Should Every Mechanically Ventilated Patient Be Monitored With Capnography From Intubation to Extubation?

Ira M Cheifetz MD FAARC and Timothy R Myers RRT-NPS

One of the most important aspects of caring for a critically ill patient is monitoring. Few would disagree that the most essential aspect of monitoring is frequent physical assessments. Complementing the physical examination is continuous monitoring of heart rate, respiratory rate, and blood oxygen saturation measured via pulse-oximetry, which have become the standard of care in intensive care units. Over the past decade one of the most controversial aspects of monitoring critically ill patients has been capnography. Although most clinicians use capnography to confirm endotracheal intubation, few clinicians use continuous capnography in the intensive care unit. This article reviews the medical literature on whether every mechanically ventilated patient should be monitored with capnography from intubation to extubation. There are numerous articles on capnography, but no definitive, randomized study has even attempted to address this specific question. Based on the available literature, it seems reasonable to use continuous capnography, for at least a

subset of critically ill patients, to ensure integrity of the endotracheal tube and other ventilatory apparatus. However, at this point definitive data are not yet available to clearly support continuous capnography for optimizing mechanical ventilatory support. We hope that as new data become available, the answer to this capnography question will become clear. *Key words: capnography, mechanical ventilation, endotracheal tube, intubation, extubation, monitoring, carbon dioxide, ventilation*. [Respir Care 2007;52(4):423–438. © 2007 Daedalus Enterprises]

Introduction

Capnography and pulse oximetry in combination is the monitoring standard of care in the operating room setting, and this combination is becoming more routinely used in several in-patient situations, including moderate sedation and patient-controlled analgesia. Furthermore, capnography has become the standard of care to confirm endotracheal intubation in all hospital settings (operating room, emergency department, and intensive care unit). Thus, the "simple" question for this paper is whether capnography should be recommended for all patients for the duration of mechanical ventilation. The controversy results from the fact that this question has not been formally studied in a prospective, randomized fashion. Additionally, there have been no published studies of any design that even attempt to address this topic.

The focus of this paper is becoming more pertinent to bedside clinicians, as important technological advances in capnography have occurred over the past decade. Previously, technical limitations often precluded the continuous use of capnography with critically ill patients. Clinicians can now continuously, noninvasively, and accurately measure CO_2 elimination (both as a partial pressure and a volume) and dead-space ventilation, with few technical hurdles.

The accepted standard for measuring CO_2 production is still arterial blood analysis. The appeal of this technique is blunted clinically because it is invasive, can be somewhat labor-intensive and expensive, and generally offers only intermittent measures of P_{aCO_2}. Although continuous monitoring of arterial blood gases is possible, it is expensive and continues to have technical limitations.

Valuable clinical information can be gained from noninvasive CO_2 monitoring. Capnometry (digital display of data) and capnography (graphical display of data) can be either time-based or volume-based (ie, volumetric). Capnography refers to the depiction of exhaled CO_2 during the entire respiratory cycle and provides a visual display of the waveform. Capnography is a better indicator of dynamic changes in gas exchange than is capnometry alone.[1,2] It must be stressed that if capnography is used, the proper clinical interpretation of the waveform is essential to the ideal management of the mechanical ventilator and to provide safe patient care. Deviations from characteristic waveforms[3,4] (Figs. 1 and 2) suggest an abnormality (Fig. 3) that requires recognition and possibly correction.

Time-based capnography is best known as end-tidal carbon dioxide (P_{ETCO_2}) monitoring. When used without qualification, the term "capnography" refers to time-based values. A time-based capnogram provides qualitative information on the waveforms associated with mechanical ventilation and a quantitative estimation of the partial pressure of expired CO_2. Volumetric capnography uses a CO_2 sensor and a pneumotachometer in combination. This permits calculation of the net volume of CO_2 expired by the patient, which is expressed as a volume of gas (generally in mL/min) rather than a partial pressure or gas fraction.

By analyzing the 3 phases of the volumetric capnogram, clinicians can potentially assess clinical issues of concern (Fig. 4). Phase 1 of the single-breath CO_2 waveform represents gas exhaled from the upper airways (ie, from anatomical dead space), which generally is void of CO_2.[1] An increase in phase 1 indicates an increase in anatomical dead space. Phase 2 is the transitional phase from upper to lower airway ventilation, and it tends to depict changes in perfusion. Phase 3 represents alveolar gas exchange, which indicates changes in gas distribution. An increase in the slope of phase 3 indicates increased maldistribution of gas delivery.

A brief review of the pertinent physiology is essential to this debate. The "normal" difference between P_{aCO_2} and P_{ETCO_2} is approximately 4–5 mm Hg, which represents the normal dead-space ventilation. In a healthy upright person,

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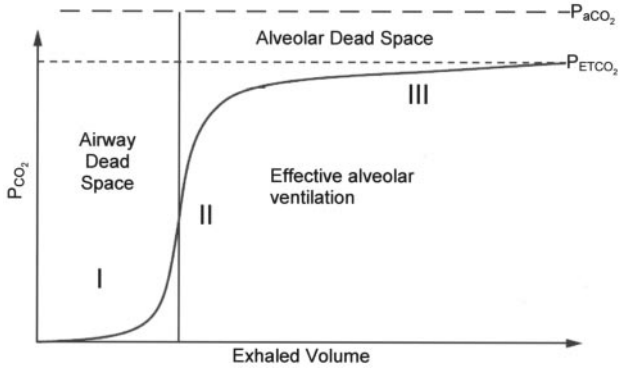

Fig. 1. This single-breath carbon dioxide waveform depicts carbon dioxide elimination as a function of the volume of gas exhaled. Note that time is not a variable in this graph. P_{ETCO_2} = partial pressure of end-tidal carbon dioxide.

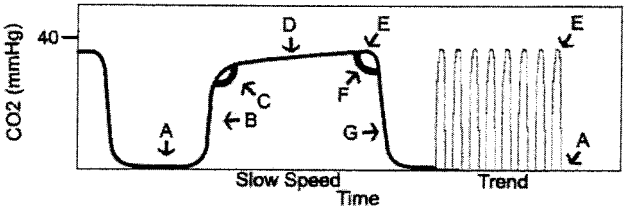

Fig. 2. Normal features of a capnogram. A: Baseline represents the beginning of expiration and should start at zero. B: The transitional part of the curve represents mixing of dead space and alveolar gas. C: The alpha angle represents the change to alveolar gas. D: The alveolar part of the curve represents the plateau average alveolar gas concentration. E: The end-tidal carbon dioxide value. F: The beta angle represents the change to the inspiratory part of the cycle. G: The inspiration part of the curve shows a rapid decrease in carbon dioxide concentration. (From Reference 4, with permission.)

gravity causes a vertical distribution difference of ventilation and perfusion that increases from the bases to the apices of the lung (Fig. 5). In the lung bases, alveoli are perfused but not ventilated (ventilation/perfusion ratio [$\dot{V}/\dot{Q}$] = zero), whereas in the apical regions, alveoli are ventilated but not perfused ($\dot{V}/\dot{Q}$ = infinity). On average, the typical $\dot{V}/\dot{Q}$ is 0.8, and the alveolar carbon dioxide concentration (P_{ACO_2}) is approximately 40 mm Hg. This results in a "regionalization" of alveolar CO_2. Thus, the relationship between P_{aCO_2} and P_{ETCO_2} must be considered in relation to a patient's $\dot{V}/\dot{Q}$ relationship, disease process, and changes in dead-space ventilation.

Because of the properties of shunt and venous admixture, there is normally a small difference between P_{aCO_2} and P_{ACO_2} ($P_{(A\text{-}a)CO_2}$). Shunt increases CO_2 and decreases O_2 in blood returning to the left side of the heart from the pulmonary capillaries. P_{ACO_2} decreases by 2 decrements during exhalation, through (1) diluted CO_2 from very poorly perfused alveoli (alveolar dead space) and (2) further by CO_2 from the conducting airways (anatomical or functional dead space). The alveolar versus end-tidal carbon dioxide difference signifies the combination of the anatomical and alveolar dead spaces.

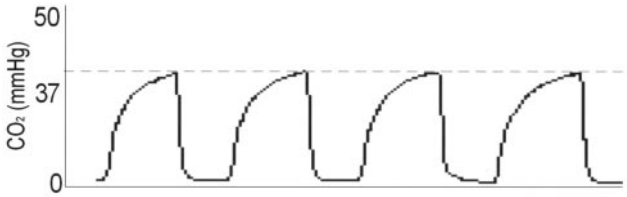

Fig. 3. Time-based capnographic waveform representing severe bronchospasm.

Capnography is a vital monitoring system for critically ill patients; however, the data obtained from capnography must be integrated with all of the available patient data, especially physical assessment. It must be stressed that capnography is not a measurement solely of respiratory function; capnograms must be interpreted in conjunction with other clinical findings. It should be noted that changes in end-tidal CO_2 and CO_2 elimination ($\dot{V}_{CO_2}$) almost always precede changes in oxygen saturation, heart rate, and blood pressure.

Although most clinicians would agree that capnography offers a unique vantage point on cardiorespiratory physiology, the role of capnography for mechanically ventilated patients outside the operating room remains highly debated. Thus, the goal of this article is to highlight the potential advantages and disadvantages of continuous capnography from intubation to extubation for every mechanically ventilated patient.

Pro: Every Mechanically Ventilated Patient Should Be Monitored With Capnography From Intubation to Extubation

Continuous capnography from intubation to extubation offers several benefits, including confirming tracheal intubation, monitoring the integrity of the endotracheal tube (ETT) and ventilatory circuit, assisting with the titration of mechanical ventilatory support, assessing pulmonary capillary blood flow, and monitoring for extubation readiness. The technology required to perform capnography on expired gas is not new, although recent advances have greatly improved the reliability and clinical applicability. From the start it must be noted that capnography has been considered a basic standard of care in anesthetic monitoring by the American Society for Anesthesiologists since 1986.[6]

The pro stance on this topic is based on the following basic underlying principles: (1) the potential clinical benefits of continuous capnography clearly outweigh any potential risks, (2) life-threatening airway disasters can be averted with continuous capnography, (3) capnography reveals changes in circulatory and respiratory status sooner

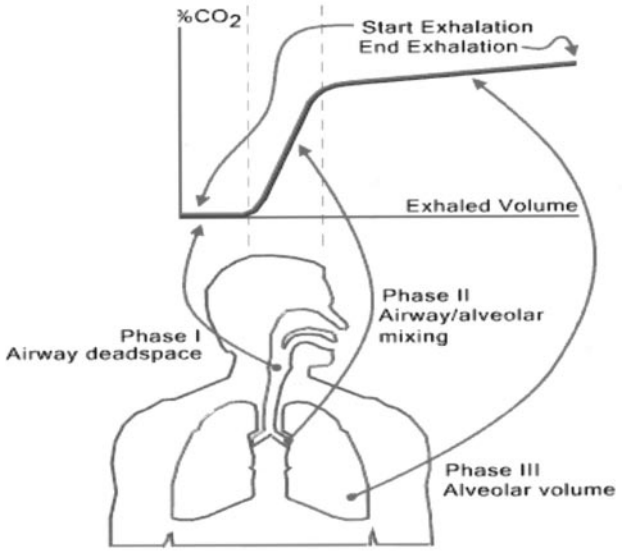

Fig. 4. Volumetric capnogram. Phase 1 represents the quantity of carbon dioxide eliminated from the upper airways. Phase 2 is the transitional zone that represents ventilation from both large and small airways. Phase 3 represents carbon dioxide elimination from the alveoli and, thus, the quantity of gas involved with alveolar ventilation. (Courtesy of Respironics Inc and its affiliates, Wallingford, Connecticut.)

