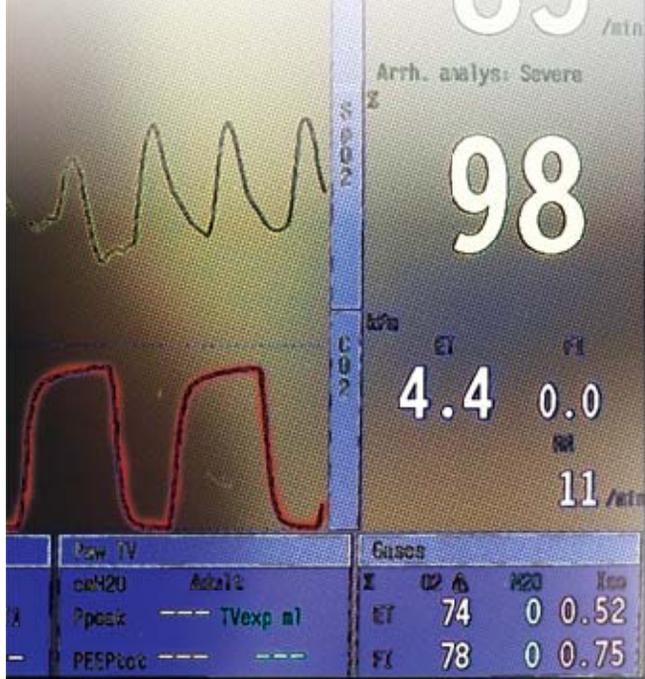




# End-Tidal Carbon Dioxide: The Most Vital of Vital Signs



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The alveolar concentration of carbon dioxide (CO<sub>2</sub>) is the result of ventilation, perfusion, metabolism, and their interactions. Change in the concentration of CO<sub>2</sub> reflects perturbations in any or all of these factors. Detection of CO<sub>2</sub> in an exhaled breath by monitoring end-tidal CO<sub>2</sub> (etCO<sub>2</sub>) via capnography has long been clinically invaluable in providing immediate information about CO<sub>2</sub> production, ventilation/perfusion (V/Q) status, elimination of CO<sub>2</sub> from the circuit and lungs, and patency and function of the breathing circuit itself.

The measure of arterial and exhaled CO<sub>2</sub> provides a metric for management and diagnosis in both normal and pathophysiologic states, and as a tool to guide clinical practice both within and outside the operating room. In non-OR procedural environments, such as the emergency room or gastrointestinal (GI) suite, capnography is more lifesaving than the use of pulse oximetry alone because it provides more rapid detection of respiratory depression or apnea leading to hypoxia than pulse oximetry (Table 1).<sup>1</sup>

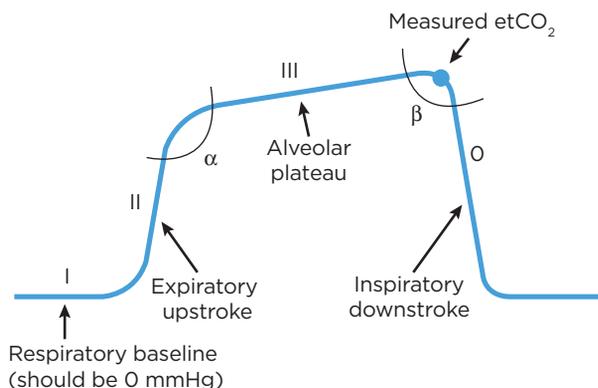
With the increasing portability of CO<sub>2</sub> analyzers, capnography likely will become the standard of care in many more locations and situations. Recently introduced recommendations and practice standards for capnography include resuscitation for cardiac arrest, continuous etCO<sub>2</sub> monitoring in the ICU, patient transport, and for moderate sedation practices.

