Representation**

In the Fletcher method, \( V_{\text{DphysF}} \) is physiologic dead space, \( V_{\text{DphysF}} \) is anatomical dead space, and \( V_{\text{DalvF}} \) is alveolar dead space calculated as follows:

\[ V_{\text{DphysF}} = VT \left( \frac{Y + Z}{X + Y + Z} \right), \]  

\[ V_{\text{DalvF}} = VT \left( \frac{Z}{X + Y + Z} \right), \]  

\[ V_{\text{Dalvh}} = VT \left( \frac{Y}{X + Y + Z} \right), \]  

where X is the area of trapezoid rbdb, Y is the area of trapezoid scbr, Z is the area of rectangle asbo (fig. 1), and r indicates the Fletcher method. Equation 8 is analytically identical to the Bohr-Enghoff equation (equation 1), and equation 10 is analytically identical to the Fowler equal area method.

**Clinical Study**

After approval by the ethics committee of the Royal Prince Alfred Hospital (Sydney, NSW, Australia) and written informed consent by the patients, 10 patients (6 male and 4 female) with American Society of Anesthesi-
ologists physical status II or III who were undergoing lower limb vascular surgery were enrolled in this study. None of the patients had clinically significant lung disease. All patients received a radial artery cannula for clinical hemodynamic monitoring and blood gas sampling. Other routine monitoring included pulse oximetry, electrocardiography, pharyngeal temperature, and capnometry. Anesthesia was induced with 2 mg/kg propofol, 2 μg/kg fentanyl, and 0.8 mg/kg rocuronium intravenously, and a cuffed endotracheal tube was inserted. Anesthesia was maintained with inhalational isoflurane, rocuronium, and fentanyl, and the patients were mechanically ventilated (Cato anesthetic machine; Dräger, Lübeck, Germany). Blood pressure was maintained within 20% of baseline with a low-dose infusion of metaraminol (0–0.05 mg/min). The baseline respiratory parameters for ventilation were as follows: tidal volume, 10 ml/kg; respiratory frequency, 10 breaths/min; inspiratory-to-expiratory ratio, 1:1.7; end-inspiratory hold, 10%; end-expiratory pressure, 0 cm H2O; and inspired oxygen concentration, 35%.

The airway gas flow, carbon dioxide fraction, and airway pressure were measured by a NICO monitor (Novametrix Medical Systems Inc., Wallingford, CT). The airway configuration from patient to machine was as follows: endotracheal tube, flexible endotracheal connector, airway filter, mainstream infrared carbon dioxide analyzer, pneumotachograph, pressure monitor, sidestream oxygen analyzer, and Y piece of the anesthetic circuit. Partial pressure of carbon dioxide, oxygen, gas flow rate, and airway pressure signals in the airway were logged at a frequency of 300 Hz through a 12-bit analog-to-digital converter (DAQPad-1200; National Instruments Corporation, Austin, TX) and recorded by a computer running MATLAB (Mathworks, Natick, MA). Barometric pressure was measured using an electronic barometer (Vaisala PTB100A; Helsinki, Finland), which was calibrated at 20°C and 760 mmHg. The baseline respiratory parameters for ventilation were as follows: tidal volume, 10 ml/kg; respiratory frequency, 10 breaths/min; inspiratory-to-expiratory ratio, 1:1.7; end-inspiratory hold, 10%; end-expiratory pressure, 0 cm H2O; and inspired oxygen concentration, 35%.

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In each patient, the ventilation parameters, which were known to affect physiologic dead space, were adjusted one at a time from the baseline in random order to one of the following settings: tidal volume 80, 100, and 120% of baseline tidal volume; end-expiratory pressure 0, 5, and 10 cm H2O; inspiratory-to-expiratory ratio 1:1.7, 1:1, and 2:1; inspiratory hold 10, 30, and 50% of the inspiratory time. After 15 min at each setting, 10 carbon dioxide expirograms were recorded for analysis, and at the same time, arterial blood was drawn into a heparinized syringe (PICCO70; Radiometer) and stored in ice slush for blood gas analysis.