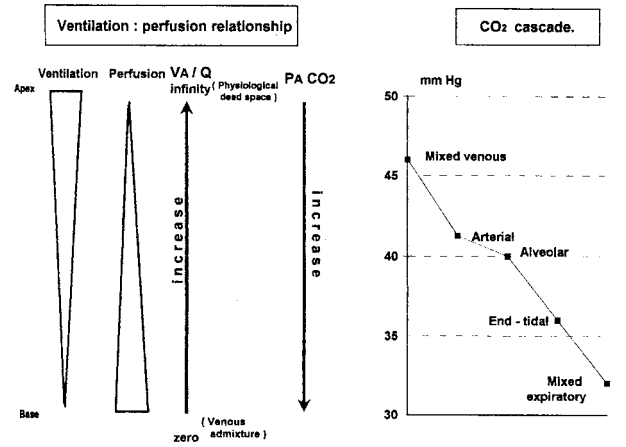

Fig. 5. Ventilation/perfusion relationship and the carbon dioxide cascade. Left: The vertical difference of ventilation and perfusion results in increasing ventilation/perfusion ratio from lung base to lung apex, whereas the alveolar partial pressure of carbon dioxide (P_{ACO_2}) increases down the lung. Right: The P_{CO_2} cascade. $\dot{V}_A/\dot{Q}$ = ratio of alveolar ventilation to perfusion. (Adapted from Reference 5, with permission.)

than does pulse oximetry, and (4) mechanical ventilation can be optimized and the duration of mechanical ventilation potentially minimized with continuous volumetric capnography. The bottom line is that capnography is an important tool for airway monitoring, ventilator management, and overall cardiorespiratory assessment.

Endotracheal Intubation

Capnography as an adjunct to determine that the ETT is in the trachea rather than esophagus is clearly well supported by the medical literature from the intensive care unit, emergency department, operating room, and in the field, by emergency medical personnel.[7–16] Capnography is the standard of care to confirm tracheal intubation.

Roberts et al[10] found in a neonatal population that capnography can more quickly and accurately determine tracheal intubation than can other clinical assessments. Capnography correctly identified errant tube placements in 98% of instances, in 1.6 ± 2.4 s. Birmingham et al[8] reported that clinical evaluation alone is not reliable for confirming endotracheal intubation. They concluded that, other than direct visualization with laryngoscopy, only capnography is consistently more reliable than any other method. Knapp et al[9] reported that the reliability of capnography, unlike other methods, including auscultation, is independent of clinician experience (Fig. 6). Kannan and Manji[14] concluded that capnography "as a mandatory monitor during tracheal intubation in the intensive care unit in conjunction with other methods might improve safety."

Recently, the American Heart Association strongly supported the use of capnography to confirm tracheal intubation of infants and children with a perfusing rhythm. The American Heart Association recommends using a colorimetric detector or capnography to detect exhaled CO_2 to confirm ETT position in the pre-hospital and hospital settings.[15–17] Puntervoll et al[18] reported limitations of the colorimetric techniques. It should be noted that, during cardiac arrest, if exhaled CO_2 is not detected, tube position must be confirmed by direct laryngoscopy, because the absence of exhaled CO_2 may reflect decreased pulmonary capillary blood flow (ie, poor cardiac output).[16]

Although time-based capnography (ie, P_{ETCO_2} monitoring) is an effective tool for validating tracheal placement of the ETT,[7–16] volumetric capnography may be even more effective.[19] Time-based (end-tidal) capnography may occasionally provide a false-positive reading (ie, the ETT is not in the trachea but the monitor displays a P_{ETCO_2} value). This is most likely with patients who (1) have recently ingested carbonated beverages or antacids, (2) have received prolonged bag-valve-mask ventilation prior to intubation, and (3) have the tip of the ETT located in the pharynx. A false-negative time-based result (ie, the ETT is in the trachea but the monitor does not display a P_{ETCO_2} value) can also occur. This is most likely in patients with severe airway obstruction, depressed cardiac output, pulmonary emboli, or pulmonary hypertension. Thus, Li[20] concluded that ETT placement should be confirmed by multiple techniques, including time-based or volume-based capnography.

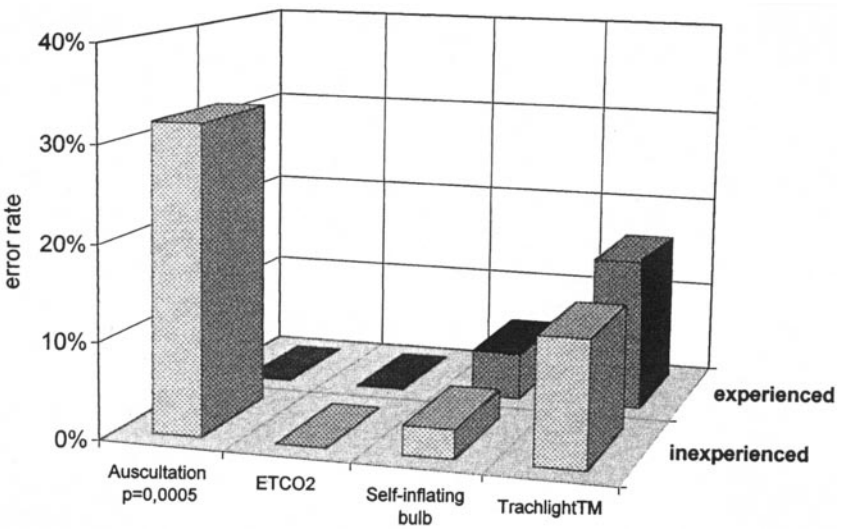

Fig. 6. Error rates of experienced and inexperienced clinicians in determining tracheal positioning of the endotracheal tube, with 4 methods: auscultation, capnography (end-tidal carbon dioxide [$ETCO_2$]), self-inflating bulb, and trachea light. (From Reference 9, with permission.)

Preventing Mishaps

Once endotracheal intubation has been confirmed, the medical literature supports the use of continuous capnography in the operating room to monitor the integrity of the ventilatory circuit, including the artificial airway.[21–23] Capnography is consistently the most sensitive indicator that an ETT has moved or dislodged. Based on the risk of an airway disaster, it seems reasonable to employ capnography in conjunction with the ventilator-disconnect alarm, as an important "double-check" for patient safety.

Continuous P_{ETCO_2} monitoring detects acute airway obstruction and hypopharyngeal extubation more rapidly than does vital-sign monitoring or continuous pulse oximetry.[24] Ahrens and Sona[25] reported that capnography in intensive care units, emergency departments, recovery rooms, and long-term ventilator facilities is an invaluable tool for the early identification of a dislodged ETT.[25] They stated that "capnography offers the most rapid alarm for a ventilator disconnection, by immediately showing loss of expired CO_2."[25] However, it should be noted that a P_{ETCO_2} reading may still be displayed if the disconnect occurs between the CO_2 detector and the ventilator circuit in a patient with spontaneous respiratory effort.

A report by the Joint Commission (formerly the Joint Commission on Accreditation of Health Care Organizations) clearly supports the need for additional monitoring of the integrity of the ventilatory apparatus. A Joint Commission Sentinel Event Alert in 2002 reported 19 ventilator-associated deaths and 4 ventilator-associated devastating neurologic injuries,[23] of which 65% were at least partly related to the malfunction or misuse of an alarm or an inadequate alarm, 52% were related to an ETT or ventilator-circuit disconnect, and 26% were related to a dislodged ETT. It is important to note that none of these adverse events were related to ventilator malfunction. Based on that Sentinel Event Alert, it seems reasonable to use capnography as an additional tool to promptly alert caregivers to an inadvertent extubation or a ventilator-circuit disconnect. Capnography can help avert airway disasters.

Recently, the American Heart Association recommended that during intra-hospital and inter-hospital transport, exhaled CO_2 (qualitative colorimetric detector or capnography) should be continuously monitored with intubated patients to assure the continued integrity of the airway.[15]

Operating Room Setting

As early as 1986, the use of capnography as a routine monitor in the operating room setting was strongly recommended. Eichhorn et al,[22] as part of a major patient-safety/risk-management effort, devised specific, detailed, and mandatory standards for minimal patient monitoring during anesthesia. They concluded that the early detection of untoward trends or events during anesthesia would prevent or mitigate patient injury, which, they speculated, might halt the substantial upward trend in anesthesia-related malpractice suits, settlements, judgments, and insurance premiums occurring at that time.

Tinker et al[26] reviewed 1,175 anesthetic-related closed malpractice claims from 17 insurance companies over 14 years, and found that 31.5% of negative anesthetic outcomes could have been prevented by additional monitoring. Furthermore, the settlements for the incidents that

were believed to be preventable by additional monitoring were 11 times more expensive than those mishaps that were deemed not preventable. Tinker et al concluded that capnography and pulse oximetry, when used in combination, could have prevented 93% of the preventable mishaps. Williamson et al[27] echoed those findings; they concluded that capnography is critical for the detection of general anesthesia adverse events. It is important to emphasize that these studies that are supportive of capnography from intubation to extubation in the operating room setting were performed with technology that is several generations older than what is available today.

The medical literature clearly supports the use of continuous capnography to prevent mishaps in the operating room. Unfortunately, data are lacking from the intensive care unit. However, one might speculate that if continuous CO_2 monitoring is required in the operating room, where the physician-to-patient ratio is at least 1:1, then continuous capnography should be required in the intensive care unit, where the physician-to-patient ratio is far less than 1:1.

Physiology of the Arterial-Versus-End-Tidal CO_2 Difference

Time-based and volume-based (ie, volumetric) capnography both display immediate responses to changes in ventilatory strategy, and they monitor a patient's overall cardiorespiratory function. Volumetric capnography simultaneously measures expired CO_2 and tidal volume to determine $\dot{V}_{CO_2}$ from 3 compartments: (1) artificial airway and anatomical dead space, (2) transition from airway to alveolar ventilation, and (3) alveolar gas. This information is obtained from the single-breath CO_2 waveform (see Figs. 1 and 4). Both P_{ETCO_2} and $\dot{V}_{CO_2}$ can be used to determine alterations in gas exchange in response to changes in mechanical ventilatory support.

