Monitoring Exhaled Carbon Dioxide

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In the past few decades, assessment of exhaled CO$_2$ in both intubated and non-intubated patients has evolved into an essential component in many aspects of patient monitoring. Besides the basic assessment of ventilation, exhaled CO$_2$ monitoring can provide valuable patient safety information and critical physiologic data in regard to the ventilation and perfusion matching in the lungs, cardiac output, and metabolic rate. Despite these important clinical monitoring benefits and widespread availability, exhaled CO$_2$ monitoring is often underutilized. The purpose of this paper is to review the importance and present the extensive body of knowledge to support the use of exhaled CO$_2$ monitoring in various areas of clinical practice. Advanced application concepts and the future development of exhaled CO$_2$ monitoring will also be discussed. *Key words: end-tidal CO$_2$; capnometry; capnography; capnogram; volumetric capnography; physiologic dead space; resting energy expenditure.* [Respir Care 2016;61(10):1397–1416. © 2016 Daedalus Enterprises]

Introduction

The measurement of CO_2 in air was first developed around 1918 and performed to analyze gas concentrations in mines.[1] This process of analysis was painstakingly tedious, using an intricate apparatus that involved measuring quantities of CO_2 and other gases that were chemically absorbed from a known gas volume. The volume of absorbed CO_2 was then compared with the total gas volume, which yielded the fraction or percentage of CO_2 present. A decade later, a technique was developed to analyze exhaled CO_2 from a single breath during vigorous exercise.[2] This process entailed capturing exhaled gas using a system the size of a telephone booth consisting of a series of electro-mechanically controlled valves, which directed sequential portions of expired air into 6 small rubber bags. The collected CO_2 in each bag was then analyzed multiple times to yield the average CO_2, which was plotted over time, thus resulting in the first exhaled capnogram. By the 1970s, exhaled CO_2 was monitored in ICUs using mass spectrometry systems that aspirated exhaled gas through long lengths of capillary tubing to a central monitoring location.[3,4] Periodic measurements of the partial pressure of end-tidal CO_2 (P_{ETCO_2}) occurred on a timed schedule or in a sequential loop as the sampling cycle rotated between a number of monitored beds.[4] With the introduction of the smaller infrared sensor, portable exhaled CO_2 monitors came to the bedside in the 1980s.[5] Miniature CO_2 monitors that can fit into the palm of the hand and are capable of displaying an exhaled CO_2 capnogram are currently available.[6,7]

The technological advancement of exhaled CO_2 monitoring has coincided with the progression of use and importance in clinical practice. The significance of exhaled CO_2 monitoring extends well beyond the very basic utilization of monitoring the adequacy of ventilation. Detection of exhaled CO_2 has proven to be an invaluable mechanism for confirming tracheal intubation, recognizing accidental esophageal intubations, and other critical patient safety benefits. The patient protection enhancements provided by CO_2 monitoring also include: the detection of invasive airway disconnection, dislodgement, or obstruc-

tion and monitoring for respiratory depression postoperatively, during procedural sedation, and during patient-controlled analgesia. Of critical significance is the use of P_{ETCO_2} to gauge the effectiveness of cardiopulmonary resuscitation (CPR), to predict outcome, and to guide the continuation of resuscitation efforts.[8] Exhaled CO_2 can also be described as the vital sign for ventilation and perfusion because the volume of CO_2 excreted by the cardio-respiratory system is a sensitive indicator not only of ventilation efficiency but also of pulmonary perfusion and cardiac output. The volume of exhaled CO_2 per minute ($\dot{V}_{CO_2}$) can also be used to estimate the metabolic rate and nutritional requirements of the critically ill patient.[9]

The recognition and importance of monitoring exhaled CO_2 in many areas of patient care has led to the expanding recommendation for its use by regulatory agencies and inclusion in the standards and practice guidelines of many professional organizations, such as the American Society for Anesthesia (ASA), the American Heart Association, the American Association for Respiratory Care, the Joint Commission, and the Centers for Medicare and Medicaid Services. Despite this heightened level of awareness and the regulatory and organizational guidance, exhaled CO_2 monitoring is often underutilized.[8,10-16]

The reasons for this disparity between knowledge and practice may be due in part to the cost burden of acquiring the technology; the clinician time required for set-up, maintenance, and troubleshooting; and the lack of awareness of best practices for optimal utilization. Universally accepted standards of care mandating the use of CO_2 monitoring in specific circumstances or patient categories yielding the highest potential to impact patient safety and influence outcomes are also lacking.

The purpose of this review is to increase the awareness and understanding of health-care providers of the importance of exhaled CO_2 monitoring and its application in clinical practice. An appraisal of the different technologies will be followed by a review of the recognized indications for monitoring and an assessment of the potential for further advancements in exhaled CO_2 monitoring.

Classification and Types of Exhaled CO_2 Monitoring

Understanding available technologies and how they functions can provide important insights into their appropriate application, potential limitations, and problems associated with use. The following is a brief review of the classification and types of exhaled CO_2 monitoring commonly utilized.

Colorimetric CO_2 Detectors

Colorimetric CO_2 detectors provide continuous qualitative and semi-quantitative exhaled CO_2 monitoring. Col-

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orimetric CO_2 detectors are the simplest form of CO_2 monitors. They are portable, disposable, inexpensive, single-use devices that can rapidly detect and confirm tracheal intubation and estimate the amount of CO_2 in exhaled gas. Colorimetric detectors contain chemically treated material that is pH-sensitive and colorimetrically reflects CO_2 concentrations in expired gas.[17] Limitations of colorimetric CO_2 detectors include false positive readings when the detection medium is contaminated with gastric acid or acidic solutions instilled through an endotracheal tube.[17,18]

Mainstream CO_2 Monitoring

Mainstream CO_2 monitoring devices utilize a small infrared sensor consisting of a sample cell or cuvette and an infrared optical bench placed within the gas flow pathway at the airway. This measurement location results in real-time CO_2 values within the airway and a real-time graphical representation of the CO_2 waveform plotted over time or by the exhaled volume. Disadvantages of mainstream CO_2 monitoring include: cost of the sensor; potential for damage to the sensor and connecting cable during handling and patient monitoring; increased circuit mechanical dead space; potential for fouling with coughed up secretions and circuit condensate; and the additional weight of the sensor, airway adapter, and cable at the patient's airway connection. Also, many mainstream devices are limited to use with intubated patients only.[19]

Sidestream CO_2 Monitoring

Sidestream CO_2 monitoring devices aspirate a gas sample from a ventilator breathing circuit or other patient interface device through a length of small-bore tubing. Different interface designs for use on non-intubated patients incorporate nasal and oral sampling points to improve measurement accuracy. Several interface designs include the ability to simultaneously administer oxygen through a split channel device. Sidestream sampling devices utilize an infrared CO_2 sensor in a monitor located away from the patient and can only be displayed in a time-based waveform. Time-based sidestream CO_2 monitoring is the type more commonly used in the operating room setting, during non-intubated patient monitoring, and during CPR.

The sidestream sample method often requires use of a water trap and or specialized tubing that removes water vapor before analysis to prevent blockage and contamination of the sample tubing. Sample analysis located away from the patient results in a time delay often several seconds in duration before measured results are displayed. Since sidestream sampling requires a continuous aspirated sample flow rate from the ventilator circuit, interference with the measurement of ventilation parameters and the
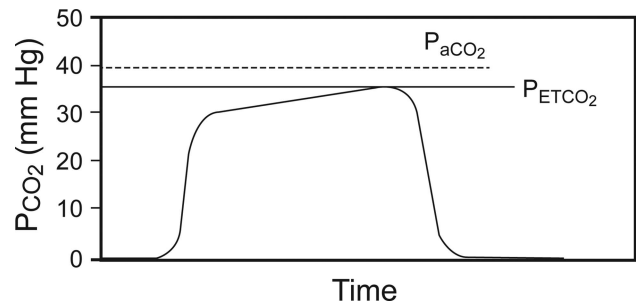

Fig. 1. Normal time-based capnogram showing the difference between the P_{aCO_2} and partial pressure of end tidal CO_2 (P_{ETCO_2}), which is normally 2–5 mm Hg.

triggering mechanism can occur. Also, when sidestream systems are used intra-operatively with inhaled anesthetic agents, a scavenging system is required to prevent ambient contamination and health-care provider exposures.[19]

Capnometry Versus Capnography

Capnometry is performed by a capnometer. A capnometer is a monitor that measures CO_2 concentrations in respired gases over time and displays numeric values for P_{ETCO_2}, respiratory frequency, and sometimes the inspired CO_2 concentration or partial pressure. Capnometers can be either mainstream or sidestream in design.[20,21]

The terms capnometry and capnography are often used synonymously, but in contrast to capnometry, capnography is performed by a capnograph, a monitor that is functionally the same as a capnometer but incorporates the additional feature of displaying the CO_2 waveform known as a capnogram (Fig. 1). Capnographs can also be mainstream or sidestream in design. The additional clinical monitoring value of capnography is the ability to visually interpret the waveform and morphology of the capnogram. The value of viewing the capnogram is synonymous with the revelation of knowing the heart rate and seeing the electrocardiogram. Interpretation of the different phases; the shape, area, and slope of the capnogram segments; and integration of the exhaled capnogram to exhaled tidal volume reveal clinically valuable information regarding ventilation and perfusion and cardiopulmonary physiology.[20,21]

Indications for Exhaled CO_2 Monitoring

Exhaled CO_2 monitoring is essential and useful in clinical practice for an array of monitoring indications, including ventilation, circulation, metabolism, improving patient safety, and influencing and predicting outcomes of care. Following is a review of the indications for exhaled CO_2 monitoring for in- and out-of-hospital monitoring of intubated and non-intubated adult and pediatric patients.