**Data Analysis**

\[ \text{FaCO}_2 = \frac{P_{\text{CO}_2}}{P_b - P_w}, \]

where \( P_b \) is barometric pressure, \( P_w \) is the saturated water vapor pressure at body temperature, and \( P_{\text{CO}_2} \) is arterial partial pressure of carbon dioxide corrected to the patient’s body temperature. Total expired carbon dioxide volume \( V_{\text{CO}_2} \) was calculated by integrating the expired carbon dioxide concentration with respect to expired volume. For each carbon dioxide expirogram, physiologic dead space was calculated by using the Bohr-Enghoff equation (equation 1), the new equal area method, and the Fletcher area method (equation 8). All methods were implemented without interpolating between data points. The points \( b \) and \( k \) were assigned by selecting the sampled data points that minimized the difference between the areas. The average and SD of each set of 10 dead spaces were calculated.

The bias and limits of agreement of the new equal area method compared with the Bohr-Enghoff equation and Fletcher methods were assessed by Bland and Altman analysis. The limits of agreement were defined as the mean difference ± 2 SD and describe the range that includes 95% of the differences between the two methods compared. All other results are reported as mean ± SD. \( P < 0.05 \) was considered to be statistically significant. All calculations were performed by software written in MATLAB.

**Results**

The ages of the patients were 67 ± 12 yr (range, 44–79 yr), the weights were 76.1 ± 9.2 kg (range, 51–90 kg), and the body mass indices were 26.6 ± 2.9 kg/m² (range, 23.6–30.4 kg/m²). A total of 120 sets of 10 expirograms were obtained from the 10 patients. Calculated \( V_{\text{Dunat}}, V_{\text{physBE}}, V_{\text{physF}}, \) and \( V_{\text{physEA}} \) were 197.7 ± 33.2, 313.6 ± 80.1, 313.6 ± 80.1, and 313.5 ± 80.1 ml, respectively. Intraindividual dead space measurements varied by −15.9 ± 5.1 to 18.4 ± 7.3% due to changes in tidal volume, by 0 to 6.7 ± 1.7% due to changes in end-expiratory pressure, by 0 to −9.7 ± 2.9% due to changes in inspiratory-to-expiratory ratio, and by 0 to −18.4 ± 6.9% due to changes in inspiratory hold. The mean intraindividual coefficient of variation of the 120 sets of 10 dead space measurements at each ventilation setting was 2.0% (range, 0.7–5.0%).

Bland-Altman analysis shows that the differences between \( V_{\text{physEA}} \) and \( V_{\text{physBE}} \) ranged from −1.65 to 0.79 ml (mean, −0.07 ml; limits of agreement, −1.27 to 1.13 ml; fig. 2A). Differences between \( V_{\text{physEA}} \) and

Anesthesiology, V 104, No 4, Apr 2006
VDphysF ranged from −2.08 to 1.19 ml (mean, 0.09 ml; limits of agreement, 1.52 to 1.34 ml; fig. 2B). The differences were all randomly distributed over the range of dead spaces, and the mean differences were not statistically significantly different from zero in either comparison. Pearson correlation analysis showed correlation coefficients of 0.999 (P < 0.05) between VDphysBE and VDphysEA and between VDphysF and VDphysEA. Analysis of variance showed that (VDphysBE − VDphysEA) and (VDphysF − VDphysEA) were not statistically different from zero (P > 0.05) over all ventilator settings (means, −0.07 and −0.09 ml; ranges, −0.25 to 0.11 and −0.30 to 0.15 ml, respectively).

Figure 3 shows typical carbon dioxide expirograms from four different patients with anatomical and physiologic dead spaces calculated by the Fowler equal area method and our new equal area method, respectively. The patients’ data and dead spaces are shown in table 1. The expirograms for patients A and D are at the extremes of the 10 patients studied.

**Discussion**

This study introduces a new equal area method for the calculation, representation, and visualization of physiologic dead space based on a principle similar to the Fowler equal area method. The new method is analytically identical to the Bohr-Enghoff equation and yields numerical results that do not differ significantly from those calculated directly by the Bohr-Enghoff equation.