Capnography in the critical care setting has been erroneously judged as unreliable because of its variability relative to arterial CO_2 measurements. The evidence available in the medical literature on P_{ETO_2} as a surrogate for P_{aCO_2} in mechanically ventilated patients is varied, which has resulted in skepticism in many clinicians. Thus, capnography has been underutilized, potentially to the detriment of patient care. Factors such as patient position, air leak, changes in airway and alveolar dead space, and alterations in cardiac output should be expected to affect P_{ETCO_2} and its relationship to P_{aCO_2}. Thus, a review of physiology is essential to addressing the relationship between P_{aCO_2} and P_{ETCO_2} ($P_{(a\text{-}ET)CO_2}$) and to correctly interpreting the available medical literature. $P_{(a\text{-}ET)CO_2}$ is an indicator of $\dot{V}/\dot{Q}$ mismatching that results from cardiopulmonary alterations, and $P_{(A\text{-}ET)CO_2}$ is directly proportional to the degree of alveolar dead space. Gas void of CO_2 from the alveolar dead space dilutes CO_2-containing gas from the gas-exchanging alveoli (alveolar ventilation, P_{ACO_2}) and, thus, influences the $P_{(a\text{-}ET)CO_2}$ difference.

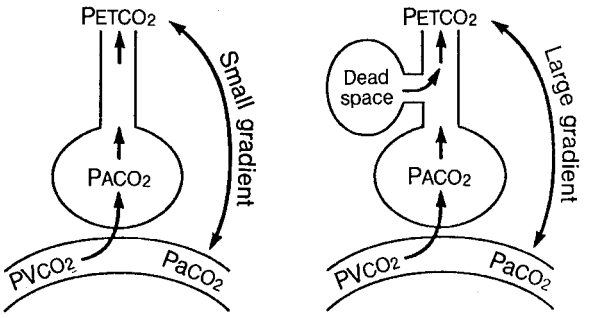

Fig. 7. Relationship between P_{aCO_2}, alveolar partial pressure of CO_2 (P_{ACO_2}), CO_2 clearance from the capillaries into the alveoli (P_{VCO_2}), and partial pressure of end-tidal carbon dioxide (P_{ETCO_2}). The difference between P_{aCO_2} and P_{ETCO_2} is directly proportional to the quantity of dead space, because CO_2-free gas from the dead space dilutes the CO_2-containing gas from the gas-exchanging alveoli. (From Reference 35, with permission.)

The alveolar concentration of CO_2 (P_{ACO_2}) is generally slightly less than that of mixed venous blood, but slightly greater than that of arterial blood. Alveolar and anatomical dead-space gas, which is void of CO_2, dilutes the alveolar CO_2 concentration. Thus, $P_{(a\text{-}ET)CO_2}$ is normally positive (approximately 2–5 mm Hg), because the anatomical dead space is large enough to decrease P_{ETCO_2} below P_{aCO_2}.[28,29]

However, if the lungs are homogeneous (ie, normal $\dot{V}/\dot{Q}$ relationship with no, or very minimal, alveolar dead space), functional residual capacity is reduced, and anatomical dead space is small (eg, during exercise and in supine pregnant women),[30–32] then the P_{ACO_2} is only minimally diluted by CO_2-free gas, which results in a P_{ETCO_2} that may be greater than P_{aCO_2}. A negative $P_{(a\text{-}ET)CO_2}$ value is physiologically possible. It should also be stressed that P_{aCO_2} represents the temporal and spatial mean alveolar concentration of CO_2, whereas P_{ETCO_2} represents the peak alveolar concentration of CO_2 eliminated, which generally reflects slow CO_2 elimination from low $\dot{V}/\dot{Q}$ areas.[28,30–32] The $P_{(a\text{-}ET)CO_2}$ value is a function of the rate of alveolar emptying and the total dead space of the lungs.[28,33]

As alveolar dead space increases, $P_{(a\text{-}ET)CO_2}$ increases.[28] In patients with substantial pulmonary disease, $P_{(a\text{-}ET)CO_2}$ may increase unpredictably, such that P_{ETCO_2} is no longer a reliable reflection of the effectiveness of ventilation and, thus, no longer accurately represents P_{aCO_2}.[34] Conversely, as pulmonary disease improves, $P_{(a\text{-}ET)CO_2}$ narrows due to improvement in $\dot{V}/\dot{Q}$ matching. In patients with lung disease, $P_{(a\text{-}ET)CO_2}$ is usually an excellent indicator of the efficiency of ventilation (ie, ratio of dead-space volume to tidal volume [V_D/V_T]) (Fig. 7). A patient's progress during weaning and the consequences of changes in the ventilator support can be determined by capnography.[36]

Carbon Dioxide Elimination

Capnography allows continuous monitoring of the volume of CO_2 eliminated through the lungs per unit time ($\dot{V}_{CO_2}$ in mL/min). Since $\dot{V}_{CO_2}$ is affected by ventilation, circulation/perfusion, and, to a much lesser degree, diffusion, it is a sensitive marker for changes in a ventilated patient's cardiorespiratory status. $\dot{V}_{CO_2}$ can signal changes in P_{aCO_2}. Volumetric capnography has been used successfully to measure anatomical dead space, pulmonary capillary perfusion, and effective ventilation, to provide a breath-to-breath indicator of changes in gas exchange in response to ventilator settings and to monitor changes in cardiorespiratory interactions.[37,38]

As with oxygen consumption, CO_2 production and elimination ($\dot{V}_{CO_2}$) is a continuous process. Therefore, $\dot{V}_{CO_2}$ rapidly reflects changes in ventilation and perfusion, regardless of etiology. Additionally, $\dot{V}_{CO_2}$ reflects the physiologic response to changes in mechanical ventilator support. Thus, capnography is a useful and sensitive clinical tool to assess a patient's cardiorespiratory and metabolic status.[2,39]

Management of Positive End-Expiratory Pressure

Determining the appropriate positive end-expiratory pressure (PEEP) setting is essential for optimal management of a mechanically ventilated patient with acute lung injury, but there is controversy concerning the best method for determining the appropriate PEEP for an individual patient. The ideal PEEP provides the optimal lung volume and, thus, the highest oxygenation for the lowest fraction of inspired oxygen (F_{IO_2}), the best pulmonary compliance, and the greatest cardiac output. In reality, there is no PEEP setting that achieves all of these goals for a specific patient at a given time. Thus, it is the clinician's responsibility to determine the PEEP setting that most optimally balances these cardiorespiratory goals, keeping in mind that this value is likely to change.

PEEP can be titrated by monitoring $\dot{V}_{CO_2}$ and the volumetric capnogram. Changes in lung volume and its associated effects on pulmonary blood flow alter CO_2 elimination. Theoretically, the optimal lung volume (associated with the optimal PEEP) should be associated with a transient increase in CO_2 elimination. $\dot{V}_{CO_2}$ is more informative than P_{ETCO_2} during PEEP titration.[1,2]

Volumetric capnography can provide valuable information for PEEP management. An increase in anatomical dead space is often present when high PEEP is applied.[39,40] In this situation, an increase in anatomical dead space can be quickly recognized by an increase in phase 1 of the capnogram (see Figs. 1 and 4) and reducing PEEP may improve alveolar minute ventilation ($\dot{V}_E$).

Decreased $\dot{V}_{CO_2}$, with a decrease in the phase-2 slope of the waveform (ie, decreased pulmonary perfusion), indicates excessive PEEP.[40–42] Decreased pulmonary perfusion secondary to excessive PEEP is generally caused by increased intrathoracic pressure, which decreases systemic venous return (ie, decreases right-ventricular preload) and increases pulmonary vascular resistance (ie, increased right-ventricular afterload).[43] Decreased pulmonary blood flow reduces CO_2 transport from the tissues to the pulmonary vasculature, which reduces CO_2 elimination.[1]

Phase 3 of the waveform represents gas distribution at the alveolar level. An increase in the phase-3 slope depicts a maldistribution of gas, which can be caused by an inappropriately low PEEP setting.

Alveolar $\dot{V}_E$

The $\dot{V}_E$ value displayed on the ventilator represents the total quantity of gas moving in and out of the lungs per minute (ie, respiratory rate times tidal volume), which represents the sum of alveolar and dead-space ventilation. On the other hand, alveolar $\dot{V}_E$ is respiratory rate times the volume of air that reaches the alveoli and participates in gas exchange at the capillary level (ie, $\dot{V}_E$ minus dead-space ventilation). Alveolar $\dot{V}_E$ is determined from the volumetric capnogram (see Fig. 4). Phase 3 of the waveform represents the quantity of gas exhaled from the alveoli. Thus, alveolar $\dot{V}_E$ is the volume of alveolar gas per breath summated over 1 min.

Traditional determination of $\dot{V}_E$ may not accurately represent the volume of gas involved in gas exchange at the alveolar level. Volumetric capnography provides continuous determination of alveolar $\dot{V}_E$, which might help optimize ventilator management. As dead-space ventilation approaches zero, then alveolar $\dot{V}_E$ approaches total $\dot{V}_E$. Unfortunately, there are no data that clearly support a clinical benefit of monitoring alveolar $\dot{V}_E$.

Minimizing the Duration of Mechanical Ventilation

Minimizing the duration of mechanical ventilation is crucial in the management of critically ill patients. Shorter ventilation should decrease the risk of ventilator-associated lung injury, overall morbidity, and hospital costs. At our institution we investigated the clinical impact of continuous volumetric capnography on shortening the duration of mechanical ventilation in a heterogeneous group of pediatric intensive-care patients, in a randomized controlled study.[44] Patients managed with continuous volumetric capnography had significantly shorter ventilation than did the control patients. In contrast to routine clinical management alone, continuous volumetric capnography combined with routine clinical management significantly reduced the du-

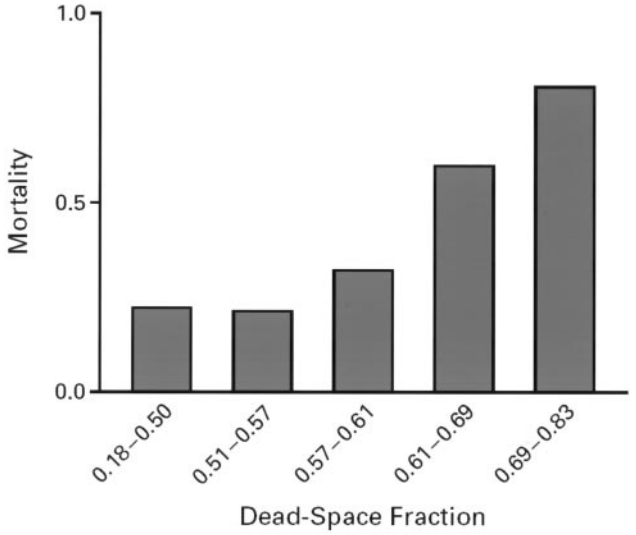

Fig. 8. Mortality relative to the quintile of dead-space fraction in adult patients with acute respiratory distress syndrome. (From Reference 45, with permission.)