Monitoring Adequacy of Ventilation

Continuous monitoring of exhaled CO_2 from the onset of intubation to extubation, whether by capnometry or capnography, is an accepted method to ensure adequate ventilation during mechanical ventilation in both adult and pediatric patients.[14,22] CO_2 monitoring in non-intubated adult,[13,23,24] neonatal, and pediatric patients[25-27] can also be effective. As a reflection of this potential benefit, the ASA has identified CO_2 monitoring as a standard of care in anesthesia monitoring since 1986.[28] In healthy patients during mechanical ventilation, P_{ETCO_2} closely approximates P_{aCO_2} and is usually 2–5 mm Hg lower[29-31] and therefore can be an effective index of the adequacy of ventilation (see Fig. 1).

However, it should be well understood by all clinicians that in diseased states, such as ARDS, COPD, and asthma, ventilation/perfusion ($\dot{V}/\dot{Q}$) mismatch in the lungs can cause the $P_{aCO_2} - P_{ETCO_2}$ difference to increase. An increased $P_{aCO_2} - P_{ETCO_2}$ difference can occur to varying degrees with increased physiologic dead space, shunt perfusion, low cardiac output, and conditions of low $\dot{V}/\dot{Q}$.

It has been suggested that the lack of agreement with P_{aCO_2} in diseased lungs has negatively impacted the perception of value and the use of CO_2 monitoring.[8] Contrary to this misinterpretation, when a large $P_{aCO_2} - P_{ETCO_2}$ difference exists, P_{ETCO_2} can be an effective means of trending changes in P_{aCO_2} and the efficiency of ventilation and changes in the physiologic dead space fraction (V_D/V_T).[32] It is therefore important to recognize that the $P_{aCO_2} - P_{ETCO_2}$ difference can be an indication of the degree of lung injury and correlates with increased V_D/V_T.[5,32,33]

Furthermore, intra-operative monitoring of the $P_{aCO_2} - P_{ETCO_2}$ difference has been shown to predict mortality in trauma patients. Patients with a $P_{aCO_2} - P_{ETCO_2}$ difference >8–10 mm Hg had higher mortality rates both intra-operatively[34-37] and following emergent surgeries.[34,37]

Other sometimes overlooked benefits of monitoring the $P_{aCO_2} - P_{ETCO_2}$ difference to assess the adequacy of ventilation include: the reduction of arterial blood gas utilization,[38] which impacts unnecessary blood loss and costs; the identification and prevention of excessive ventilation and hyperventilation in neurotrauma patients[39-43]; and the affect that visual interpretation of the capnogram has had on enhancing monitoring during mechanical ventilation and airway management.[44]

Confirmation of Endotracheal Intubation

Perhaps one of the most significant impacts of exhaled CO_2 monitoring is in its use as a definitive method for confirming endotracheal intubation and the reduction in harm associated with identifying the serious consequences of accidental esophageal intubation, death and anoxic brain injury. Use of a CO_2 monitor in addition to direct visualization of the endotracheal tube passing through the vocal cords represent the accepted standards in clinical practice for confirming intubation in adult, pediatric, and neonatal patients.[45-49]

Capnography and capnometry compared with auscultation have been shown to be the most reliable methods to confirm endotracheal tube placement in the prehospital emergency setting.[50] Several studies have demonstrated that when continuous P_{ETCO_2} monitoring is used, the sensitivity (true positive rate) and specificity (true negative rate) for confirming endotracheal intubation are both 100%.[50-52] Colorimetric detectors were also found to be highly sensitive (88–98%) and 100% specific in confirming proper endotracheal intubation[17,18] and useful in guiding and predicting successful resuscitation in non-cardiac arrest patients.[17,18,53] Rates of unrecognized misplaced endotracheal tubes in out-of-hospital arrests as high as 23% have been reported when continuous P_{ETCO_2} monitoring was not used.[52]

Recognition of these important facts by the ASA,[28,54] the American Association for Respiratory Care,[55] the American Heart Association,[56,57] Emergency Medical Services systems,[42,58] the Intensive Care Society in the United Kingdom,[42] the Royal College of Anesthetists, and the Association of Anesthetists of Great Britain and Ireland,[16] has resulted in the inclusion of the use of CO_2 monitoring during intubations in their respective standards of practice, clinical practice guidelines, and practice recommendations. This compelling body of evidence mandates the use of CO_2 monitoring during intubation as a universal standard of care for confirming endotracheal intubation.[11] Nevertheless, It should be well understood that during cardiac arrest, the accuracy for confirming proper endotracheal intubation using CO_2 monitoring is diminished due the absence of cardiac output, pulmonary blood flow, and therefore exhaled CO_2.[17,18,50] In this situation, the absence of exhaled CO_2 using any CO_2 monitoring device may be mistakenly interpreted as an esophageal intubation.

Monitoring Respiratory Status

The use of exhaled CO_2 to monitor respiratory status is another area of growing significance and interest. Exhaled CO_2 offers an accurate and reliable means of measuring respiratory frequency. An elevated respiratory frequency is a sensitive and reasonably specific marker of respiratory dysfunction.[59] A low respiratory frequency is an indicator of respiratory depression from opioid analgesia and can be detected early by exhaled CO_2 monitoring.[60]

Opioid-induced respiratory depression in the post-anesthesia care period is a major concern emphasized by ASA-mandated standards,[28] the Joint Commission Sentinel Event Alerts,[61] and the Centers for Medicare and Medicaid Ser-

Table 1. Characteristics of Bradypneic (Type 1) and Hypopneic (Type 2) Hypoventilation[70]

Hypoventilation Classification	Respiratory Frequency	Tidal Volume	Anatomic Dead Space	V_D/V_T	P_{ETCO_2}	P_{aCO_2}
Type 1 (bradypneic)	– – –	–	No change	Minimal change	+	+
Type 2 (hypopneic)	–	– – –	No change	+ + +	− or no change	+

V_D = dead space volume
V_T = tidal volume
P_{ETCO_2} = end-tidal CO_2
− = decrease
+ = increase

vices Regulations and Interpretive Guidelines for Hospitals.[62] Because oxygenation and ventilation are separate physiologic processes, pulse oximetry monitoring of oxygenation alone should not be considered a suitable monitor of ventilatory function.[61-64] Oxygen saturation is frequently maintained, even at a low breathing frequency, and pulse oximetry alone often fails to detect respiratory depression, hypoventilation, and apnea episodes primarily when the patient is receiving supplemental oxygen.[65] Therefore, the application of exhaled CO_2 monitoring in the post-anesthesia setting, during procedural sedation, and when administering opiate analgesia can provide an important early warning of ventilatory compromise in adult and pediatric patients.[65–69]

A significant limitation to consider while using P_{ETCO_2} monitoring to detect respiratory depression is that there are 2 different types of drug-induced hypoventilation (Table 1). Type 1 or bradypneic hypoventilation is characterized by a decreased respiratory frequency, a slightly decreased tidal volume, and an increased P_{ETCO_2} and P_{aCO_2}. Type 2 or hypopneic hypoventilation, on the other hand, is characterized by a significant decrease in tidal volume, slightly decreased respiratory frequency, and a decreased or normal P_{ETCO_2}, whereas the P_{aCO_2} can be elevated.[70]

During hypopneic hypoventilation, the shallow breathing and smaller tidal volumes in proportion to the anatomical dead space cause decreased alveolar ventilation, increased dead space ventilation, increased P_{aCO_2}, and an increased $P_{aCO_2} - P_{ETCO_2}$ difference. This significant distinction between bradypneic and hypopneic hypoventilation is critical for clinicians to acknowledge and comprehend. Low or normal P_{ETCO_2} during hypopneic hypoventilation can be accompanied by significant respiratory depression and a markedly elevated P_{aCO_2}, which may go unrecognized if patient monitoring focuses on the value of P_{ETCO_2}.

Another area of concern is the growing evidence that the use of patient-controlled analgesia (PCA) imposes significant risks to patients and potential liability exposure to health-care providers and hospitals. This is again reflected in position statements and guidelines from the ASA,[71,72] the Centers for Medicare and Medicaid Services,[62] the Joint Commission,[73] the Anesthesia Patient Safety Foundation,[74,75] and the Institute for Safe Medication Practices,[64] which recommend continuous P_{ETCO_2} monitoring to guard against opioid-induced respiratory depression during PCA use. Of particular concern driving these recommendations are well-documented cases of "PCA by proxy" in which a family member or health-care provider, and not the patient, administers PCA doses. This has led to serious and fatal outcomes considered possibly preventable if P_{ETCO_2} monitoring were being used.[73,76-78]

Furthermore, the value of CO_2 monitoring during procedural sedation[8,26,28,71,79,80] and in the emergency department as an early indication of respiratory depression, especially when patients are receiving oxygen,[65,81,82] to aid in the identification of the severity of illness and to improve patient safety[13,70,83-85] is also increasingly being mandated for adult and pediatric patients.