Capnography (derived from the Greek *kapnos* ("smoke") and *graphein* ("to write")) is the graphic display of the measurement of CO<sub>2</sub> in the respiratory gases and has become an integral part of anesthesia monitoring. In 1978, the Netherlands became the first country to adopt capnography as a standard monitor during anesthesia.<sup>2</sup> Time-based capnography, the most commonly displayed measure of etCO<sub>2</sub>, displays the respiratory phases in inspiration and expiration. Volumetric capnography can measure the volume of

**Table 1. Uses for Capnography**

|  |
|--|
| Adequacy of fresh gas flow   |
| Adequacy of mechanical ventilation                                       |
| Adequate reversal of neuromuscular blockade                              |
| Asthma/chronic obstructive pulmonary disease                             |
| CO <sub>2</sub> absorption (laparoscopic)                                |
| Cardiac arrest/evaluation of cardiac compressions                        |
| Detection of blocked or kinked tracheal tube                             |
| Detection of breathing/sampling circuit leak                             |
| Detecting circuit disconnection  |
| Detection of dead space  |
| Detection of pulmonary embolism  |
| Endotracheal intubation  |
| Evaluation of dual lumen endotracheal tubes                              |
| Feeding tube insertion   |
| Functional analysis of rebreathing apparatus                             |
| Indirect estimate of cardiac output/cardiac index (fluid responsiveness) |
| Measurement of cardiac output  |
| Metabolic acidosis   |
| Non-OR deep sedation, conscious sedation                                 |
| Nutritional support  |
| Onset or waning of neuromuscular blockade                                |
| Patient transport  |
| Shunts in cyanotic heart diseases  |
| Ventilator management (titration of PEEP/weaning and extubation)         |

OR, operating room; PEEP, positive end-expiratory pressure



**Figure 1.** Typical time-based capnography.

expired CO<sub>2</sub> over time and provide information about physiologic dead space and the effects of positive end-expiratory pressure (PEEP) on expiratory phase morphology.

### Basic Physiology

At the end of inspiration, assuming no rebreathing, the airway and lungs are filled with CO<sub>2</sub>-free gases. Carbon dioxide diffuses into the alveoli and equilibrates with the end-alveolar capillary blood. The concentration of CO<sub>2</sub> in the alveoli is determined by the V/Q ratio. Alveoli with a higher V/Q ratio have lower CO<sub>2</sub> than low V/Q alveoli. During exhalation, CO<sub>2</sub> is evident on the capnogram, reflecting dead space, but gradually a peak appears. At the end of exhalation with inhalation of CO<sub>2</sub>-free gases, the capnogram goes to baseline (O) and the end result is a characteristic shape of the CO<sub>2</sub> curve (Figure 1).

The 2 segments of the capnogram are expiration and inspiration. During inspiration, the graph represents the amount of CO<sub>2</sub> in the inspirate. Rebreathing of dead space volume and exhaustion of CO<sub>2</sub> absorber elevate the normal baseline of inspired CO<sub>2</sub>. The expiration segment of the capnogram is more complex and provides more clinical information. It is divided into 3 phases: Phase I represents physiologic dead space and contains no sampled CO<sub>2</sub>. Phases II (plateau) and III represent the evolution of CO<sub>2</sub> from an exhaled breath measured at frequent intervals and displayed over time. For simplicity, many capnograms appear to exhibit a flattened plateau, but the dynamic removal of CO<sub>2</sub> from the alveoli and thus the CO<sub>2</sub> partial pressure is not uniform, and should have an upward rather than flat slope (Table 2).

For a numerical display, etCO<sub>2</sub> is read at the end of phase II and represents the maximum amount of CO<sub>2</sub> measured. If the observer is serious about obtaining dead space and flow mechanics, however, volumetric capnography should be employed (Figure 2).

In contrast to time-based capnography, volumetric capnography is essentially an etCO<sub>2</sub> curve plus flow and volume. Whereas time-based capnography records partial pressure of CO<sub>2</sub>, etCO<sub>2</sub>, and respiratory rate, volumetric capnography records the gas fraction and time-based measurements plus VCO<sub>2</sub>, dead space, and other respiratory mechanics, including flow and airway pressure. Volumetric capnography is more informative than time-based capnography as it provides a measure of not only respiratory rate, but a more in-depth understanding of the ventilation-perfusion relationships of the lung as exhibited by the slope of phase III of the capnogram, as long as the ventilation system is not leaking, including a pneumothorax or leaks from the cuff of an endotracheal tube (ETT). Volumetric capnography is more complicated to employ and interpret, and therefore is not used routinely.