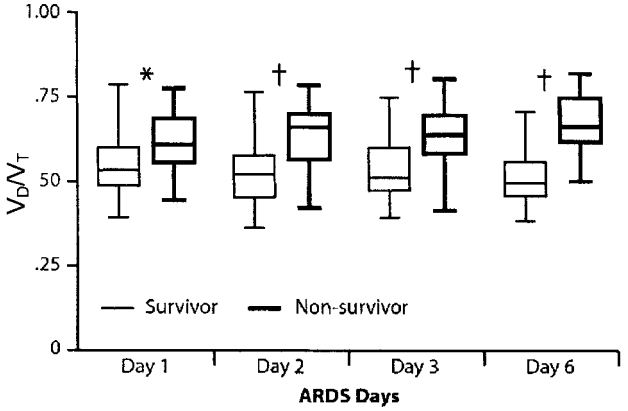

Fig. 9. Changes in the ratio of pulmonary dead space to tidal volume (V_D/V_T) in adult patients with acute respiratory distress syndrome (ARDS). The boxes represent the 25–75% data interval. The horizontal lines in the boxes represent the mean V_D/V_T values. The error bars represent the 95% confidence intervals. * $p < 0.05$ between survivors and nonsurvivors on the same day. † $p < 0.001$ between survivors and nonsurvivors on the same day. (From Reference 46, with permission.)

ration of ventilation in a heterogeneous sample of infants and children.

Acute Respiratory Distress Syndrome: Prognosis

Capnography can also be a valuable tool in the prognosis for adult patients with acute lung injury. Nuckton et al[45] reported that during the first day of onset of acute respiratory distress syndrome (ARDS), an increased physiologic dead-space fraction was an independent and powerful predictor of mortality (Fig. 8). The relative risk of death increased by 45% for every 0.05 increase in dead-space fraction. This increased risk was greater than any other predictive factor, including severity of illness or respiratory compliance. Nuckton et al were the first to report a lung-specific predictor of mortality for ARDS. In a follow-up study, Kallet et al[46] found that a sustained V_D/V_T elevation in adult ARDS patients was characteristic of nonsurvivors (Fig. 9). In a univariate analysis, a $V_D/V_T > 0.55$ during the first 6 days of ARDS was associated with a significantly higher risk of mortality. Kallet et al concluded that dead-space measurements made beyond the first 24 hours of ARDS might be prognostic.[46]

Cardiovascular Physiology

Time-based capnography can be very useful in assessing changes in a patient's cardiovascular status. In the extreme, increases in P_{ETCO_2} and $\dot{V}_{CO_2}$ during cardiopulmonary resuscitation signify an increase in cardiac output (ie, pulmonary capillary blood flow) as spontaneous circulation returns.[47] On the other hand, a reduction in cardiac output produces a high $\dot{V}/\dot{Q}$ ratio, which decreases P_{ETCO_2} and increases $P_{(a\text{-}ET)CO_2}$. Thus, P_{ETCO_2} is a function of cardiac output for a given $\dot{V}_E$.[48] Hence, P_{ETCO_2} and $\dot{V}_{CO_2}$ are noninvasive indicators of pulmonary capillary blood flow. Utilizing this principle, $\dot{V}_{CO_2}$ and P_{ETCO_2} can be used to monitor pulmonary capillary blood flow in many common clinical scenarios, and the effectiveness of cardiorespiratory resuscitation.

Extubation

Predicting successful extubation remains a challenge, especially in the neonatal and pediatric populations. Though many measures have been suggested as reliable predictors of successful extubation, few have been definitively proven, and of those a large percentage require multiple tests over a potentially lengthy period.[49–52] In adults, spontaneous breathing trials are helpful.

With extubation failure rates reported to be as high as 20%, accurately predicting extubation readiness remains an important clinical focus.[53,54] Because of the greater risks with prolonged ventilation[49,50,55–59] and the risks of reintubation,[55,60–67] the decision to extubate must be timed carefully. Though many extubation failure predictors exist,[68–70] a limited number of studies have shown effective success indicators.

The physiologic V_D/V_T is a reliable marker of lung disease in adult critical care patients.[71] With the advances in technology over the past decade, physiologic V_D/V_T can be obtained quickly, accurately, and noninvasively at the bedside. Using a modified Bohr equation, volumetric capnography can rapidly calculate and display

V_D/V_T values. Though there have been no studies on the effectiveness of physiologic V_D/V_T as a predictor of extubation success in adults, $V_D/V_T < 0.5$ is predictive of extubation success in infants and children.[72] An increased physiologic V_D/V_T warrants investigation prior to an extubation trial.

Pro Summary

Capnography noninvasively and continuously monitors CO_2 elimination throughout the respiratory cycle. Both time-based and volume-based capnography allow for mechanical ventilation and extubation strategies to be designed with clear, precise, objective criteria. With the objective data provided by capnography, adequate gas delivery, optimal PEEP, effective ventilation, and timing for extubation can be established regardless of clinician or institutional preferences.

Continuous capnography as an additional clinical tool from intubation to extubation quickly alerts clinicians to important changes in a patient's cardiorespiratory status. Although there are few data to support continuous capnography in the intensive care unit, extrapolating the substantial data from the operating room setting is reasonable. Additionally, basic physiologic principles support the routine use of capnography. However, education is a key component of the successful use of capnography. The multidisciplinary bedside clinical team must know how to interpret the individual data points, the trends over time, and the capnograms.

Overall, capnography is a safe, cost-effective, noninvasive monitoring technology that enhances patient safety and may optimize mechanical ventilation while minimizing the duration of ventilation. The bottom line is that a simple, relatively inexpensive monitor can prevent airway disasters and save lives.

Con: Not Every Mechanically Ventilated Patient Should Be Monitored With Capnography From Intubation to Extubation

Even from the con position it must be acknowledged that capnography has demonstrated its value in confirming correct placement of the ETT and monitoring the integrity of mechanical ventilation equipment. Furthermore, in the operating room it is common practice to adjust ventilator settings based on P_{ETCO_2}, assuming a more or less constant relationship between P_{aCO_2} and P_{ETCO_2}.[73] The purpose of this review is to use the medical literature to demonstrate that this practice is not applicable to other areas of the hospital, especially the intensive care unit.

When assessing the applicability of capnography for all mechanically ventilated patients, the disease states or conditions that affect the relationship between P_{aCO_2} and P_{ETCO_2} must be carefully considered.[5] More specifically, the disease states and conditions described below create important problems for reliable patient monitoring with capnography. The bottom line is that the monitoring of exhaled CO_2 does not serve as an important tool for airway monitoring, ventilator management, or overall cardiorespiratory assessment because of the common (and unpredictable) discrepancy between P_{aCO_2} and P_{ETCO_2}

Patient Position

In a prospective study by Grenier et al,[74] the ability of P_{ETCO_2} to accurately estimate P_{aCO_2} during neurosurgical procedures was assessed in relation to surgical position. Patients were classified into groups according to position: supine, lateral, prone, or sitting. The mean $P_{(a\text{-}ET)CO_2}$ was 6 ± 4 mm Hg. Grenier et al compared 624 simultaneous measurements of P_{aCO_2} and P_{ETCO_2} and found no difference in P_{aCO_2}, P_{ETCO_2}, or $P_{(a\text{-}ET)CO_2}$ for the supine, prone, or sitting groups. In the lateral-position group, P_{ETCO_2} was significantly lower, whereas P_{aCO_2} was not different, which resulted in a significantly higher $P_{(a\text{-}ET)CO_2}$ (7 ± 3 mm Hg, $p < 0.05$).

Negative $P_{(a\text{-}ET)CO_2}$ values, where P_{ETCO_2} is greater than P_{aCO_2}, were first reported by Nunn and Hill in 1960.[75]

In the study by Grenier et al,[74] a negative difference was found in 4% of the comparisons, but only in the prone and sitting positions. A more frequent occurrence was changes in opposite directions (decrease in P_{ETCO_2} with increase in P_{aCO_2} or vice versa), which occurred in 25% of the measurements. These changes occurred more frequently in the sitting, lateral, and prone groups. Grenier et al also found large difference variations (up to 19 mm Hg) in the values from individuals. In all, 11% of measurements obtained varied by > 5 mm Hg, especially in the prone and sitting groups.

Grenier et al[74] concluded that, though the mean $P_{(a\text{-}ET)CO_2}$ was similar to values reported in the literature, P_{aCO_2} could not be reliably estimated by P_{ETCO_2} because of scattering of individual values (in Bland-Altman analysis), negative $P_{(a\text{-}ET)CO_2}$ values, large variations in opposite directions, large difference changes between successive measurements, and instability of $P_{(a\text{-}ET)CO_2}$ values over time, according to position.

Cyanotic Congenital Heart Disease

$P_{(a\text{-}ET)CO_2}$ is generally determined by 4 components: alveolar ventilation, pulmonary perfusion, CO_2 production, and $\dot{V}/\dot{Q}$. In children with cyanotic congenital heart disease, alveolar ventilation typically is normal, whereas pulmonary perfusion and CO_2 production may be abnormal, resulting in $\dot{V}/\dot{Q}$ mismatch. In congenital heart disease, low pulmonary perfusion and/or right-to-left shunting of

low-CO_2/high-CO_2 venous blood leads to cyanosis and, theoretically, an increased $P_{(a\text{-}ET)CO_2}$. The following studies demonstrate the difficulty in using capnography as a surrogate for arterial blood gas analysis in children with cyanotic congenital heart disease.

In one of the earliest studies to assess the accuracy of capnography in congenital heart disease, Burrows[76] simultaneously assessed P_{ETCO_2} and P_{aCO_2} in patients with cyanotic and acyanotic lesions. P_{ETCO_2} significantly underestimated P_{aCO_2} in all cyanotic patients; however, P_{ETCO_2} correlated closely with the P_{aCO_2} in the acyanotic group. V_D/V_T values from the cyanotic patients were significantly greater than those from the acyanotic group. Burrows concluded that, while P_{ETCO_2} may be an acceptable estimate of P_{aCO_2} in children with acyanotic congenital heart disease, P_{ETCO_2} significantly underestimates P_{aCO_2} in children with cyanotic congenital heart disease.