Monitoring During CPR

It has been well substantiated that exhaled CO_2 monitoring during CPR provides invaluable information regarding the correct placement of an advanced airway,[28,50,52,56,57,86] the effectiveness of cardiac compressions,[56,86-88] the return of spontaneous circulation,[56,86,87,89,90] and the prediction of outcome and survival during cardiac arrest.[86,87,91]

The value of exhaled CO_2 monitoring as a guide to the effectiveness of cardiac compressions was first demonstrated in 1978 from a series of 3 patients during CPR.[91] Subsequent animal studies demonstrated that P_{ETCO_2} correlated with cardiac output and the adequacy of CPR and was useful as a guide to successful CPR and predicted the return of spontaneous circulation.[92-95] These findings were confirmed in 4 studies of human subjects, which indicated that when P_{ETCO_2} was <10 mm Hg during CPR, patients did not survive[96-99] (Fig. 2).

These data provide evidence to support a P_{ETCO_2} threshold target value >10 mm Hg during CPR. Additional investigations also demonstrated that changes in P_{ETCO_2} during resuscitation attempts predicted outcomes and return of spontaneous circulation,[89,100] suggesting that P_{ETCO_2} could be useful in deciding when to terminate resuscitation efforts in adult and pediatric patients.[101] When the value of

P_{ETCO_2} at 20 min after the initiation of CPR was used as a screening test to predict return of spontaneous circulation, a threshold value of 14 mm Hg or less had a sensitivity, specificity, positive predictive value (accuracy of positive results), and negative predictive value (accuracy of negative results) of 100%.[100]

P_{ETCO_2} monitoring during CPR can be an effective tool to detect the effectiveness of external cardiac compression and the development of rescuer fatigue. Additionally, a sudden increase in continuously monitored P_{ETCO_2} during high quality CPR was associated with the return of spontaneous circulation[89] (Fig. 3).

This evidence supports the use of P_{ETCO_2} monitoring during CPR in both in- and out-of-hospital resuscitations. The use of quantitative waveform capnography interpretation has been incorporated into advanced cardiac life support training to confirm advance airway placement and

to monitor resuscitation effectiveness since 2010.[56] The union between evidence for clinical practice and technology has resulted in the availability of exhaled CO_2 monitoring as a feature incorporated into new state-of-the-art defibrillators and transport monitors.

Volumetric Capnography

Volumetric capnography differs from standard capnography in that exhaled CO_2 is plotted against the exhaled tidal volume. Analysis of the phases of the volumetric capnogram, the shape and curve morphology, and measurements based on calculations from the volumetric capnogram can reveal important information in regard to the efficiency of ventilation and perfusion, the physiologic dead space fraction, and the metabolic rate of the patient.[102]

Phases of the Volumetric Capnogram

The 3 phases of the volumetric capnogram are synonymous with the phases of the time-based capnogram. Phase 1 characterizes emptying of the anatomic dead space (the conducting airways), where exhaled CO_2 is near zero. Phase 2 represents a mixture of gas from the anatomic dead space and alveolar gas containing CO_2. Phase 3 signifies emptying of alveolar air spaces (also known as the alveolar plateau), the end point of which is equal to the end-tidal CO_2 (Fig. 4). An increase in slope of the rise of phase 3 signifies an increase in the number alveolar gas exchange units with varying degrees of $\dot{V}/\dot{Q}$ mismatch, such as during airway obstruction and elevated alveolar dead space.[102]

Fowler Dead Space

Using the principles described by Fowler,[103] the anatomical dead space volume can be identified and measured

Fig. 2. Mean end tidal carbon dioxide (P_{ETCO_2}) differences between survivors and non-survivors after 20 min of advanced cardiac life support during out-of-hospital cardiac arrest. Subjects with P_{ETCO_2} levels of ≤10 mm Hg died before reaching the hospital. Data from Reference 98.
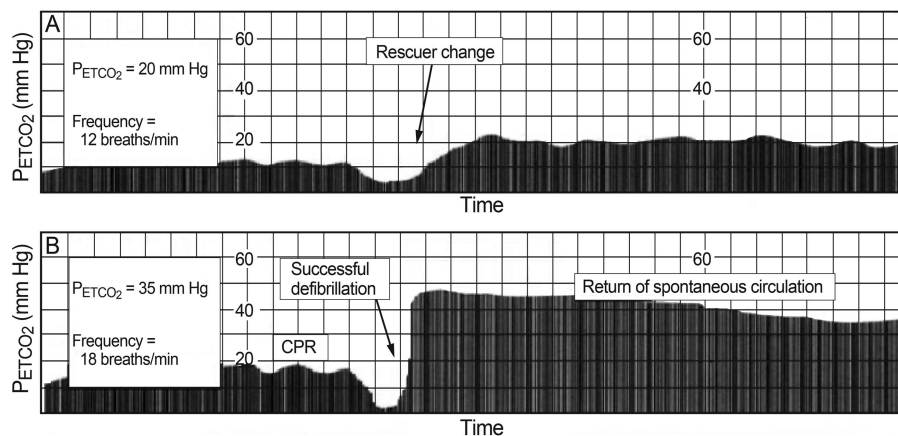
Fig. 3. Time-compressed capnograms of end-tidal carbon dioxide (P_{ETCO_2}) during cardiopulmonary resuscitation (CPR), showing ineffective cardiac compressions or rescuer fatigue (A) and return of spontaneous circulation (B). Courtesy Philips Healthcare.
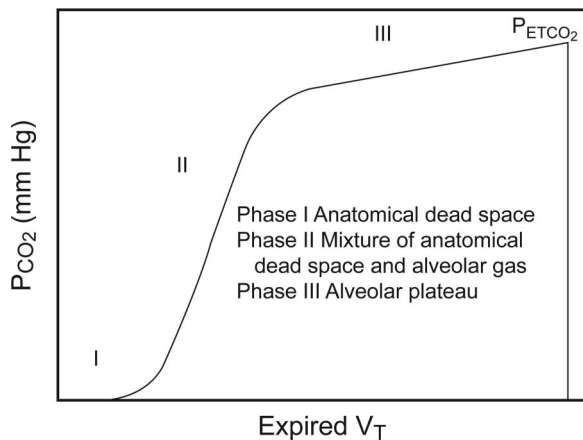
Fig. 4. The 3 phases of the exhaled CO_2 volumetric capnogram indicate the different stages of airway and alveolar gas emptying and terminate at the end-tidal carbon dioxide (P_{ETCO_2}). Phase I = anatomical dead space. Phase II = mixture of anatomical dead space and alveolar gas. Phase III = alveolar plateau. From Reference 102.
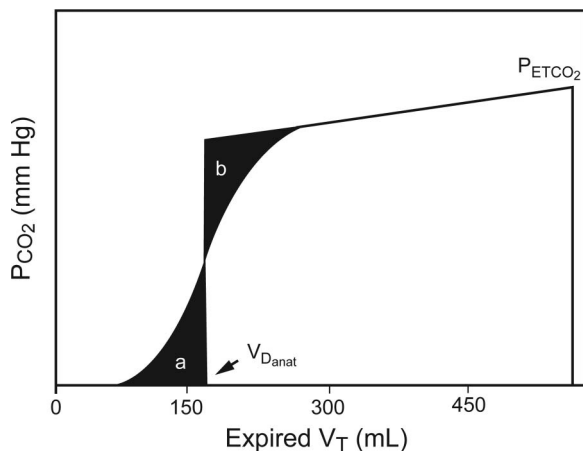

Fig. 5. Fowler's method for identifying anatomic dead space (V_{Danat}) in relation to the slope of phase III and the end-tidal CO_2 (P_{ETCO_2}) on the volumetric capnogram, where phase II is divided into equal areas a and b. From References 103 and 104.

by computer analysis of the volumetric capnogram.[104] The midpoint of phase 2 of the volumetric capnogram signifies the boundary between conducting airways and gas-exchange airways (respiratory bronchioles). When phase 2 is dissected by a vertical line originating from a line superimposed on the incline of phase 3, the intersection at the x axis such that the 2 areas on either side of the vertical line that are equal in area can be created. This point of intersection and equivalent areas is equal to the anatomic dead space volume on the volumetric capnogram (Fig. 5).

Anatomical dead space in male and female volunteers at rest was originally approximated to be 156 and 104 mL, respectively.[103] Since the conducting airways are distensible, the anatomic dead space volume can increase with

maximal voluntary inspiratory lung volume[103] and by the application of positive pressure.[105] The application of PEEP up to 18 cm H_2O was shown to increase the anatomic dead space volume by an average of 5%.[105] This increase in the anatomical dead space volume causes an incremental increase in the total physiologic dead space. The ability to measure anatomical dead space by volumetric capnography enables the components of physiologic dead space to be partitioned by single-breath analysis.