### Physics of Capnography

There are 5 methods for detecting CO<sub>2</sub>: infrared (IR) spectroscopy, molecular correlation spectroscopy

(MCS), Raman spectroscopy, mass spectroscopy, and photoacoustic spectroscopy (PAS).

**Infrared Spectroscopy.** In IR spectroscopy, beams are emitted from a light source into a sample. As the beam passes through the sample, CO<sub>2</sub> absorbs a specific wavelength of light (4.3 μm). This measurement is used to calculate the amount of CO<sub>2</sub> in the sample. IR spectroscopy is the most widely used and cost-effective method for detecting CO<sub>2</sub> and is found in most portable etCO<sub>2</sub> devices.

**Molecular Correlation Spectroscopy.** MCS is a laser-based technology that generates an IR emission that precisely matches the CO<sub>2</sub> wavelength. This precision can be important if the spectrometer must differentiate perfectly between nitrous oxide (N<sub>2</sub>O) and other gases that absorb at ranges close to that of CO<sub>2</sub>. The technology allows for refined measurements of small sample size. Because MCS is highly specific with all gas samples, the monitor does not require special algorithms to correct for high concentrations of oxygen, N<sub>2</sub>O, or other anesthetic gases, as required by other capnography technologies.

**Raman Spectroscopy.** This technology uses the principle of Raman scattering, whereby a laser illuminates a sample of gas such as CO<sub>2</sub> or N<sub>2</sub>O, or water vapor. As CO<sub>2</sub> selectively absorbs specific wavelengths of IR light, the amount absorbed is proportional to the amount of CO<sub>2</sub> in the sample.

**Photoacoustic Spectroscopy.** PAS is based on the same principle as IR-based analyzers: The CO<sub>2</sub> molecules absorb the IR light. However, whereas IR spectroscopy uses optical methods of detection, PAS records acoustic signals. A CO<sub>2</sub> sample is bombarded with pulses of IR waves, making the sample rapidly expand and contract, producing sound waves. A sensitive microphone picks up these sound waves, which vary according to how much CO<sub>2</sub> is present in the sample.

**Mass Spectroscopy.** This is a bulky and expensive technique that measures the charge-to-mass relationship of molecules in sample. It is not commonly used clinically.

It is possible also to detect CO<sub>2</sub> with calorimetry. An indicator treated with chemical foam is contained in a plastic housing that attaches to the ETT following intubation. A color change from purple to yellow indicates the presence of CO<sub>2</sub>. This technique cannot provide continuous or numeric information and thus has limited utility other than for confirming the placement of an ETT.

### Pathophysiologic States Detected by Capnography

As etCO<sub>2</sub> measurements generally reflect ventilation, perfusion, and metabolism, change in etCO<sub>2</sub> is an invaluable aid in the diagnosis of a range of pathophysiologic states. A sudden or gradual increase in etCO<sub>2</sub> can signal fever associated with sepsis, malignant hyperthermia, decreased ventilation, venous pulmonary embolus (with CO<sub>2</sub>), increased carbon monoxide, return of circulation

## Table 2. Checklist for Assessing The Capnogram

The primary usefulness of capnometry is to determine whether there is evidence of patient ventilation.

Is the patient breathing and therefore is there a plateau/onset of the capnogram?

Is there evidence of slow exhalation (slanted upstroke)?

On the horizontal plateau of the capnogram is there uneven emptying of the lungs?

In mechanically ventilated patients, is there evidence of interrupted inspiratory efforts on the horizontal plateau?

Is the down-stroke steep (normal) or is there slow inspiration or rebreathing of CO<sub>2</sub>? Could there be an incompetent ventilator inspiratory valve?

Adapted from Capnography in Clinical Practice. Gravenstein, Paulus, Hayes. Anesthesia Patient Safety Foundation. 1988.

following cardiopulmonary resuscitation (CPR), and chronic obstructive pulmonary disease. Decreasing CO<sub>2</sub> may indicate pulmonary embolism, cardiac arrest, hypothermia, excess ventilation, hypometabolic state, hypotension, low cardiac output, esophageal intubation, and a disconnected ventilator.