In a follow-up study, Lazzell and Burrows[77] evaluated the stability of $P_{(a\text{-}ET)CO_2}$ during surgery in children with congenital heart disease. Children were divided into 4 equal groups: (1) no interchamber communication and normal pulmonary blood flow (normal group); (2) acyanotic children with increased pulmonary blood flow (acyanotic shunting group); (3) cyanotic children with mixing lesions and normal or increased pulmonary blood flow (mixing group); and (4) cyanotic children with right-to-left intracardiac shunt, which indicates decreased and variable pulmonary blood flow (cyanotic shunting group). Simultaneous P_{aCO_2} and P_{ETCO_2} measurements were obtained from each patient during identifiable intraoperative events, including arterial line placement, patient preparation, post-sternotomy, post-heparin-administration, and immediately after aortic cannulation.

The cyanotic children had a greater $P_{(a\text{-}ET)CO_2}$ than the acyanotic children in the initial measurement comparison. No differences existed in $P_{(a\text{-}ET)CO_2}$ during the course of surgery in the control, acyanotic shunting, or mixing groups. $P_{(a\text{-}ET)CO_2}$ in children with cyanotic shunting lesions was significantly greater after patient preparation and sternotomy than during the initial comparison. Lazzell and Burrows[77] found considerable inter-individual and intra-individual $P_{(a\text{-}ET)CO_2}$ variability in the children who had mixing and right-to-left shunting congenital heart disease.

Lazzell and Burrows[77] concluded that $P_{(a\text{-}ET)CO_2}$ is not stable in children with cyanotic congenital heart lesions and cannot be used during surgery to reliably estimate P_{aCO_2}. Though the $P_{(a\text{-}ET)CO_2}$ in children with acyanotic shunting and mixing congenital heart lesions is stable intraoperatively, mixing congenital heart lesions can cause large individual variations, which brings into question the reliability of P_{ETCO_2} monitoring in these children.

The accuracy and reliability of P_{ETCO_2} monitoring in infants and children with congenital heart disease were also brought into question in a study by Short et al.[78] Simultaneous P_{aCO_2} and P_{ETCO_2} measurements in children with saturations of 65–97% (median 85%) while breathing room air were obtained during surgery. $P_{(a\text{-}ET)CO_2}$ was greater-than-predicted, despite corrections for right-to-left shunting. The patients had a mean $P_{(a\text{-}ET)CO_2}$ of 8.1 ± 4.4 mm Hg, versus a mean predicted value of 2.9 ± 2.3 mm Hg ($p < 0.001$). Short et al concluded that the $P_{(a\text{-}ET)CO_2}$ difference in children with congenital heart disease is difficult to predict, and they hypothesized that this greater-than-predicted $P_{(a\text{-}ET)CO_2}$ indicated that factors other than right-to-left shunting were contributing to this difference in gas exchange.

De Vries and colleagues[73] evaluated the relationship between P_{CO_2} and arterial oxygen saturation measured via pulse oximetry (S_{pO_2}), and, if a consistent relationship was found, to assess whether S_{pO_2} could be applied as a correcting factor to estimate P_{aCO_2} from P_{ETCO_2} in patients with congenital heart disease. The study consisted of (1) a retrospective study to evaluate the relationship between S_{pO_2} and the change in P_{CO_2} to arrive at a more reliable estimate of P_{aCO_2} from P_{ETCO_2} (ie, derivation set to correct for degree of hypoxia), and (2) a prospective observational study to test the clinical usability and reliability of the correction formula (ie, validation set). The correlation between P_{aCO_2} and the raw P_{ETCO_2} values was $r^2 = 0.17$ ($p < 0.05$), whereas the correlation between P_{aCO_2} and the corrected P_{ETCO_2} values was $r^2 = 0.94$ ($p < 0.001$). There was no significant difference between the actual values and the corrected values. Accurate decision making on ventilator settings would have been supported in 92% of the cases with the corrected P_{ETCO_2} values, compared to just 5% when using the raw P_{ETCO_2} values. De Vries and colleagues[73] concluded that, while capnometry is a useful tool in respiratory monitoring, it has important physiologic limitations in estimating P_{aCO_2} in children with congenital heart disease. The authors believed that the utility of capnometry in these children can be enhanced by correcting the P_{ETCO_2} value for the degree of hypoxia.

Transcutaneous Monitoring

Wilson et al[79] prospectively compared 2 methods of noninvasive CO_2 measurement: P_{ETCO_2} and transcutaneously measured CO_2 (P_{tcCO_2}) in infants and children scheduled for repair of congenital heart disease (32 cyanotic and 21 acyanotic patients). Before cardiopulmonary bypass, they obtained simultaneous arterial blood gas, P_{ETCO_2}, and P_{tcCO_2} measurements. The mean difference between the P_{ETCO_2} and P_{tcCO_2} values ($P_{(a\text{-}tc)CO_2}$) (2 ± 1 mm Hg) was significantly less ($p < 0.001$) than $P_{(a\text{-}ET)CO_2}$ (5 ± 3 mm Hg). $P_{(a\text{-}ET)CO_2}$ was lower in 6 patients, whereas $P_{(a\text{-}tc)CO_2}$ was lower in 39 patients. $P_{(a\text{-}ET)CO_2}$ and $P_{(a\text{-}tc)CO_2}$ were equally accurate in 8 patients. The difference was most significant in patients with cyanotic congenital heart disease, in whom

P_{tcCO_2} (2 ± 1 mm Hg) was significantly more accurate than P_{ETCO_2} (7 ± 3 mm Hg, $p < 0.001$). This study by Wilson et al[79] indicates that transcutaneous monitoring provides a better estimation of P_{aCO_2} than does capnography. They also noted that this difference was especially apparent in patients with cyanotic congenital heart disease and in those < 1 year of age.

In another prospective comparison, Tobias and colleagues[80] investigated the efficacy and accuracy of transcutaneous monitoring in infants and children after cardiothoracic surgery. They studied 33 consecutive patients who had undergone cardiothoracic surgery. P_{ETCO_2} was determined via infrared spectroscopy with a sidestream aspirator. Within the first postoperative hour, if the P_{ETCO_2} and P_{aCO_2} values did not correlate (difference ≥ 5 mm Hg), a P_{tcCO_2} electrode was placed. In only 3 cases was $P_{(a\text{-}ET)CO_2}$ < 5 mm Hg, so a P_{tcCO_2} electrode was placed in 30 patients. In 3 patients, all of whom exhibited cardiovascular instability, $P_{(a\text{-}tc)CO_2}$ was ≥ 5 mm Hg. In the remaining 27 patients, a total of 101 pairs of P_{tcCO_2} and P_{aCO_2} values were analyzed. Mean absolute $P_{(a\text{-}tc)CO_2}$ was 1.7 ± 1.4 mm Hg (range 0–9 mm Hg). In the 101 paired values, $P_{(a\text{-}tc)CO_2}$ was ≤ 2 mm Hg in 82 (81%), 3–5 mm Hg in 18 (18%), and ≥ 6 mm Hg in 1 (1%). Linear regression analysis revealed a slope of 0.90 and an r^2 of 0.885 ($p < 0.001$).

In summary, Tobias and colleagues[80] found that transcutaneous monitoring provides clinically acceptable estimates of P_{aCO_2} in infants and children after cardiothoracic surgery, unlike end-tidal CO_2 monitoring. The authors did note that P_{tcCO_2} may be inaccurate in patients who require vasoactive agents (especially in large doses) for cardiovascular dysfunction.

Trauma

Trauma patients frequently have cardiopulmonary involvement that requires mechanical ventilation. The ability to monitor P_{ETCO_2} to detect changes in cardiorespiratory status and/or to adjust ventilator settings could have a major impact on patient care. Russell and Graybeal[81] assessed the accuracy and reliability of 171 P_{ETCO_2} measurements, relative to P_{aCO_2} values, from 9 mechanically ventilated trauma patients. The mean $P_{(a\text{-}ET)CO_2}$ was 14 ± 11 mm Hg and showed a positive correlation ($p = 0.001$, $r^2 = 0.41$); however, only 40% of the changes reflected a linear relationship. Though 78% of the individual patients had significant correlations ($p < 0.02$–0.001) of the $P_{(a\text{-}ET)CO_2}$ differences, P_{ETCO_2} erroneously predicted changes in 27% of the comparisons. To make matters worse, the errors were not consistent, as 15% of the errors were false decreases and 12% were false increases. The authors concluded that, for this trauma population, trends in $P_{(a\text{-}ET)CO_2}$ magnitude cannot be reliably monitored, and concordant directional changes in end-tidal and arterial CO_2 are not assured in a linear fashion.

Mechanical ventilation of patients with head injury, who are at risk for intracranial hypertension, requires high awareness of CO_2 level. Kerr et al[82] conducted a prospective, repeated-measures study to examine the agreement between P_{aCO_2} and P_{ETCO_2} and the magnitude of $P_{(a\text{-}ET)CO_2}$, to track P_{ETCO_2} prior to and after endotracheal suctioning, and to identify factors that affect the accuracy and usefulness of capnography in the clinical management of mechanically ventilated adults with severe head trauma 48–72 hours after injury. They studied 35 consecutive patients (62 observations) admitted to the emergency department with severe head injury (Glasgow Coma Scale score ≤ 8). The Pearson correlation coefficient indicated a weak relationship between P_{aCO_2} and P_{ETCO_2}, regardless of whether the measurement was made immediately prior to or after endotracheal suctioning ($r^2 = 0.09$ and 0.11, respectively). Following the Bland-Altman technique, the mean $P_{(a\text{-}ET)CO_2}$ was 5.8 ± 5.9 mm Hg before suctioning and 7.1 ± 6.4 mm Hg after suctioning. The estimated upper and lower limits of agreement showed that 95% of the $P_{(a\text{-}ET)CO_2}$ differences were between −5.9 mm Hg and 17.5 mm Hg prior to suctioning and between −5.5 mm Hg and 19.7 mm Hg after suctioning. This large range in the limits of agreement confirms a lack of agreement between P_{aCO_2} and P_{ETCO_2}.

Kerr et al[82] noted that larger $P_{(a\text{-}ET)CO_2}$ values (maximum 25 mm Hg) were in patients with atelectasis, pneumonia, or a chest tube. PEEP also significantly affected the difference between P_{ETCO_2} and P_{aCO_2}. As PEEP increased, $P_{(a\text{-}ET)CO_2}$ increased. In patients who were not breathing spontaneously there was a stronger correlation between P_{ETCO_2} and P_{aCO_2} ($r^2 = 0.25$), which was even stronger ($r^2 = 0.77$) when PEEP was < 5 cm H_2O or when the ratio of P_{aO_2} to F_{IO_2} was < 250 mm Hg.