Single-Breath CO_2 Analysis

The single-breath CO_2 waveform analysis builds upon identification of the Fowler anatomical dead space and enables extraction of additional information regarding ventilation efficiency and further analysis and study of physiologic dead space.

When the perpendicular line that identifies the anatomic dead space is drawn through the volumetric capnogram to the x axis, the point of intersection to this line from an additional line superimposed on phase 3 of the capnogram allows the component volumes in a exhaled tidal breath to be partitioned into anatomical V_D, alveolar V_D, and alveolar V_T[106,107] (Fig. 6).

This dissection of the volumetric capnogram area allows further study of the various components and their relationships. For instance, alveolar V_D and anatomical V_D were both found to be indices of lung recruitment and overdistention,[105] and the alveolar V_D/alveolar V_T ratio decreased or increased in parallel to a positive or negative response to PEEP with respect to oxygenation and shunt.[108]

Additionally, the classic sloping "shark's fin" shape and morphology of the time-based or volume-based volumetric capnogram can be a visual indication of $\dot{V}/\dot{Q}$ mismatch due to bronchospasm and airway obstruction[14,109,110] (Fig. 7) and an elevated V_D/V_T in patients with ARDS (Fig. 8).

Measuring Physiologic Dead Space

The traditional technique for bedside measurement of V_D/V_T used the method of exhaled gas collection and analysis to measure the partial pressure of the mean expired CO_2 ($P_{\bar{E}CO_2}$).[111,112] Advancements in technology introduced the use of metabolic analyzers[113,114] and volumetric capnography to measure the $P_{\bar{E}CO_2}$.[115,116]

The simplified bedside calculation of V_D/V_T uses the Enghoff modification of the Bohr equation.[117] 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}).[118] Since P_{ACO_2} was difficult to accurately measure or estimate at the bedside, the Enghoff equation became the standard method for many years in
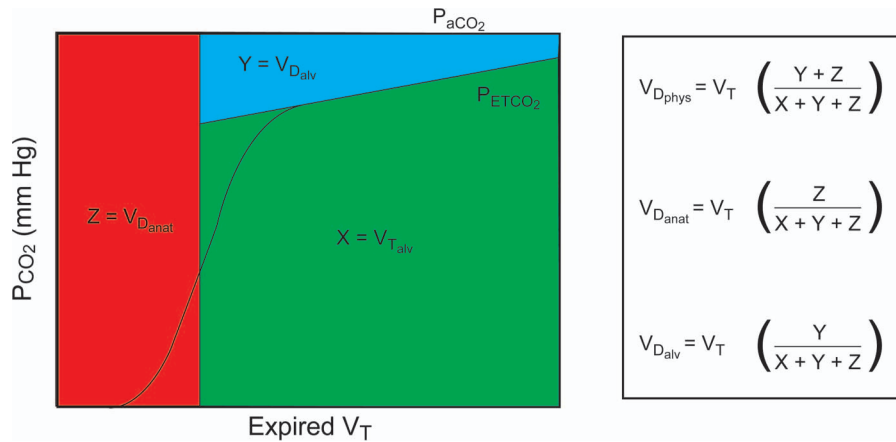
Fig. 6. Single-breath CO_2 analysis further dissects the area of the volumetric capnogram and allows for the calculation of the alveolar dead space volume (V_{Dalv}), anatomic dead space volume (V_{Danat}), alveolar tidal volume (V_{Talv}), and the physiologic dead space volume (V_{Dphys}) in relation to P_{aCO_2} and partial pressure of end-tidal CO_2 (P_{ETCO_2}). From Reference 106, with permission.
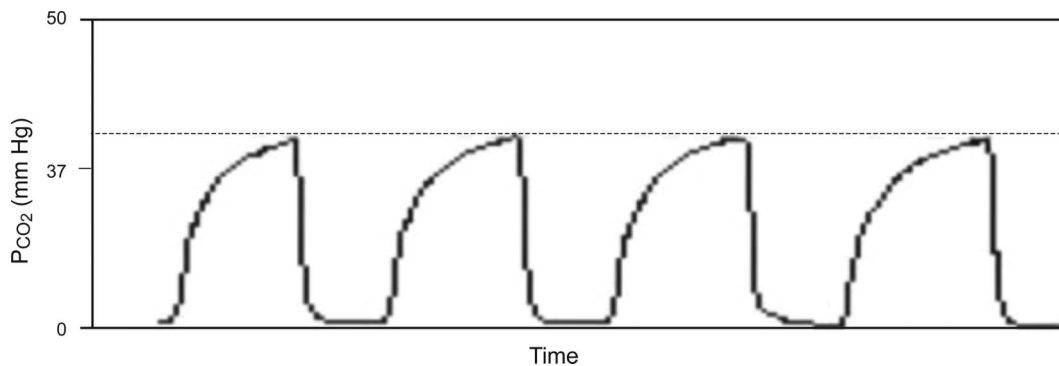

Fig. 7. A "shark's fin" time-based capnogram waveform showing severe airway obstruction. From Reference 14.

Fig. 8. A shark's fin volumetric capnogram of a patient diagnosed with ARDS with elevated dead-space fraction.

bedside clinical practice for calculation of V_D/V_T, where the Enghoff-Bohr equation is

$$V_D/V_{TEngh} = (P_{aCO_2} - P_{\bar{E}CO_2})/P_{aCO_2} \qquad (1)$$

and the original Bohr equation is

$$V_D/V_{TBohr} = (P_{ACO_2} - P_{\bar{E}CO_2})/P_{ACO_2}. \qquad (2)$$

In the past, $P_{\bar{E}CO_2}$ measurements using the gas collection bag method[111,112] were cumbersome, time consuming, and error-prone and entailed collecting up to 30–60 L of expired gas for a mean CO_2 sample measurement. Also, the gas collection bag method is no longer feasible due to the common presence of bias flow on current ventilators. The introduction of metabolic analyzers for the $P_{\bar{E}CO_2}$ measurement requires use of a correction for ventilator circuit compression volume[116] and relies on the accurate measurement of the fraction of mean expired CO_2 ($F_{\bar{E}CO_2}$), whereby

$$P_{\bar{E}CO_2} = F_{\bar{E}CO_2} \times (P_B - 47). \qquad (3)$$

(P_B represents barometric pressure, 47 is water vapor pressure at 37°C) The introduction of the volumetric CO_2 monitor has simplified the bedside measurement by continuously measuring $P_{\bar{E}CO_2}$ and allowing intermittent input of P_{aCO_2} for the calculation of V_D/V_T.[115]

$P_{\bar{E}CO_2}$ can also be derived from ventilator volumetric capnography measurements using $\dot{V}_{CO_2}$ and expired minute ventilation ($\dot{V}_E$),[116] whereby
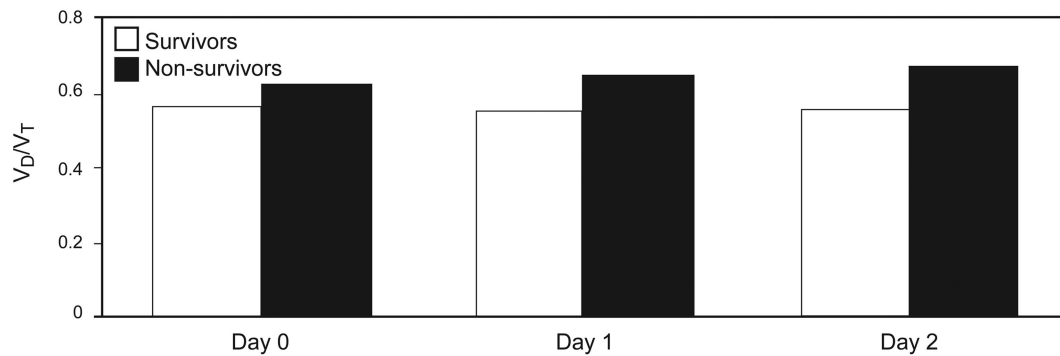
Fig. 9. Dead space/tidal volume (V_D/V_T) in non-survivors compared with survivors was significantly higher on study day 1 and day 2 after diagnosis of ARDS. Data from Reference 131.

$$F_{\bar{E}CO_2} = \dot{V}_{CO_2}/\dot{V}_E. \qquad (4)$$

By using Equation 3 to calculate $P_{\bar{E}CO_2}$, Equation 1 can then be used for the calculation of V_D/V_T.[116]

Clinical Usefulness of Physiologic Dead Space Measurements

Measuring V_D/V_T in the critically ill patient during mechanical ventilation is important for several reasons. The prognostic value of V_D/V_T has been linked to the severity of lung injury and the risk of death in patients with ARDS. Furthermore, V_D/V_T can be useful as an indicator of lung recruitment versus overdistention in patients with ARDS, may be helpful as a predictor of extubation success in adult and pediatric patients, and may be useful in assessing the severity and confirming the suspicion of pulmonary embolism.