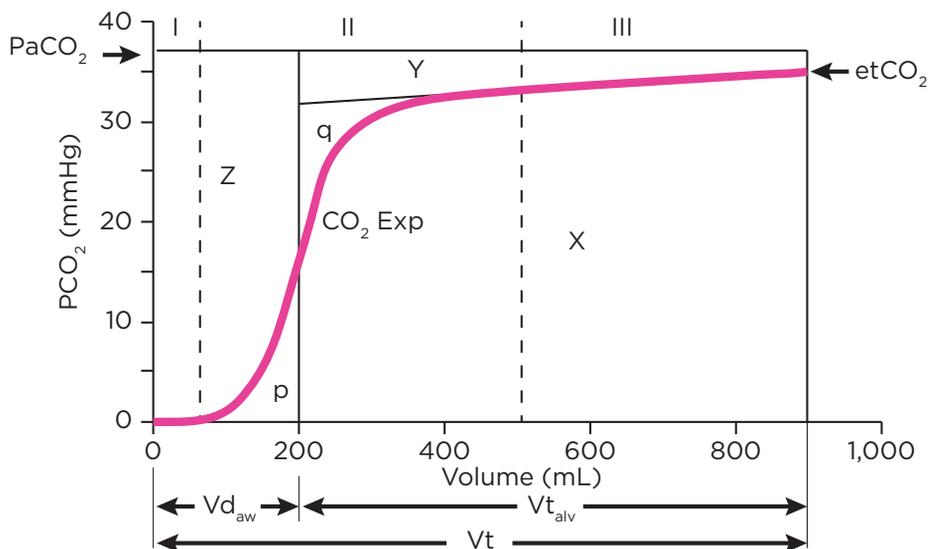
### Methods for CO<sub>2</sub> Detection

There are 2 types of ways to measure etCO<sub>2</sub>: using either a mainstream or a sidestream detector. Sidestream analysis capnography is convenient because a lightweight, inexpensive connector can be attached near a patient's mouth or nares. Delays in sidestream analysis vary with long sampling lines, the rate of air aspiration into the capnometer, and the efficiency of the capnometer itself. The mainstream analyzer generates a capnogram almost instantly as the gas passes through a cuvette almost immediately after exiting the lungs. With mainstream devices, the sensor—consisting of the sample cell and infrared bench—is placed at the airway, revealing an accurate capnogram that reflects in real time the partial pressure of CO<sub>2</sub> within the airway. Sidestream devices aspirate a sample of gas from the breathing circuit through a long (6-8 feet) small-bore tube at a flow rate ranging from 50 to 250 mL per minute. In infants and children, aspiration of large volumes for etCO<sub>2</sub> measurement loses a significant amount of ventilation to the analyzer.

The Microstream (Oridion) can use smaller sampling volumes (30-50 mL/min) to avoid excessive removal of ventilation gases and thus tidal volume.

### Safety and Monitoring Trends

Inadequate ventilation of the patient—including failure of the anesthesiologist to adequately



**Figure 2.** Volumetric capnogram.

ventilate—traditionally accounted for the greatest number and most severe anesthesia-related catastrophes. In 1986, the American Society of Anesthesiologists (ASA) first encouraged the use of capnography for certain patients receiving anesthesia. In 1999, the ventilation-monitoring standard was modified to include capnography as a standard for virtually every patient receiving general anesthesia:

“Continual monitoring for the presence of expired carbon dioxide shall be performed unless invalidated by the nature of the patient, procedure, or equipment. Quantitative monitoring of the volume of expired gas is strongly encouraged.”<sup>3</sup>

This standard has an asterisk referring to the ability of the responsible anesthesiologist to waive the requirements under extenuating circumstances. Indeed, patients receiving electroconvulsive therapy and cardioversion do not routinely undergo etCO<sub>2</sub> monitoring.

Anesthesiologists have taken a step in improving patient safety outside the OR by recognizing capnography as the appropriate measure of adequacy of ventilation during nonintubated procedures requiring moderate or deep sedation. The ASA standards evolved in 2010-2011 in part because of the persistent risk for respiratory compromise in cases of procedural sedation. The past 20 years of ASA Closed Claims data demonstrate that respiratory events and events leading to death occurred twice as often when patients were sedated outside the OR.<sup>4</sup> A 2011 meta-analysis found that respiratory depression was 17.6 times more likely to be detected during sedation cases using capnography.<sup>5</sup> Ironically, the use of a pulse oximeter alone with supplemental oxygen can increase a patient’s risk for hypoxic events because supplemental oxygen maintains oxygenation longer during periods of apnea,

which frequently goes undetected.