Kerr and colleagues[82] concluded that P_{ETCO_2} was less valid as a surrogate for P_{aCO_2} in patients with the following characteristics: spontaneously breathing, receiving assist-control ventilation, PEEP > 5 cm H_2O, low P_{aO_2}/F_{IO_2}, or any combination of the above. The $P_{(a\text{-}ET)CO_2}$ bias raises serious questions about the clinical utility of this instrument in spontaneously breathing patients and patients developing pulmonary complications.

Obesity

$\dot{V}/\dot{Q}$ abnormalities are an important factor in capnography. $\dot{V}/\dot{Q}$ variations can greatly occur in situations where functional residual capacity is reduced. Griffin et al[83] studied patients with severe obesity (body mass index > 40 kg/m^2) undergoing gastric bypass surgery to determine the accuracy of P_{ETCO_2} and P_{tcCO_2} monitoring. Clinically indicated arterial blood gas samples were obtained with si-

multaneously recorded P_{ETCO_2} and P_{tcCO_2} readings. The differences between the end-tidal and arterial values were averaged.

The absolute difference was significantly lower for the P_{tcCO_2} readings than for the P_{ETCO_2} readings (1.5 ± 1.5 mm Hg vs 5.3 ± 2.9 mm Hg, $p < 0.001$). P_{tcCO_2} more closely correlated with P_{aCO_2} in 83% of patients, whereas P_{ETCO_2} was closer in just 13% (no difference in one patient). Griffin et al[83] created Bland-Altman plots and found that obese patients with the greatest hypercapnia also had the largest $P_{(a\text{-}ET)CO_2}$ values. It was presumed that these patients had greater $\dot{V}/\dot{Q}$ inequality. The authors concluded that transcutaneous monitoring was more accurate than capnography in patients with a body mass index > 40 kg/m^2.

Surgery Patients

Casati and colleagues[84] prospectively studied 17 consecutive geriatric patients (age > 60 y) who were receiving general anesthesia to evaluate the accuracy of capnography and transcutaneous monitoring. After 30 min of hemodynamic stability (systolic arterial pressure within 20% of baseline) and constant ventilatory variables, arterial blood was drawn and immediately analyzed for P_{aCO_2}. At the same time, both P_{ETCO_2} and P_{tcCO_2} values were recorded. The P_{aCO_2} values ranged between 21 mm Hg and 58 mm Hg. The mean $P_{(a\text{-}tc)CO_2}$ was 2 ± 4 mm Hg (95% confidence interval -6 to 9 mm Hg), whereas the mean $P_{(a\text{-}ET)CO_2}$ was 6 ± 5 mm Hg (95% confidence interval -3 to 16 mm Hg, $p = 0.001$). The $P_{(a\text{-}ET)CO_2}$ difference was ≤ 3 mm Hg in only 7 (15%) of the 45 P_{aCO_2} versus P_{ETCO_2} comparisons, whereas $P_{(a\text{-}tc)CO_2}$ was ≤ 3 mm Hg in 21 (46%) of those 45 comparisons ($p = 0.003$). Linear regression analysis for $P_{(a\text{-}tc)CO_2}$ gave a slope of 0.84 ($r^2 = 0.73$), whereas linear regression analysis for $P_{(a\text{-}ET)CO_2}$ gave a slope of 0.54 ($r^2 = 0.50$). Casati et al[84] concluded that in a population of ventilated, elderly patients, transcutaneous monitoring provided a statistically more accurate estimation of P_{aCO_2} than did capnography.

Nosovitch et al[85] prospectively compared the accuracy of capnography and transcutaneous monitoring in 30 pediatric surgery patients. When clinically indicated, arterial blood gases were obtained and simultaneous P_{ETCO_2} and P_{tcCO_2} measurements were recorded. The absolute differences (ie, no negative numbers) were calculated to avoid artificially lowering the mathematical mean of the differences.

The P_{aCO_2} values ranged from 21 mm Hg to 122 mm Hg. The mean $P_{(a\text{-}ET)CO_2}$ was 4.4 ± 7.1 mm Hg. The mean $P_{(a\text{-}tc)CO_2}$ was 2.8 ± 2.9 mm Hg ($p =$ not significant). $P_{(a\text{-}ET)CO_2}$ was ≤ 3 mm Hg in 58% of those pair comparisons, whereas $P_{(a\text{-}tc)CO_2}$ was ≤ 3 mm Hg in 77% of those comparisons ($p = 0.038$). Four transcutaneous values and 12 capnography measurements were 5 mm Hg $> P_{aCO_2}$ ($p = 0.06$). Linear regression analysis of the $P_{(a\text{-}ET)CO_2}$ differences revealed a slope of 0.43 and an r^2 of 0.77. Linear regression analysis of the $P_{(a\text{-}tc)CO_2}$ differences revealed a slope of 0.91 and an r^2 of 0.90. Nosovitch and colleagues[85] concluded that transcutaneous CO_2 monitoring was more accurate than capnography during pediatric intraoperative care.

Russell and colleagues[86] prospectively studied 59 postoperative cardiac surgery patients for $P_{(a\text{-}ET)CO_2}$ differences from admission to extubation in the intensive care unit. A total of 382 individual difference comparisons were made. The relationship between P_{aCO_2} and P_{ETCO_2} was assessed during widely differing conditions of cardiorespiratory support. No respiratory, hemodynamic, or pharmacologic factors assessed significantly changed $P_{(a\text{-}ET)CO_2}$. Mean P_{aCO_2} was 36.5 ± 5.9 mm Hg, and mean P_{ETCO_2} was 31.0 ± 6.4 mm Hg, resulting in a mean $P_{(a\text{-}ET)CO_2}$ of 5.5 ± 5.2 mm Hg (range -8 to $+21.9$ mm Hg). For the population as a whole, the correlation between P_{aCO_2} and P_{ETCO_2}, determined by regression analysis, was maintained ($r = 0.64$, $p < 0.001$). However, the $P_{(a\text{-}ET)CO_2}$ values analyzed for many individual patients did not have a statistically significant correlation (p values ranged from < 0.001 to 0.90). Negative differences constituted 8.1% of the measurements. Despite a significant $P_{(a\text{-}ET)CO_2}$ difference correlation, Russell et al[86] concluded that individual variation observed in postoperative cardiac patients necessitates periodic assessment of ventilation with arterial blood gas analysis.

Specialty Gases

Since 1935, heliox has been used as a therapeutic bridge to improve airflow past pulmonary obstructions.[87] Over the past 2 decades, the use of heliox has gained support in many emergency departments and intensive care units.[88] Ball and Grounds[89] developed a device to generate variable mixtures of helium, O_2, and CO_2 within the normal physiologic range, and they tested the performance of 2 sidestream capnographs and one in-line capnograph.[89] The addition of helium caused all 3 monitors to underestimate the CO_2 concentration. This underestimation increased proportionally as the concentration of helium increased. Though further data are needed, these results could lead to an inappropriate reduction in ventilator settings (and hypercapnia) in patients mechanically ventilated with heliox and managed with capnography.

Transport

Tingay and colleagues[90] conducted a prospective, unblinded study to assess the accuracy and reliability of P_{ETCO_2}

monitoring during neonatal transport. Specifically trained transport pediatricians started P_{tcCO_2} and P_{ETCO_2} monitoring before the first arterial blood gas measurement in 26 infants ≤ 28 days old who had capillary refill time of < 2 s. Paired arterial, transcutaneous, and capnography CO_2 measurements were recorded every 20 min, starting at stabilization and continuing throughout the transport. Twenty-one $P_{(a\text{-}tc)CO_2}$ and $P_{(a\text{-}ET)CO_2}$ values and 82 $P_{(tc\text{-}ET)CO_2}$ values were obtained. The mean $P_{(a\text{-}ET)CO_2}$ was 7.8 mm Hg ($p < 0.001$). Only 48% of the P_{ETCO_2} recordings were within 7 mm Hg of the paired P_{aCO_2} values. This capnography bias was independent of P_{aCO_2}. There was no significant difference for the $P_{(a\text{-}tc)CO_2}$ difference (mean −0.97 mm Hg, $p = 0.4$). Compared to the paired P_{aCO_2} values, 67% of the transcutaneous readings were within 5 mm Hg, and 81% of P_{tcCO_2} readings were within 7 mm Hg. There was no significant difference between P_{tcCO_2} and P_{aCO_2} as the CO_2 level changed. Tingay and colleagues[90] concluded that, for neonates who require ventilation during transport, P_{tcCO_2} more accurately reflects P_{aCO_2} than does P_{ETCO_2}.

Belpomme and colleagues[91] conducted a single center prospective descriptive study of the accuracy of capnography in 100 consecutive adult patients who required intubation and ventilation outside the hospital. The $P_{(a\text{-}ET)CO_2}$ values showed important differences, between −19.7 mm Hg and +75 mm Hg at the time of intubation, and −11.8 mm Hg to +98 mm Hg on arrival at the hospital. Even when the mean $P_{(a\text{-}ET)CO_2}$ was not extremely elevated, it differed widely among the patients: 36% of patients at intubation and 27% on arrival to the hospital had $P_{(a\text{-}ET)CO_2}$ values > 10 mm Hg. Several patients had negative $P_{(a\text{-}ET)CO_2}$ values > 10 mm Hg. The $P_{(a\text{-}ET)CO_2}$ difference did not differ according to disease pathology but was significantly more important ($p < 0.001$) in hypercapnic patients than in normocapnic or hypocapnic patients. The study concluded that capnography is not reliable to accurately estimate P_{aCO_2} and is not sufficient by itself to adjust respiratory settings for patients outside the hospital setting.

Pediatric Respiratory Disease

Tobias and colleagues[92] studied 25 infants and toddlers who required intubation for respiratory failure, to determine the accuracy of capnography and transcutaneous monitoring. When clinically indicated, arterial blood gases were obtained in conjunction with P_{ETCO_2} and P_{tcCO_2} values. Only absolute values (ie, no negative numbers) were used to avoid artificially lowering the mathematical mean of the differences in the values from the noninvasive monitors.

The mean $P_{(a\text{-}ET)CO_2}$ was 6.8 ± 5.1 mm Hg, whereas the mean $P_{(a\text{-}tc)CO_2}$ was 2.3 ± 1.3 mm Hg ($p < 0.001$). The absolute $P_{(a\text{-}tc)CO_2}$ value was ≤ 4 mm Hg in 96% of the comparisons. The absolute $P_{(a\text{-}ET)CO_2}$ value was ≤ 4 mm Hg in 38% of the comparisons ($p < 0.001$). The authors concluded that, in infants and toddlers who require ventilation for respiratory failure, transcutaneous monitoring is more accurate than capnography. P_{ETCO_2} inaccuracy was greatest at higher CO_2 values in patients with severe lung disease managed with permissive hypercapnia.