Assessing the Severity of Lung Injury

V_D/V_T is known to be a marker of the type[119] and severity of lung injury during ARDS in regard to the degree of hypoxemia,[120] histopathological changes,[120,121] $\dot{V}/\dot{Q}$ defects,[122,123] intrapulmonary shunt,[119,123,124] and the need for supportive rescue therapies.[119,124] Monitoring serial changes in V_D/V_T over the course of critical illness in addition to other markers of disease severity is therefore warranted.

Predicting Survival in ARDS Patients

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.[125-131] During the first 2 d following an ARDS diagnosis, V_D/V_T was significantly higher among non-survivors[131] (Fig. 9). Patients with $V_D/V_T = 0.57$ were found to have higher mortality, with a 45% increase in the odds of dying for every 0.05 increase

Fig. 10. Dead-space fraction differences (mean $\pm$ SD) in ARDS survivors (0.63 $\pm$ 0.09) compared with non-survivors (0.54 $\pm$ 0.09) ($P < .001$). Data from Reference 127.

in dead-space fraction.[127] The mean dead-space fraction was also significantly higher in patients who died compared with those who survived (Fig. 10). Consequently, in the face of continually rising V_D/V_T during the course of ARDS as a sign of possible futility, it may be appropriate to use this information to help guide plan of care decisions during critical illness.

Indication of Lung Recruitment Versus Overdistention

V_D/V_T measurements in patients with ARDS have been found to be useful for titrating PEEP and optimizing cardiopulmonary function[105,108,132] and may be useful as a tool to monitor lung recruitment versus overdistention.[133-135]

In one of the classic papers in critical care medicine published in 1975, Suter et al[105] demonstrated the value of measuring V_D/V_T as a guide to optimizing gas exchange and pulmonary mechanics in patients with lung injury (Fig. 11). This early work has been repeatedly validated and therefore supports assessing and monitoring V_D/V_T to assist with management decisions in patients with ARDS.[108,132,134,135]
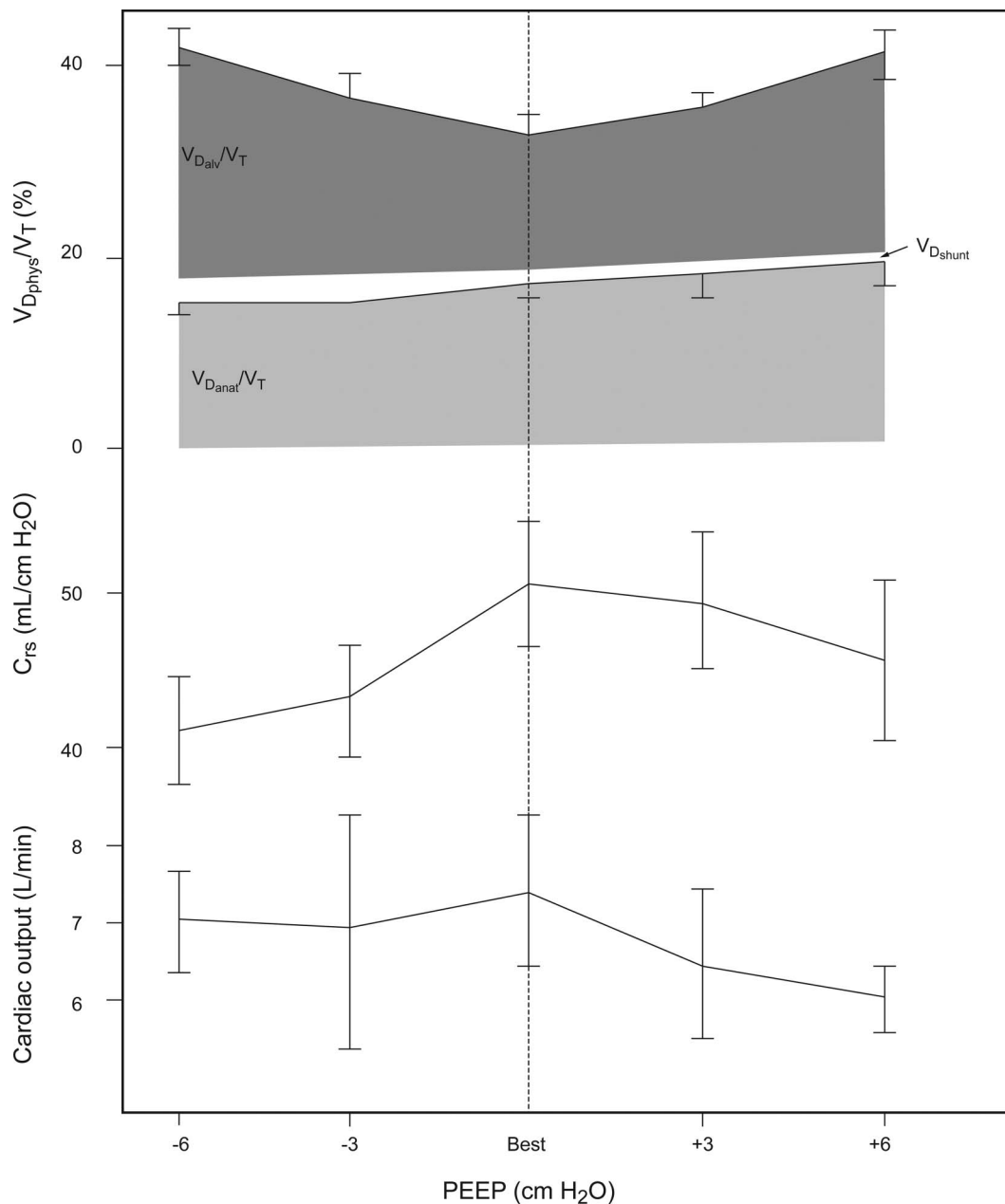
Fig. 11. Changes in physiologic dead space (V_{Dphys}/V_T), alveolar dead space (V_{Dalv}), and anatomic dead space (V_{Danat}) fraction, in relation to shunt (V_{Dshunt}), total respiratory system compliance (C_{rs}), cardiac output, and incremental changes in PEEP. From Reference 105, with permission.

Predicting Successful Liberation From Mechanical Ventilation

V_D/V_T assessments may also be used to predict extubation success in pediatric[136] and adult patients.[137,138] Values for $V_D/V_T \leq 0.50$ and ≥ 0.65 in infants and children were found to predict extubation success or failure[136] (Fig. 12), whereas in adult patients, the cutoff value for $V_D/V_T = 0.58$ offered the best sensitivity and specificity for predicting extubation failure.[137] It has

also been suggested that elevated V_D/V_T may be useful for predicting the need for noninvasive ventilation after extubation[138] and therefore the potential for averting the need for re-intubation.

Diagnosis of Pulmonary Embolism

V_D/V_T, in addition to other clinical assessments and diagnostic tests, can be useful in excluding or diagnosing pulmonary embolism. $V_D/V_T > 40\%$ was found to be

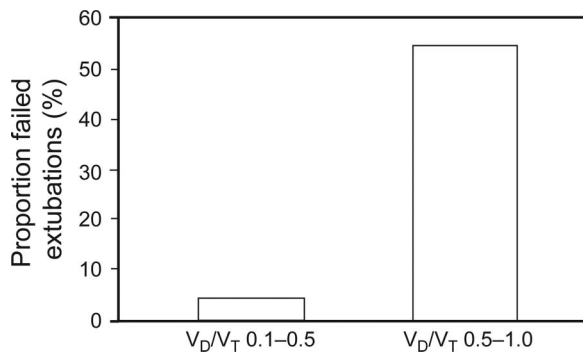Fig. 12. Graph plotting the differences of physiologic dead space to tidal volume (V_D/V_T) range against the percentage of subjects requiring additional ventilatory support after extubation. Data from Reference 136.

highly suggestive of pulmonary embolism and was comparable in terms of sensitivity and specificity with a lung perfusion scan.[139] Assessment of the size of the capnogram waveform area was identified as a useful screening method for pulmonary embolism. When the capnogram area was low, signifying a larger P_{aCO_2} to P_{ETCO_2} difference, the presence of pulmonary embolism was more likely.[140] Conversely, when P_{ETCO_2} was normal (>36 mm Hg), the narrow $P_{aCO_2} - P_{ETCO_2}$ difference reliably excluded pulmonary embolism compared with contrast-enhanced helical computed tomography or ventilation/perfusion scan.[141]

The arterial to end-tidal alveolar dead space ratio ([$P_{aCO_2} - P_{ETCO_2}$]/P_{aCO_2}) cutoff value of 15% has also been shown to help exclude or confirm pulmonary embolism.[141] When the alveolar V_D/alveolar V_T ratio is <20%, the probability of pulmonary embolism is low[142-146] and was found to reduce the need for further diagnostic tests.[148] On the other hand, an elevated alveolar V_D/alveolar V_T also predicts pulmonary embolism, the severity of the perfusion defect, and the degree of vascular occlusion.[148]

Bohr Versus Enghoff Approach to Physiologic Dead Space Measurements

The Bohr dead space equation relies on the calculation or estimation of P_{ACO_2} from mixed alveolar gas and $P_{\bar{E}CO_2}$, which signifies the combined effect of the volume of anatomical V_D, alveolar V_D, and alveolar V_T. P_{ACO_2} is affected by the dilution of CO_2 from the alveolar side of the alveolar-capillary membrane from gas exchange units with low or no perfusion. $P_{\bar{E}CO_2}$ is determined by the volume of CO_2 excreted from the lungs ($\dot{V}_{CO_2}$) compared with the total $\dot{V}_E$ (Equations 3 and 4). Bohr dead space is affected by areas of ventilation to perfusion inequality, such as during alveolar overdistention by excessive PEEP and/or V_T, occlusion of the pulmonary vasculature, and low pul-

monary perfusion secondary to hypovolemia or shock. Bohr dead space is recognized as true dead space, or the balance between effective and ineffective ventilation occurring in the lungs[149] (Fig. 13).