Safety organizations representing cardiology, critical care medicine, pediatrics, and emergency medicine have either mandated or strongly recommended continuous use of capnography for patient monitoring for other purposes including conscious sedation outside the OR, resuscitation, ventilator weaning, and patient transport. A host of organizations besides the ASA also recognize the importance of non-OR monitoring of the adequacy of ventilation, including the Joint Commission, the Anesthesia Patient Safety Foundation, and the Institute for Safe Medication Practices.

Measuring etCO<sub>2</sub> via nasal cannula complies with these standards because of its use of qualitative rather than quantitative clinical signs. Accuracy of the etCO<sub>2</sub> is not required.

The ASA’s new standards on capnography have not gained universal acceptance. The American Gastroenterological Association (AGA) considers the use of capnography for routine, moderate GI sedation cases intrusive, expensive, and unnecessary. According to the AGA, the superior safety in moderate sedation administered by an endoscopist is evidenced by a fatality rate of 8 deaths per 100,000 routine procedures. (The rate when an anesthesiologist administers moderate sedation is as much as one-eighth as high.) Importantly, could those patients have avoided death by the use of properly implemented capnography? The AGA also argues that there are no pertinent randomized trials to support capnography for moderate sedation for routine GI cases. However, the updated ASA standards were in part devised by examining closed claims, and whether deaths or serious claims could have been prevented by the use of a particular monitor.

Expert opinion also is considered important because many studies do not define “near misses,” an important

subset of clinical experience in anesthesia that is not easily quantifiable in other ways. Claims in the Closed Claims database suggest, for example, that most deaths from erroneous esophageal intubation could have been prevented with the use of capnography. A prospectively designed study to prove this would be unnecessary, and possibly harmful. Nearly one-quarter (24%) of the claims in the Closed Claims database are related to endoscopy; capnography may have prevented many, if not most, of these.<sup>6</sup>

Importantly, the ASA has argued that sedation itself does not neatly fall into a prescribed and orderly response for every patient. Similar drug dosages resulting in moderate sedation for 95% could produce deep sedation for the other 5%. Sedation is a pharmacodynamic continuum rather than a set point. To further complicate matters, the ASA standards for providing anesthesia apply to anesthesiologists and anesthesia providers, but not necessarily to other clinicians, who do not necessarily accept the society's definition of anesthesia. Similarly, the Centers for Medicare & Medicaid Services (CMS) do not consider moderate/conscious sedation to be anesthesia. This remains a political sticking point toward reaching a more acceptable practice for those administering moderate sedation and the use of etCO<sub>2</sub> in such cases (Box 1).

### Waveform Capnography and Resuscitation

Among the primary interventions of CPR—ventilation, intubation, and electric shocks—the initial and continued act of precordial compressions remains the most effective life-saving measure. Compressions should not be interrupted for long periods, even to perform endotracheal intubation. The utility of continuous etCO<sub>2</sub> during CPR to assess effectiveness of chest compressions has been documented for more than 20 years,<sup>7</sup> but it was not until 2010 that the Advanced Cardiovascular Life Support (ACLS) guidelines incorporated the use of the technology. For the management of cardiac arrest that includes chest compressions, intubation, and the administration of drugs, capnography is considered useful, if not lifesaving. The 2010 ACLS guidelines carry strong recommendations for the use of quantitative waveform capnography for confirmation of ETT placement, to determine the effectiveness of chest compressions, and to determine if a return of spontaneous circulation (ROSC) has occurred. Portability, learning curve for all first responders, and cost of such an endeavor is likely a major factor in hindering the adoption sooner.

In states of very low cardiac output, blood flow rather than content determines oxygen delivery. Invasive arterial monitoring is ideal but highly impractical in most emergent settings, as a measure of effective circulation and monitor of ROSC. Palpation of distal arterial pulses is relatively unreliable as a method for assessing the effectiveness of cardiac compressions.