Berkenbosch et al[93] prospectively compared the accuracy of P_{tcCO_2} and P_{ETCO_2} in 25 pediatric patients who required mechanical ventilation for respiratory failure. When clinically indicated, arterial blood gas measurements were performed, with simultaneous recording of P_{ETCO_2} and P_{tcCO_2}. The mean $P_{(a\text{-}ET)CO_2}$ was 6.4 ± 6.3 mm Hg. The mean $P_{(a\text{-}tc)CO_2}$ was 2.6 ± 2.0 mm Hg ($p < 0.001$). In 71% of the measurements transcutaneous monitoring was more accurate, whereas in 20% of the measurements capnography was more accurate. In 9% of the measurements P_{ETCO_2} and P_{tcCO_2} were equally accurate. In a subgroup analysis in patients who weighed > 40 kg, the mean $P_{(a\text{-}ET)CO_2}$ was 8.4 ± 7.7 mm Hg, compared to a mean $P_{(a\text{-}tc)CO_2}$ of 2.8 ± 2.4 mm Hg.

Berkenbosch et al[93] concluded that transcutaneous monitoring more accurately estimated P_{aCO_2} than did capnography in pediatric patients who required mechanical ventilation for respiratory failure. If it is accepted that a monitored P_{CO_2} value within 3–5 mm Hg of the actual P_{aCO_2} is acceptable for clinical decision making, then 93% of the transcutaneous measurements were within that range, whereas capnography provided that degree of accuracy less than 60% of the time.

In a prospective nonrandomized consecutive enrollment study, McDonald et al[94] evaluated the correlation between P_{ETCO_2} and P_{aCO_2} in mechanically ventilated critically ill infants and children to determine whether P_{ETCO_2} reliably estimated ventilation. They analyzed 1,708 pairs of P_{ETCO_2} and P_{aCO_2} values. P_{ETCO_2} correlated with P_{aCO_2} ($r^2 = 0.72$, $p = 0.001$), and they concluded that their data strongly supported the utility of capnography as a noninvasive method to assess ventilation in critically ill patients with minimal-to-moderate lung disease. However, closer review of their data calls into question the clinical utility of the results. The absolute $P_{(a\text{-}ET)CO_2}$ values were < 5 mm Hg in only 54% of the comparisons, and were > 10 mm Hg in 20% of the comparisons. And in 1,423 consecutive blood gas analyses, P_{aCO_2} and P_{ETCO_2} changed in the opposite direction 26% of the time. A multivariate analysis by the investigators showed that P_{aO_2}/F_{IO_2} and the ventilator index (ie, (P_{aCO_2} – peak inspiratory pressure) – respiratory rate)/1,000) significantly influenced ($p = 0.001$ and 0.01, respectively) $P_{(a\text{-}ET)CO_2}$. The authors also noted that $P_{(a\text{-}ET)CO_2}$ becomes more variable as the number of pairs available for analysis increases for a single subject.

Con Summary

In summary, several factors can dramatically alter the accuracy of capnography. Both sampling errors and alterations in $\dot{V}/\dot{Q}$ status can cause inaccuracy. Diseases and conditions that increase dead space and/or intrapulmonary (eg, parenchymal diseases or conditions) or extrapulmonary (eg, cyanotic congenital heart diseases) shunt increase the difference between P_{ETCO_2} and P_{aCO_2}. Furthermore, alterations in $\dot{V}/\dot{Q}$ matching, secondary to increased dead space or shunt fraction, limit the accuracy of capnography in patients with abnormal pulmonary function.

Summary

Despite an extensive review of the medical literature, there does not appear to be a definitive answer to the question, "Should every mechanically ventilated patient be monitored with capnography from intubation to extubation?" The lack of a clear answer is because no definitive, randomized studies have attempted to address this question. The pro position is supported by the physiology of the $\dot{V}/\dot{Q}$ relationship in the lung and capnography's ability to prevent airway mishaps. On the other hand, the con position is supported by literature that brings into question the relationship between P_{ETCO_2} and P_{aCO_2} in the clinical setting.

Thus, in conclusion, it seems reasonable to continuously monitor at least a subset of critically ill patients with capnography to ensure the integrity of the ventilatory apparatus and the ETT. However, at this point, definitive data are not yet available to clearly support continuous capnography to optimize mechanical ventilatory support. We hope that as new data become available, the answer to this capnography question will become obvious.

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Discussion

Steinberg: It seems there are 2 uses for capnometry: preventing catastrophes, and titrating mechanical ventilation. Tim [Myers], though the technology might not be good enough for us to titrate therapies, is the technology good enough to help us monitor for disasters? That seems to me the more important reason to use capnography.

Myers: Yes, I think it's cost-effective from a disaster standpoint, and there are probably no major arguments about that. But I think the catastrophes capnography can help us avoid are relatively rare. Ira [Cheifetz] showed us Joint Commission data on 23 patients, but that is only 23 out of how many thousands intubated during that period? And it wasn't a question of not having monitoring capabilities; rather, it was inappropriately-set ventilator alarms or alarms that were turned off.

I think the bigger question is that we come to look at various monitors—electrocardiogram, pulmonary graphics, waveforms, pulse oximetry—as the accepted standards, and when we get a number that we think matches the patient condition, we typically accept it as accurate and move on. That is potentially problematic in some situations with patients who have a P_{aCO_2}-to-P_{ETCO_2} difference to start with and who get worse with certain conditions. If we could use it for a training mechanism, that might be beneficial, but the data shows that in 10–25% of the cases cited the P_{ETCO_2} value trends in the opposite direction of the P_{aCO_2}.

Cheifetz: With regard to using capnography for clinical management, which is what we do every day

for every ventilated patient in our ICU, I presented preliminary data that indicated significantly shorter duration of mechanical ventilation in a heterogeneous group of pediatric ICU patients. The key in using capnography for clinical management is to go back to the basic physiology. In most of the studies that Tim mentioned that claimed a significant difference between P_{aCO_2} and P_{ETCO_2}, the difference was about 5 mm Hg. Well, 5 mm Hg represents the expected airway dead space, so the key here is that you need to employ capnography within the context of your overall knowledge of the patient, the patient's pathophysiology, and basic physiology. As dead-space ventilation changes, the difference between P_{ETCO_2} and P_{aCO_2} changes as well, and that represents a key component in the clinical management of a patient. It does not mean that the monitor is wrong. In fact, the monitor is telling you what is going on—you must use all of the available information to manage your patient accordingly.

Kallet: Two comments. First, we use pulse oximetry as a standard monitoring. We wouldn't get rid of that, and there are definite situations where there is artifact in pulse oximetry that doesn't match the S_{aO_2} [oxygen saturation measured via blood-gas analysis], but we work around that; we live with it! Second, I think the future in capnography is probably going to be volumetric, because a lot of the things Tim alluded to, I think, can be solved when we start measuring mixed expired CO_2 and also being able to determine the slope of phase 3 for alveolar dead space. So, again, when the gradients change, we need to have a therapeutic intervention. Particularly in ARDS, in the future I think these tools might be helpful in titrating PEEP, V_T, or recruitment in lung-protective ventilation.

Hess: I agree with the issues about dead space and the gradient. I don't think the problem with capnography is the technology; it's the physiology and understanding the physiology. Most clinicians want to use capnography as a substitute for an arterial blood gas, so when looking at the P_{aCO_2}-P_{ETCO_2} difference, most clinicians are not trying to assess the physiology and the dead space and so forth—they want to make a ventilator adjustment because the P_{ETCO_2} goes up or down and eliminates the need for an arterial blood gas part. And I think that is where problems can arise, as Tim pointed out, because the numbers can move in opposite directions in a significant number of cases.

Rubin: A lot of this is centered around physiology and the appropriate interpretation. I'd like to address the issue with a cost/benefit analysis, particularly if you are basing this on legal costs. Lawyers like numbers, and the more numbers you give them, the more they are going to be able to pick things apart and use the numbers to talk about appropriate or inappropriate response. Many would expect that oxygen saturation measurements are the standard of care. There was an editorial in *Chest* a few years back calling oxygen saturation the "5th vital sign."[1]

I'm currently an expert in a legal case where there is a practice that consistently measures oxygen saturation in children who come in. There is a child who came in, doing well, had a bit of pneumonia, had oxygen saturation that they measured at 93%, sent the child home, appropriately on an antibiotic, and a few days later the child died. The concern from the lawyers was that they didn't admit the child immediately to the hospital with oxygen saturation of 93%. I said this is unusual that they are grabbing on to that number. And the lawyer that I'm working with said, "Not at all. Here are some publications in the legal literature telling lawyers how to use oxygen saturation measurements to their benefit in malpractice suits." So I would contend that if you give them more numbers, they will find more ways to sue us, and it won't necessarily reduce legal costs.

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Deem: With regard to pulse oximetry, we assume it is the standard of care, but in the only large randomized trial that has compared pulse oximetry to no pulse oximetry,[1,2] which was done in Scandinavia and enrolled more than 20,000 patients, there was no benefit. But we still assume that pulse oximetry is the standard of care. And so, given that there were 26 cases, and that your assumption is that those cases would have been prevented by capnometry—which we don't really know to be true—in terms of the economic impact that means there were only 26 hospitals that were affected across the country. For the individual hospital the cost would be considerable to buy a capnometer for each patient, and very few if any of those patients would actually benefit. For that matter, very few hospitals would benefit. So I think you have to look at the economics a little bit differently, as opposed to looking at the legal savings.

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Cheifetz: I presented the financial argument as a preemptive strike, expecting Tim to come back at me with finances, but it did not happen. There are advantages and disadvantages of not sharing your talks ahead of time, and we had not shared ours. My important arguments for capnography are that it can prevent airway disasters and help optimize mechanical ventilation.

When it comes to lawyers and administrators, and what they are going to do with the numbers, we can argue about that all day; but there are data and experience that you can prevent disasters with capnography. Preventing an airway disaster obviously goes a long way. Imagine if that patient is in your ICU or is a loved one in another ICU. In terms of spreading the costs around, yes, the financial impact of the litigations may hit just a few hospitals, obviously not all hospitals, but what if it's your hospital and your unit?

MacIntyre: It will hit your premiums.

Cheifetz: It will definitely hit you. Somehow, an airway disaster is going to affect you. In our ICU we have had several cases where kids were inadvertently extubated, generally small sick babies. In each case, the problem was caught quickly and the patient did fine. But the first warning sign of an inadvertent extubation to the bedside staff is the end-tidal capnography alarm; it generally is more sensitive than the ventilator alarm.