The Enghoff dead space equation, on the other hand, relies on the P_{aCO_2} of arterial blood and is thus affected by global gas exchange inefficiency and the effects of shunt and venous admixture (Fig. 14). P_{aCO_2} can be elevated from all sources of low ventilation to perfusion matching and shunt, such as atelectasis, pneumonia, COPD, and asthma. P_{aCO_2} can also rise when an increase in metabolism and CO_2 production is not accompanied by an increase in CO_2 excretion. When $\dot{V}_{CO_2}$ increases without a proportional rise in alveolar ventilation, production of CO_2 exceeds the rate of excretion, and P_{aCO_2} increases. Therefore, it is important to understand that the Enghoff equation overestimates V_D/V_T in the presence of shunt and low $\dot{V}/\dot{Q}$.

The determination of P_{ACO_2} using volumetric capnography for the calculation of Bohr dead space has been demonstrated by mathematical modeling.[152] and measured in an animal model of lung injury.[153] P_{ACO_2} calculated from the phase 3 midpoint of the volume capnogram was compared with the P_{ACO_2} derived mathematically using the multiple-inert gas elimination technique. This demonstrated a close linear correlation between the 2 methods for P_{ACO_2} calculation (r = 0.99, $P < .001$) and Bohr dead space (r = 0.96, $P < .001$). The Bohr dead space and the mean P_{ACO_2} from volumetric capnography were similar to the multiple-inert gas elimination technique calculations, with a mean bias of 10 mL (95% CI −44 to 64 mL) and −0.10 mm Hg (95% CI −2.18 to 1.98 mm Hg), respectively.

The ability to measure P_{ACO_2} from the volumetric capnogram and therefore enabling the calculation of Bohr dead space has several significant implications. Measurement of Bohr dead space returns a more accurate reflection of effective and ineffective ventilation and perfusion in the lungs that is not impacted by the effects of shunt and low $\dot{V}/\dot{Q}$ on P_{aCO_2} (Fig. 15).

The effects of shunt on the measurement of V_D/V_T was investigated using a computer model simulation that controlled for variations of P_{aCO_2}, alveolar V_D, anatomical V_D, pulmonary shunt, and $\dot{V}/\dot{Q}$ ratio distribution[154] (Fig. 16) and in a lung lavage animal model using the midpoint of phase 3 to define P_{ACO_2}[155] (Fig. 17). Both experiments confirmed that increasing levels of shunt and low $\dot{V}/\dot{Q}$ markedly affects dead space values calculated by Enghoff's (Equation 1) but not Bohr's equation (Equation 2).

An estimate of the Bohr dead space can also be calculated by substituting P_{ETCO_2} for P_{aCO_2}, whereby the Bohr estimate equation is
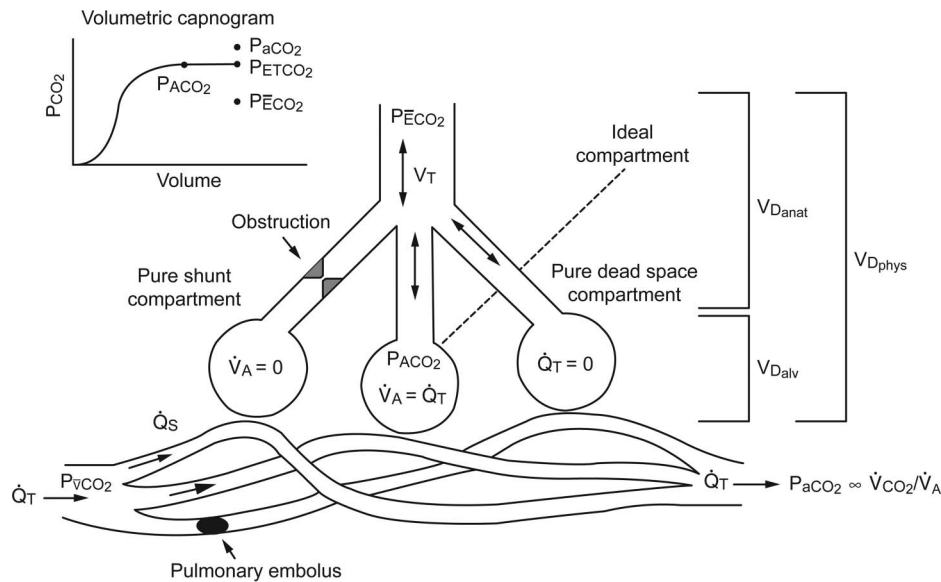
Fig. 13. The 3-compartment lung model described by Riley and Cournand[151,152] represents gas exchange in the lung in regard to the matching of alveolar gas volume ($\dot{V}_A$) and perfusion ($\dot{Q}_T$), shunt ($\dot{Q}_S$), and dead space (V_D). The ideal compartment represents areas of perfect alveolar gas volume 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_{Dalv}) and anatomic dead space (V_{Danat}) equal the physiologic dead space (V_{Dphys}). The dead space fraction is equal to V_{Dphys} divided by tidal volume (V_T). Also shown are 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 alveolar gas volume, the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}), the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}), and the $P_{\bar{E}CO_2}$ in relation to the model and the volumetric capnogram. From Reference 116.
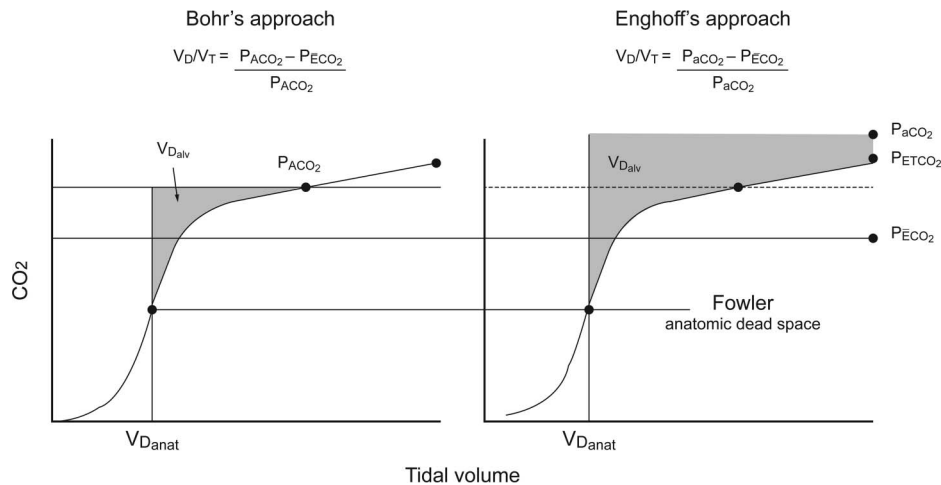
Fig. 14. Graphical representation of physiologic dead space fraction determined by volumetric capnography, using the approaches of Bohr and Enghoff, which shows how use of the Enghoff equation can overestimate alveolar dead space (V_{Dalv}) (shaded areas) by substitution of the P_{aCO_2} for the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}), determined by identifying the midpoint of phase III of the expired volumetric capnogram.[153,154] Also shown are the airway or anatomical dead space (V_{Danat}; determined by the Fowler method identified at the midpoint of phase II of the expired volumetric capnogram),[103] the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}), and the partial pressure of mean expired carbon dioxide ($P_{\bar{E}CO_2}$) in relation to the volumetric capnogram.[150] From Reference 116.

$$V_D/V_{TBohr\ Est} = (P_{ETCO_2} - P_{\bar{E}CO_2})/P_{ETCO_2}. \quad (5)$$

The comparison of V_D/V_{TEngh}, V_D/V_{TBohr}, and $V_D/V_{TBohr\ Est}$ in regard to the area representing anatomical

V_D and alveolar V_D on the volumetric capnogram is depicted in Figure 18. Example calculations based on the different equations in relation to the volumetric capnogram are shown in Figure 19.