Using the principal determinants of etCO<sub>2</sub>—alveolar ventilation, pulmonary perfusion (cardiac output), and

### Box 1. ASA Procedural Mandate on Capnography: etCO<sub>2</sub> for Moderate Sedation

Effective July 1, 2011, Basic Anesthetic Monitoring Standard 3.2.4., now reads: "During regional anesthesia (no sedation) or local anesthesia (no sedation), the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs. During moderate or deep sedation, the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs and monitoring for the presence of exhaled carbon dioxide unless precluded or invalidated by the nature of the patient, procedure, or equipment."

The ASA's former Standard for Basic Anesthesia Monitoring read:

"During regional anesthesia and monitored anesthesia care, the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs and/or monitoring for the presence of exhaled carbon dioxide."

production of CO<sub>2</sub><sup>8</sup>—and by holding alveolar ventilation and CO<sub>2</sub> relatively constant, an increase in etCO<sub>2</sub> for example should reflect ROSC. Specifically, during acutely low cardiac output states such as during cardiac arrest, decreased pulmonary blood flow will manifest as very low etCO<sub>2</sub>; and continuous etCO<sub>2</sub> will represent the primary determinant of changes in cardiac output, assuming that ventilation and production of CO<sub>2</sub> are relatively constant. Thus, with chest compressions being relatively constant as well, etCO<sub>2</sub> can be used as a quantitative index in evaluating adequacy of ventilation and pulmonary blood flow during CPR.<sup>7</sup> By extension, continuous etCO<sub>2</sub> monitoring during CPR is a useful gauge of the effectiveness of chest compressions and rescuer exhaustion.

Depending on the type of arrest requiring CPR (asystole, respiratory, etc.), measuring continuous etCO<sub>2</sub> may be a valuable predictor of a positive outcome with ROSC. Patients who experience ROSC during CPR will show a rise in etCO<sub>2</sub> as a first indicator before palpable pulse or blood pressure. On the other hand, with CPR lasting at least 20 minutes, if etCO<sub>2</sub> remains below 10 mm Hg, survival is unlikely (Box 2). However, when etCO<sub>2</sub> remains below 10 mm Hg after 20 minutes of CPR following an asystolic event, the sensitivity and specificity for predicting ROSC are 100% sensitivity and 61%, respectively.<sup>9</sup> Continuous monitoring, therefore, would provide caregivers a more rational approach to prolonged CPR and allow them to assess the adequacy of their efforts without suspending compressions.<sup>9</sup>

### Postoperative Patients on Narcotic PCA And Capnography

etCO<sub>2</sub> monitoring also may be used to monitor patients following surgery who are receiving narcotics by patient-controlled analgesia or who may be at significant risk for apnea following surgery. Respiratory

## Box 2. The 96-Minute CPR

The dilemma of when to stop performing CPR on a victim suffering an out-of-hospital cardiac arrest remains acute. One case exemplifies how the monitoring of etCO<sub>2</sub> was used in a rational albeit prolonged manner to decide the fate of a man who suffered an out-of-hospital cardiac arrest. An astonishing 96 minutes of CPR (chest compression) were administered to save the life of a 54-year-old man in cardiac arrest. In almost any other scenario, cardiac compressions and electrical shocks would have been discontinued after 30 to 40 minutes. What saved this patient was the availability of etCO<sub>2</sub> monitoring during CPR. Because the etCO<sub>2</sub> monitor consistently showed an etCO<sub>2</sub> of more than 30 mm Hg, CPR was continued until the etCO<sub>2</sub> rose to 37, suggesting that return of spontaneous circulation was achieved. The man underwent cardiac catheterization and stenting, and unbelievably had no permanent neurologic deficits on discharge from the hospital.

Reported on National Public Radio, Oct. 3, 2011

depression is relatively common postoperatively. When combined with other parameters such as pulse oximetry and heart rate, etCO<sub>2</sub> may help discern significant changes in patient status while ruling out false-positives and preventing unnecessary interventions.