Fessler: I've never believed that we suffer from too little information in the ICU. I'm skeptical when anyone tells me that I need to monitor something more, and I'm even more skeptical when they tell me that it's going to come with no costs and no risks. One of the additional costs is all the unnecessary tests that will be done to track down spurious inaccurate results. I think you estimated the acquisition costs for hospitals throughout the United States to be about $85 million. For a simple cost/benefit analysis, if we consider a best-case scenario that we would prevent 17 deaths by spending that $85 million, that's $5 million per death. That's no one's definition of a cost-effective intervention. It sounds like a tremendous waste of health-care dollars.

Hess: I'm trying to think of a disaster that would occur on a ventilator that a capnograph would pick up rather than appropriately-set ventilator alarms. For example, if a patient self-extubates, there should be a disconnect alarm that sounds on the ventilator virtually right away. Or if a tube occludes, there should be a high-pressure or low-V_T alarm. I can't think of a disaster that a capnograph might pick up before an appropriately-set ventilator alarm would.

MacIntyre: If I may preemptively strike here, I remember a case in which a young person became disconnected from the ventilator, but the circuit fell on the patient's chest, and the pressure and volume alarms were not tight enough to pick up the fact that ventilation was not being delivered to the patient. Now, you could argue, maybe the alarm should have been set a little bit tighter, and that's reasonable. But that's an example of why at one point the Food and Drug Administration was suggesting redundant alarm systems for life-support systems.

Hess: Let me give you another scenario. You have your capnograph hooked onto the endotracheal tube; the ventilator disconnects from the capnograph, which is still attached to the endotracheal tube; the patient is able to do some breathing on their own, and the capnograph would not be useful in determining that there is no CO_2 or there's no ventilation coming from the ventilator.

Cheifetz: Redundancy in life-support monitoring systems is important. Any time anyone investigates any patient disaster, there is never a single root cause of the incident. There is always more than one underlying problem. If you rely on one alarm, one single process, it may not be enough, so redundant alarm systems and several layers of safety checks are essential to prevent disasters. This is no different from chemotherapy administration, where every step of the ordering and administration process has a double-check to prevent a medication disaster. The aviation industry also has redundancy built into their safety checks and alarm systems.

Hess: Correct, and then you add more ICU monitors that produce spurious alarms, and then nobody pays attention to *any* of them.

Rubin: We've already stated that good clinical assessment is more important, so I would argue that, rather than getting capnographs, it would be more effective to spend the money on an additional well-trained respiratory therapist in the ICU, to provide the eyes and ears and careful assessment skills to determine what's going on, when, and with which patients.

Cheifetz: I think that would be great if we had an abundance of respiratory care practitioners to put in the hospitals. Ray [Masferrer, Associate Executive Director, American Association for Respiratory Care], how many respiratory therapists are we short right now in the United States, based on the recent AARC work survey study? Ray says many!

Myers: Ira pointed out that a lot of those P_{aCO_2}-P_{ETCO_2} differences were 5–6 mm Hg, which is right on the cusp of what is normal anatomical physiology for a gradient. Interestingly enough, most of these studies were designed not to track negative numbers, to make it statistically "nice" to calculate their mean. So that could be 6 in the opposite direction of the difference you're expecting. If they had looked at negative numbers, the pCO_2 values could have been in the 40–50 mmHg range. With normal arterial CO_2 values, where you are in there actually increasing ventilator settings and those types of things to bring your CO_2 back into range, it's a negative correlation or a negative gradient that you are really dealing with. Those were

kind of statistical flaws, I think, in some of those studies that didn't look at negative numbers or negative gradients in most of them.

MacIntyre: Ira, can I switch gears from monitoring disconnects? Obviously, what's critical is how you *use* the monitor, and in your weaning study[1] you only reported those who had the monitor and those who didn't have the monitor. What did you do with the capnograph that caused the shorter ICU stay?

1. Hamel D, Cheifetz I. Continuous monitoring of volumetric capnography reduces length of mechanical ventilation in a heterogeneous group of pediatric ICU patients (abstract). Respir Care 2005;50(11):1517.

Cheifetz: That is the commonly asked question about our volumetric capnography study. We compared duration of ventilation between 2 groups: a volumetric capnography group and a standard of care group. Our goal was to study the effects of monitoring volumetric capnography on routine ventilator management and duration of ventilation. We intentionally did not protocolize the 2 groups. We used volumetric capnography, based on the available data. First, we used capnography to predict the likelihood of successful extubation. We used Hubble's study of the V_D/V_T ratio as a predictor of extubation.[1] A V_D/V_T less than 0.5 was associated with a 96% successful extubation rate, a V_D/V_T of 0.51–0.65 was associated with a 67% successful extubation rate, and a V_D/V_T greater than 0.65 was associated with only a 20% success rate. In our study, we trended V_D/V_T over time. It may have been that our results were based on simply pulling the endotracheal tubes a little quicker. Of note, the extubation-failure rates were identical in the 2 groups.

For weaning we used carbon dioxide elimination ($\dot{V}_{CO_2}$) and alveolar minute ventilation (and their trends over time) to optimize patient-ventilator interactions. Volumetric capnography also enabled us to continuously monitor V_T at the endotracheal tube, which is important for infants and small children,[2–4] and the goal V_T was 6 mL/kg for patients with acute lung injury.[5] I realize that the need to monitor V_T at the endotracheal tube is more of an issue for infants and children than for adults.

I also must acknowledge that it is possible that the patients in the intervention group received more attention from the bedside staff, although we will never be able to prove or disprove that. Staff may have paid more attention to the numbers, leading to more interactions with the ventilators, and being more involved with the patients in the capnography group. This is obviously a risk in any unblinded study.

We are now working to assess patterns of how $\dot{V}_{CO_2}$, alveolar minute ventilation, and the other volumetric capnography variables relate to changes in patient management and the implications on duration of ventilation. We are also working to develop protocols to better define the role of volumetric capnography to optimize mechanical ventilation. So in summary, we still have many questions as well.

1. Hubble CL, Gentile MA, Tripp DS, Craig DM, Meliones JN, Cheifetz IM. Dead space to tidal volume ratio predicts successful extubation in infants and children. Crit Care Med 2000;28(6):2034–2040.
2. Castle RA, Dunne CJ, Mok Q, Wade AM, Stocks J. Accuracy of displayed values of tidal volume in the pediatric intensive care unit. Crit Care Med 2002;30(11):2566–2574.
3. Cannon ML, Cornell J, Tripp-Hamel DS, Gentile MA, Hubble CL, Meliones JN, Cheifetz IM. Tidal volumes for ventilated infants should be determined with a pneumotachometer placed at the endotracheal tube. Am J Respir Crit Care Med 2000; 162(6):2109–2112.
4. Chow LC, Vanderhal A, Raber J, Sola A. Are tidal volume measurements in neonatal pressure-controlled ventilation accurate? Pediatr Pulmonol 2002;34(3):196–202.
5. The Acute Respiratory Distress Syndrome Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000;342(18):1301–1308.

MacIntyre: It always worries me when we have the "usual care" control groups, especially in weaning trials. As Ely found many years ago in adult patients,[1] and which was subsequently confirmed by Kollef et al,[2] if you protocolize your weaning with rules that have aggressive spontaneous breathing trials and regular assessments, you will shorten weaning time, compared to physician-guided weaning. So getting the staff on board to do these things in a regular fashion is important. *That* should be the control group, not the uncontrolled behavior patterns.

1. Ely EW, Baker AM, Dunagan DP, Burke HL, Smith AC, Kelly PT, et al. Effect on the duration of mechanical ventilation of identifying patients capable of breathing spontaneously. N Engl J Med 1996;335(25): 1864–1869.
2. Kollef MH, Shapiro SD, Silver P, St John RE, Prentice D, Sauer S, et al. A randomized, controlled trial of protocol-directed versus physician-directed weaning from mechanical ventilation. Crit Care Med 1997;25(4):567–574.

Cheifetz: When we designed the study, we considered using detailed protocols for both groups, but we feared that we would be studying the protocols rather than the technology. Either way, the study could be faulted. So what you have to do is perform the study one way and then come back and confirm the results the other way, which we are planning to do.

MacIntyre: Protocol with a machine and protocol without a machine, I think would be a pretty good study.

Branson: Nobody has mentioned the actual devices. We have Dräger ventilators, which have a sensor that goes in the airway, and whenever I put it in the airway, I guarantee you when I come back in 4 hours, the sensor will be out, because it alarms, saying "clean the cuvette," because of the humidity. How much problem is there

with failure of side-stream versus mainstream technology in anesthesia? My biggest limitation is that I can't get a therapist to leave the sensor in line.

Cheifetz: For years the policy in our unit has been to monitor capnography from "intubation to extubation." It is rare that the capnostat is taken out of line by the bedside staff because of a technical issue or secretions. I can count on my fingers how many times it happens in a year. The key is educating the staff to keep the sensor clean and to keep the tubing vertical instead of horizontal, so secretions do not enter the lines. With staff education, we have not had a problem.

Branson: I recently reviewed a paper about controlling end-tidal CO_2 in head-injured patients, especially during the pre-hospital phase. And the issue becomes, if you control it—let's say the normal range is 35–45 mm Hg—this issue of the physiology and not matching the arterial CO_2, what happens when the end-tidal CO_2 is very low, because of the large $\dot{V}/\dot{Q}$ mismatch because the patient also has aspirated or has a pulmonary contusion? Then do you have the paramedic not actually ventilating the patient adequately, to provide adequate CO_2 elimination and oxygenation trying to get the CO_2 to rise? And what happens when it is very high—again because of the $\dot{V}/\dot{Q}$ mismatch—and you have the patient being very aggressively ventilated and killing the cardiac output and the blood flow to the brain? That's my *big* concern. I think Dean probably said it very well: it's not the monitor; it's the physiology and understanding behind it.

Kallet: There were a couple of studies[1,2] in which they looked at capnography in the pre-hospital setting with head-injured patients, and in terms of trying to maintain a normal CO_2, statistically there were better outcomes. It was a useful tool in the pre-hospital setting with head-injured patients.

1. Helm M, Schuster R, Hauke J, Lampl L. Tight control of prehospital ventilation by capnography in major trauma victims. Br J Anaesth 2003;90(3):327–332.
2. Davis DP, Dunford JV, Ochs M, Park K, Hoyt DB. The use of quantitative end-tidal capnometry to avoid inadvertent severe hyperventilation in patients with head injury after paramedic rapid sequence intubation. J Trauma 2004;56(4):808–814.

Branson: What it shows is that *if* it's normal the patients do better. It doesn't show that if people actively *make* it normal that it makes a difference. And therein lies the problem: if it's normal in the normal range, patients do have better outcomes. But if it's very low, meaning high V_D/V_T, they don't do very well because of lung injury. If it is very high, perhaps for another reason, they also don't do very well. But there is nothing that says that forcing it into a range improves the outcome in those head-injured patients. That particular study has not been done.