Figures 18 and 19 demonstrate that the Enghoff equation overestimates true V_D/V_T. Using the Bohr estimate equation also overestimates V_D/V_T, but this difference will always be closer to the true Bohr dead space than the Enghoff equation, whether V_D/V_T is normal or elevated. Although identifying P_{ACO_2} from the midpoint of phase 3 of the volumetric capnogram is technically achievable, using the Bohr estimate equation and substituting P_{ETCO_2} for P_{ACO_2} would simplify the calculation, especially when the midpoint of phase 3 is not clearly identifiable.

Since $P_{\bar{E}CO_2}$ can be calculated using Equation 4, and P_{ETCO_2} is available during volumetric CO_2 monitoring, the continuous measurement of $V_D/V_{TBohr\ Est}$ is technically feasible and would eliminate the requirement of periodic arterial blood gas sampling to measure P_{aCO_2} for V_D/V_T calculation. The clinical value of constant monitoring and trending of $V_D/V_{TBohr\ Est}$ during mechanical ventilation of the critically ill patient requires further investigation.

It has also been suggested that simultaneous assessment of Enghoff and Bohr dead space using volumetric capnog-

raphy may be useful in regard to recognizing the effects of shunt and $\dot{V}/\dot{Q}$ inequality versus true dead space or wasted ventilation in critically ill patients with elevated V_D/V_T.[149] Since many studies that identified V_D/V_T as a predictor of outcome, disease diagnosis, and disease severity used the Enghoff equation,[125-131,136-138,141-148] the conclusions of these studies may need to be reexamined using this new approach.

Estimating Metabolic Rate and Resting Energy Expenditure

Estimation of metabolic rate can be accomplished by $\dot{V}_{CO_2}$ measurements from volumetric capnography. The Weir equation is the accepted standard used during metabolic testing for calculating the nutritional support requirements in critically ill patients. Modifications to the Weir equation can be used to calculate resting energy expenditure (REE) by deriving a value for $\dot{V}_{O_2}$ adjusted for a normal respiratory quotient (RQ) based on a measurement of $\dot{V}_{CO_2}$. The REE by the Weir equation and the REE based on $\dot{V}_{CO_2}$ (REE-CO_2) can be calculated, where

$$REE = (3.9 \times \dot{V}_{O_2}) + (1.1 \times \dot{V}_{CO_2}) \times 1.44 \quad (6)$$

and

$$REE\text{-}CO_2 = (3.9 \times \dot{V}_{CO_2}/.85) + (1.1 \times \dot{V}_{CO_2}) \times 1.44. \quad (7)$$

When the actual RQ is equal to 0.85, the REE-CO_2 calculation results in an REE value equivalent to the value calculated by the standard Weir equation. The CCM Ex-
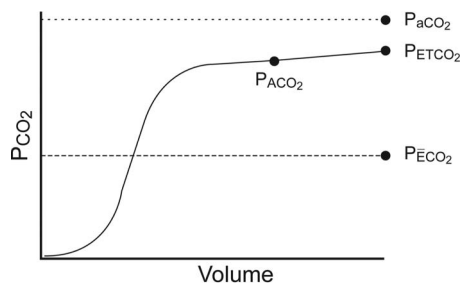
Fig. 15. Volumetric capnogram showing the relationship between P_{aCO_2}, the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}), the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}), and the partial pressure of mean expired carbon dioxide ($P_{\bar{E}CO_2}$).
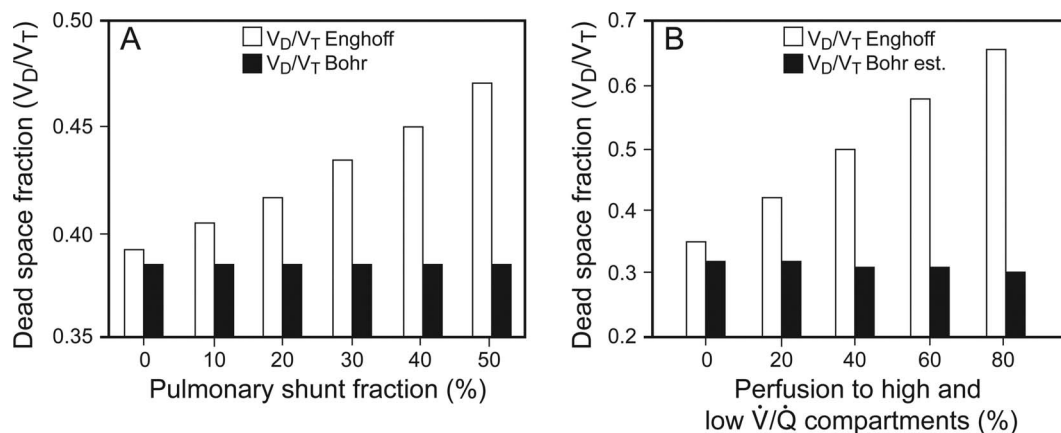
Fig. 16. Dead-space (V_D/V_T) calculations using a mathematical computer model of the cardiorespiratory system. A: The effects of pulmonary shunt. B: The effects of pulmonary perfusion of high and low $\dot{V}/\dot{Q}$ compartments. V_D/V_{TEngh} is the dead-space calculated by using Enghoff's modification of the Bohr equation (Equation 1). V_D/V_{TBohr} is the dead space calculated by using the Bohr equation (Equation 2). $V_D/V_{TBohr\ est}$ is the dead space calculated by using the Bohr estimate equation, which substitutes the partial pressure of end-tidal carbon dioxide (P_{ETCO_2}) for the partial pressure of mixed alveolar carbon dioxide (P_{ACO_2}) (Equation 5). Data from Reference 154.
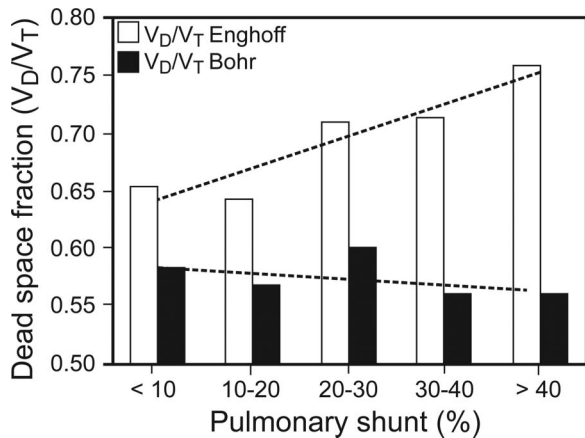
Fig. 17. Ratio of dead space to tidal volume (V_D/V_T) stratified according to the level of shunt in a surfactant-depleted swine model induced by repeated lung lavage. V_D/V_{TEngh} is calculated by Enghoff's modification of the Bohr equation (Equation 1). V_D/V_{TBohr} is calculated by Bohr's dead-space equation (Equation 2). Dashed trend lines show that the difference between V_D/V_{TEngh} and V_D/V_{TBohr} increases as pulmonary shunt increases. Data from Reference 155.

Fig. 18. Areas on the volumetric capnogram (in gray) representing the contribution of alveolar dead space to total physiologic dead space using P_{aCO_2} (area a + b + c), the partial pressure of end tidal carbon dioxide (P_{ETCO_2}) (area b + c), or the partial pressure of 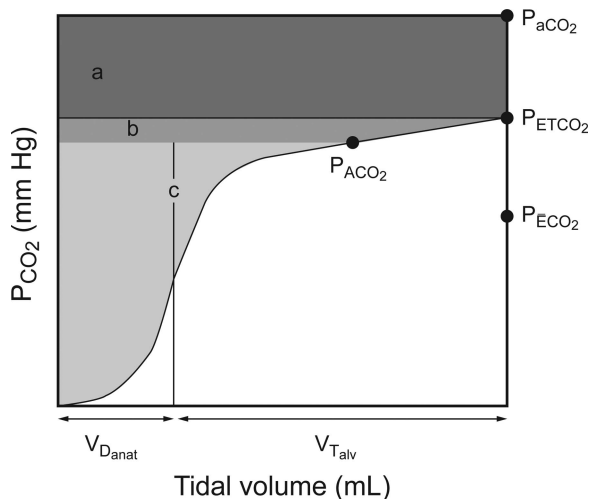mixed alveolar carbon dioxide (P_{ACO_2}) (area c) in relation to the partial pressure of mean expired carbon dioxide (P_{ECO_2}), the anatomic dead space volume (V_{Danat}), and the alveolar tidal volume (V_{Talv}).

press metabolic analyzer (Medical Graphics Corporation, St Paul, Minnesota) uses Equation 7 to calculate REE-CO$_2$ with an accuracy of approximately ±10% compared with the REE.[156] The REE measured by the CCM Express using the standard Weir method was compared retrospectively with the REE-CO$_2$ calculation in 67 adult ICU patients.[157] The correlation coefficient r = 0.99 and the coefficient of determination r^2 = 0.98, with bias and precision between measurements of -15 ± 126 cal/d. When
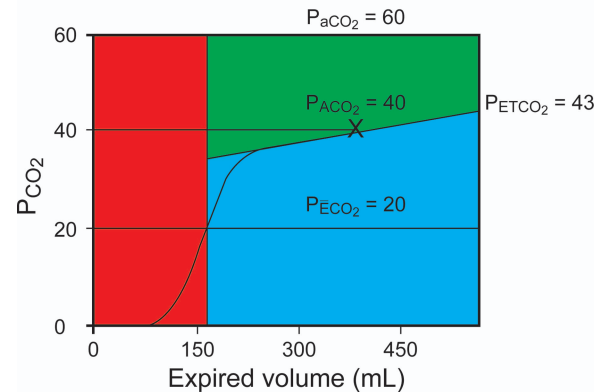
Fig. 19. Example calculations based on the different equations in relation to the volumetric capnogram.

the differences between REE and REE-CO$_2$ were compared with the measured RQ, as the value for RQ moved toward 0.70, the percentage error (mean bias/mean REE for the range of RQ) became more positive, and as RQ moved toward 1.0, the percentage error became more negative. Furthermore, when RQ was normal in the range between 0.80 and 0.90, the average error was approximately ±5% (Fig. 20).[157]

It should be noted that when using this approach, if the $\dot{V}_{CO_2}$ measuring device has a substantial bias and precision difference from measurements by a metabolic analyzer, additional variance between REE and REE-CO$_2$ will result. This difference in measurement accuracy can be compensated for by use of a measurement bias correction.