## Integrated Pulmonary Index

The Integrated Pulmonary Index (IPI; Covidien) is a new technology (FDA-approved in 2009) that uses etCO<sub>2</sub>, respiration rate, pulse rate, and SpO<sub>2</sub> to provide an uncomplicated, inclusive, real-time assessment of a patient's ventilatory and oxygenation status into a single index value ranging from 1 to 10. Fuzzy logic (mathematical model mimicking human logic) and the input of experienced clinicians developed the algorithms used in the final single numerical output.<sup>10</sup> The clinician can use the trends and changes of the IPI to assess the interrelationships of a patient's respiratory parameters, and to intervene if clinically indicated. The IPI also provides an early indication of changes in a patient's respiratory status that may not be indicated by the values of the individual parameters.<sup>11</sup> Interestingly, the IPI also helps delineate clinically insignificant (false-positive) alarms as well. In short, the IPI theoretically can increase patient safety by indicating the presence of slow-developing patient respiratory issues not easily identified with individual instantaneous data to the caregiver in real time.

Because normal values for the physiologic parameters are different for different age categories, the IPI algorithm differs for different age groups (3 pediatric age groups and adult). The IPI is not available for neonatal and infant patients (up to the age of 1 year).

It remains to be seen how quickly clinicians will adopt the IPI given the expense of the technology, elimination of false-positive and negative alerts, training issues, and other considerations.

## Capnography in the ICU and for Transport

Continuous capnography for mechanically ventilated patients in the ICU is uncommon, and particularly rare in North America. However, inadvertent ETT dislodgment and its consequences account for unnecessary deaths in critical care settings. According to a 2011 audit of major airway complications in the United Kingdom, 75% of airway-related deaths or severe neurologic injuries in the ICU could have been prevented with the use of continuous capnography.<sup>12</sup> The authors of the audit strongly encourage continuous waveform capnography for all intubated patients, including those ventilated through tracheostomy tubes.

Continuous capnography seems ideally suited for the ICU, as it aids in detection of misplacement of feeding tubes; gauges changes in metabolic rate; aids in the weaning off the ventilator in patients without serious lung pathology; guides the titration of PEEP (volumetric capnography); and can assess in the kinking, disconnection, or failure of the patient's ETT. In the United States, no specific standards currently address the use of waveform capnography in intubated patients in the ICU.

Transportation of critical intubated patients from one hospital to another does not require the use of continuous capnography. Certainly, airway mishaps can be detected with the use of capnography, but added expense and time for education limit its rapid introduction for emergency medical service providers.

## Other Uses for Capnography

Studies suggest that capnography can be used as an indirect estimate of cardiac index/cardiac output. etCO<sub>2</sub> has been shown to correlate strongly with changes in cardiac output. In determining fluid responsiveness, passive leg raise (PLR) has been shown to dynamically evaluate cardiac preload. The PLR test has been used in resuscitation of critical patients such as septic patients. Several studies have shown that the PLR can be evaluated using etCO<sub>2</sub> in ventilated patients to evaluate for fluid responsiveness. An increase of at least 5% in etCO<sub>2</sub> after PLR suggests fluid responsiveness with a sensitivity of 71% to 91% and a specificity of 94% to 100%.

## New Devices

Ultraportable waveform capnograph monitors and CPR/defibrillators with mainstream etCO<sub>2</sub> attachments are now available. Cost is a major consideration for defibrillators equipped with etCO<sub>2</sub> technology, ranging from \$10,000 to \$20,000. Portable handheld capnograph/oximeters are less expensive—\$2,000 to \$3,000—but also might carry nontrivial per-use costs.

Innovations to sidestream capnography also include improvements to capturing etCO<sub>2</sub> during procedural sedation in nonintubated patients. The Smart Capnoline (Oridion) uses a special cannula that measures exhaled etCO<sub>2</sub> from the nose and mouth while delivering oxygen. This feature is useful in endoscopic procedures in which detection of etCO<sub>2</sub> can be difficult. Oridion also

developed a combination bite block and etCO<sub>2</sub> line into the Capnoblock for use primarily in endoscopy.

## Conclusion

Capnography allows for the detection of life-threatening conditions of the lungs and cardiovascular system more rapidly than pulse oximetry alone. Studies have expressly validated the usefulness of waveform capnography in saving lives in many clinical environments. Waveform capnography has found its way into clinical practice to confirm and now monitor ETT placement,

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*For an excellent and more thorough review of capnography, please visit the website [www.capnography.com](http://www.capnography.com).*