Advantages of this new method include the following: (1) the graphical representation on a linear scale of the relations between all of the dead space volumes and fractions, including VDanat, VDalv, VDphys, VT, VDanat/VT, VDalv/VT, VDphys/VT, and VDalv/VTalv, which is especially helpful for the visualization of dead spaces during bedside monitoring of patients; (2) the use of a principle similar to that used in the Fowler equal area method, which makes the calculation of anatomical and physiologic dead spaces on the carbon dioxide expirogram consistent; (3) the use of a more straightforward method than the partitioning of areas on a carbon dioxide expirogram proposed by Fletcher et al.; (4) the equal area method is simpler than the classic Douglas bag method, an advantage it shares with other open-circuit methods, although all three methods require arterial blood sam-

![Fig. 2. Bland-Altman plots of the differences between physiologic dead space estimated by three methods. (A) The differences between physiologic dead space measured by the new equal area method (VDphysEA) and by the Bohr-Enghoff equation (VPphysBE) as a function of the mean of VDphysEA and VDphysBE. (B) The differences between VDphysEA and physiologic dead space measured by the Fletcher area method (VDphysF) as a function of the mean of VDphysEA and VDphysF.](image)

![Fig. 3. Examples of the calculation and displays of physiologic dead space in four different patients (A, B, C, and D) using our equal area method. The expirograms for patients A and D are at the extremes of the patients studied. The solid horizontal line represents the arterial carbon dioxide fraction (FacO2). The dotted vertical line intersects the x-axis at the anatomical dead space (VDanat) using the Fowler equal area method. The dashed vertical line intersects the x-axis at the physiologic dead space (VDphys) using our new equal area method. The horizontal distance between the dotted and dashed vertical lines represents alveolar or parallel dead space (VDalv). The solid vertical line intersects the x-axis at tidal volume (VT).](image)

<table>
<thead>
<tr>
<th>Table 1. Patient Data and Dead Space Volumes in Figure 3</th>
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<tbody>
<tr>
<td><strong>Subjects</strong></td>
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BMI = body mass index; VDalv = alveolar dead space; VDanat = anatomical dead space; VDphysEA = physiologic dead space measured by the equal area method; VT = tidal volume.
pling. In addition, this new equal area method emphasizes the relations that exist between the various respiratory dead spaces and thus will greatly assist in understanding and teaching of their concepts. Once synchronized flow and carbon dioxide signals are digitized, the new method requires a few lines of code more than the open-circuit Bohr-Enghoff method, but it is not difficult to implement. With the advance of computing technology, the calculation and visualization of the dead spaces can be easily implemented for clinical application.

Theoretically, the physiologic dead space obtained by the three methods, our new equal area method, the classic Bohr-Enghoff equation, and the Fletcher method, should be identical. The small differences are due to quantization of the data in time by the analog-to-digital converter and the fact that our software did not interpolate between data points when locating the division between the equal areas. The differences between the results due to quantization would be bigger if the analog-to-digital sample rate were lower and smaller if the sample rate were higher, but could be eliminated almost completely if the software interpolated between data points when determining the equal areas.

This new equal area method for calculating physiologic dead space has been evaluated in patients without severe lung diseases. It should be noted that the difference between physiologic dead space calculated by our new equal area method and the Bohr-Enghoff equation method is not affected by the alteration of phase II of a carbon dioxide expirogram and is thus independent of changes in the carbon dioxide expirogram caused by lung diseases. Compared with the Bohr-Enghoff equation method, this new method has similar sensitivity to measurement signal noise and the synchronization of carbon dioxide and flow data, which could affect the accuracy of dead space measurement.19 The delay between carbon dioxide analyzer and flow signals and the rise time of the carbon dioxide analyzer, especially in sidestream carbon oxide analyzers, should be corrected to reduce error.19

In conclusion, this new equal area method for calculating, displaying, and visualizing physiologic dead space is easy to understand and yields the same results as the classic Bohr-Enghoff equation. All the three dead spaces—physiologic, anatomical, and alveolar—together with their relations to expired volume, can be displayed conveniently on the x-axis of a carbon dioxide expirogram to demonstrate their values and relations.

References

Anesthesiology, V 104, No 4, Apr 2006

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