The REE-CO$_2$ equation can be further simplified by solving the equation with any combination of $\dot{V}_{CO_2}$ and $\dot{V}_{O_2}$ that equals an RQ of 0.85, and dividing the calculated REE by the measured $\dot{V}_{CO_2}$, a single factor can be derived for calculating REE-CO$_2$, whereby

$$\text{REE-CO}_2 = 8.19 \times \dot{V}_{CO_2}. \tag{8}$$

For example, when $\dot{V}_{CO_2}$ = 221 mL/min and $\dot{V}_{O_2}$ = 260 mL/min, RQ = 221/260 = 0.85, and the Weir equation returns a calculated REE of 1,810 kcal/d, whereby

$$\text{REE} = (3.9 \times 260) + (1.1 \times 221) \times 1.44 = 1,810 \text{ kcal/d.} \tag{9}$$

REE-CO$_2$ can be calculated as follows:

$$\text{REE-CO}_2 = [3.9 \times (221/0.85) + (1.1 \times 221) \times 1.44$$
$$= 1,810 \text{ kcal/d,} \tag{10}$$

Fig. 20. Comparison of the differences between resting energy expenditure (REE) and resting energy expenditure based on $\dot{V}_{CO_2}$ (REE-CO$_2$) to the measured respiratory quotient (RQ). From Reference 157.

Table 2.   Caloric Equivalent of Oxygen and Carbon Dioxide in Relation to the Respiratory Quotient and Nutritional Substrate[9,158]
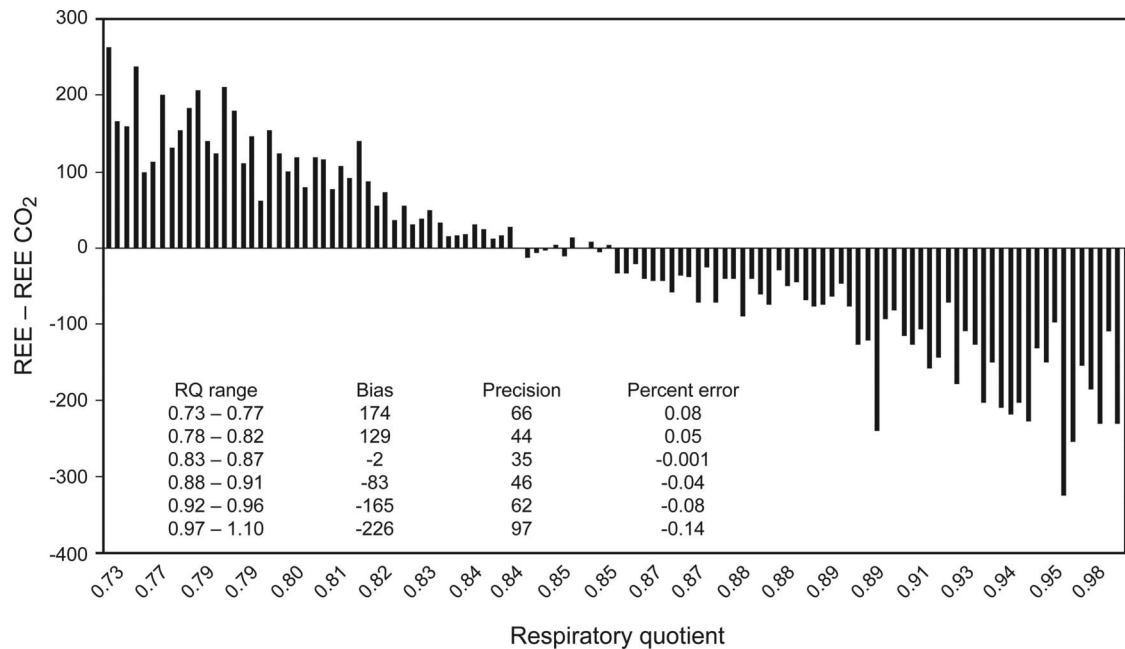
Substrate	Respiratory Quotient	Oxygen Caloric Equivalent (kcal/L)	Carbon Dioxide Caloric Equivalent (kcal/L)
Carbohydrate	1.0	5.05	5.05
Mixed	0.90	4.83	5.52
Protein	0.80	4.46	5.57
Fat	0.71	4.74	6.67

Table 3.   Comparison of 4 Methods to Determine Basal Energy Expenditure or Resting Energy Expenditure[158]

Method	Mean	SD
BEE by Harris-Benedict equation, kcal/d	1,716	225
REE by Weir equation, kcal/d	2,755	969
REE by O$_2$ caloric equivalent, kcal/d	2,712	971
REE by CO$_2$ caloric equivalent, kcal/d	2,677	854

BEE = basal energy expenditure
REE = resting energy expenditure

$$\text{REE-CO}_2 \text{ factor} = 1{,}810/221 = 8.19, \quad (11)$$

and

$$\text{REE-CO}_2 = 8.19 \times 221 = 1{,}810 \text{ kcal/d}. \quad (12)$$

The caloric equivalence and carbon dioxide and oxygen can also be used to indirectly calculate REE from measurements of $\dot{V}_{CO_2}$ (Table 2).[158-160] When the RQ = 0.90, the CO$_2$ caloric equivalent factor equals 5.52 kcal/L, where

$$\text{REE-CO}_2 \text{ equivalent} = 5.52 \times \dot{V}_{CO_2} \times 1.44 \quad (13)$$

This technique was compared with the Harris-Benedict calculation and the Weir equation. The Harris-Benedict equation significantly underestimated REE, but there was no significant difference between the Weir and REE-CO$_2$

equivalent calculation[158] (Table 3). Because of the technical difficulty of measuring $\dot{V}_{O_2}$, the REE-CO$_2$ equivalent calculation is simpler and should be the preferred method, especially when the F_{IO_2} is >0.60.[159]

The ability to perform metabolic measurements using $\dot{V}_{CO_2}$ from volumetric capnography has several important implications. $\dot{V}_{CO_2}$ measurement capabilities are increasingly more available on standalone monitors and ventilators. This makes estimates of REE more readily accessible when metabolic analyzers are not available. When $\dot{V}_{CO_2}$ is being monitored either continuously or intermittently during mechanical ventilation, if the REE-CO$_2$ calculation is incorporated into the ventilator, estimates of the metabolic rate and nutritional requirements could be available in real time and trended over the course of critical illness.[9]

Additionally, since F_{IO_2} does not affect the accuracy of the REE-CO$_2$ calculation, $F_{IO_2} > 0.60$ may no longer be a limitation of measuring a reasonable estimate of REE. The

implications of using the REE-CO_2 calculations are significant in that even the most severe critically ill patients receiving mechanical ventilation receiving 100% oxygen and high levels of PEEP can have REE estimates performed to manage their complex nutritional needs.

Since volumetric capnography and $\dot{V}_{CO_2}$ monitoring are becoming more readily available and are less costly than traditional metabolic testing, their use should be considered for incorporation into a standard nutrition assessment and treatment process. Further validation studies and measurements of outcome are needed to verify the impact of these alternative methods of indirect calorimetry.

Summary

Monitoring exhaled CO_2 goes beyond the basic use of evaluating and assessing ventilation. The uses of exhaled CO_2 monitoring include improvements in patient safety, utilization in assessing care and evaluating interventions, identifying abnormal physiology, quantifying the severity of illness, and predicting outcomes. In recognition of these significant benefits, the importance of exhaled CO_2 monitoring has been increasingly emphasized by practice standards, guidelines, and advisory statements from professional organizations and regulatory agencies.

Future advancements in volumetric capnography will include the capability to continuously estimate Bohr dead space and metabolic rate during mechanical ventilation. These advancements are currently at the verge of technical feasibility, and device manufacturers will soon bring these important enhancements in patient monitoring into clinical practice at the bedside. The critical impact and implications of these valuable monitoring methods utilizing exhaled CO_2 will be important for all health-care providers to comprehend and utilize.

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