Carbon Dioxide Physiology

Carbon dioxide is transported in the body in 3 forms: after conversion in the red blood cells, 60- to 70% is transported as bicarbonate ion, another 20- to 30% is transported while bound to proteins, and the remaining 5- to 10% is dissolved in plasma. The latter is what is actually measured during blood gas analysis and is known as the arterial partial pressure of carbon dioxide (PaCO₂). End-tidal carbon dioxide (ETCO₂) is the result of expired gases from the alveoli. The site of gas exchange occurs in the alveolar capillary beds lying between the blood and air within the lungs. Under normal circumstances, ETCO₂ typically underestimates the PaCO₂ by a clinically insignificant 2- to 5 mmHg. Therefore, because of the extremely close proximity of gas exchange between the alveoli and pulmonary capillaries, ETCO₂ ≈ PaCO₂ ≈ alveolar CO₂ (PACO₂).

What is Capnography?

Capnography has become an essential part of monitoring anesthetized and critical care patients since 1943, when Luft introduced the first infrared carbon dioxide measuring and recording device. Since that time, other methods of measuring ETCO₂ have been documented (e.g., laser-based molecular correlation spectrography and Raman spectrography, magnetic-based mass spectrography, and photoacoustic spectrography), but infrared technology remains the most compact, least expensive and most popular method of ETCO₂ measurement.

Capnography provides a non-invasive method that permits the assessment of systemic metabolism, cardiac output, pulmonary perfusion and the adequacy of patient ventilation in a variety of clinical situations, such as during anesthesia when effects of drugs and inhalants can cause respiratory depression or during long-term ventilatory assistance as with the use of a mechanical ventilator. Normal ETCO₂ values are 35- to 45 mmHg. End-tidal CO₂ values above 45 mmHg indicate inadequate ventilation, necessitating ventilatory assistance via manual or mechanical means. Conversely, by allowing modest increases in PaCO₂ (up to 50 mmHg) the anesthetist can augment arterial blood pressure via endogenous catecholamine release. However, prolonged periods of hypercapnia can lead to myocardial depression and respiratory acidosis. The highest ETCO₂ permissible should be 60 mmHg.

Capnography is superior over pulse oximetry for the prompt identification of apnea and airway mishaps, since changes in the percentage of hemoglobin saturated with oxygen (SpO₂) will be delayed as compared to the instantaneous changes that occur with ETCO₂ when the next breath fails detection. When alveoli are not perfused, carbon dioxide is unable to diffuse out of the bloodstream. But as blood flow improves and alveoli are perfused, carbon dioxide can then be excreted. Therefore an abrupt decrease in ETCO₂ can be an early and reliable indication of an impending cardiovascular collapse or cardiac arrest. Since delivery of carbon dioxide from the lungs requires blood flow, cellular metabolism, and alveolar ventilation, the presence of ETCO₂ can also be used to assess the effectiveness of cardio-pulmonary cerebral resuscitation (CPCR) efforts.

Measuring End-Tidal CO₂ - Capnometry/Capnograph

There are two types of monitors available for assessing end-tidal carbon dioxide—the capnometer or capnograph. Capnometers provide only minimum and maximum ETCO₂ values, while capnographs can provide a graphic representation (capnogram) of exhaled carbon dioxide in respiratory gases over time. Both capnometers and capnographs monitor ETCO₂ by evaluating samples of the patient’s exhaled gases taken from the anesthetic circuit via an adapter placed on the end of the patient’s endotracheal tube. With the patient’s head and neck in a natural position, this adapter must be placed as close to the tracheal entrance as possible (or at the point of the patient’s nose) to eliminate excessive dead space and prevent rebreathing of CO₂. Cutting the endotracheal tube to shorter lengths allows the adapter to be placed at the end of the nose while still allowing the cuff to sit distal to the larynx, but no further than the thoracic inlet.

In 1949, Fowler described a single-breath test for nitrogen that included a 4-phase nitrogen curve. This terminology was adapted to the currently utilized descriptions for a time capnogram, and is also represented by 4 phases: three expiratory phases and one inspiratory phase. (See Figure 1.) Phase 0 occurs as the inspiratory downstroke and contains CO₂-free gas, phase I is the expiratory baseline (which should be zero) and represents the beginning of exhalation, phase II occurs during the expiratory upstroke and includes a rapidly increasing level of CO₂, and phase III represents the expiratory plateau when alveolar air is completely expelled. The highest point of phase III correlates with
the actual ETCO$_2$ value. Recognizing abnormalities (e.g., breathing system leaks, apnea, dead space ventilation and bronchospasm) in ventilation or anesthetic circuit function is easier using the graphical data provided by a capnogram.

Figure 1. Normal capnogram. (Diagram courtesy of Mele Tong.)

Capnometers and capnographs may be categorized as *mainstream* or *sidestream*, based on the location of the sensing device. **Mainstream (non-diverting) monitors** analyze the respiratory gases locally (at the endotracheal tube-breathing system interface) using infrared light rays that distinguish respiratory gases in a photodetector, located within a heated cuvette to prevent water condensation. Mainstream monitors provide rapid (< 100 milliseconds!) results and encounter few problems secondary to secretions or moisture as compared to sidestream technologies. Furthermore mainstream monitors utilize few disposable supplies and do not require scavenging of sampled gases.

Nonetheless there are drawbacks associated with mainstream monitors. Due to the weight and location of the monitor they are prone to accidental disconnection, leaks, and damage, and can cause kinking of the endotracheal tube. Mainstream monitors also require a longer warm-up period. Furthermore the heated cuvette may cause patient burns.

**Sidestream (diverting) monitors** employ small, lightweight, sensing tees placed at the endotracheal tube-breathing system interface and pump respiratory gases for analysis up into the measurement chamber via a length of tubing. Sidestream monitors warm-up quickly thereby allowing immediate ETCO$_2$ results, and are amendable to remote use (e.g., MRI). Furthermore they can be used on intubated and non-intubated patients. However high fresh gas flow rates in small patients may yield falsely low ETCO$_2$ values and waveform changes due to sample dilution. A moderate reduction in the fresh gas flow rate (10- to 30 ml/kg/min) can help increase the accuracy of ETCO$_2$ in these small patients.

The disadvantages of sidestream monitors include a 2- to 3 second delay in response time, periodic calibration requirements, frequent replacement of disposable supplies (e.g., sample tubing and sensing tees), and an increased likelihood of sample tubing obstruction due to respiratory moisture, blood, or secretions. Beware that the sample size required using either mainstream or sidestream technologies entails a draw of 50- to 150 ml/minute (or more!) of exhaled gas. This may be of particular importance when utilizing low-flow anesthetic techniques.

**Interpreting Waveform Abnormalities**

End-tidal carbon dioxide monitoring can prove pivotal in the prevention of potentially catastrophic anesthetic disasters. In fact, one study performed by the American Society of Anesthesiologists (ASA) claimed that the combined use of capnography and pulse oximetry could have helped prevent 93% of avoidable anesthetic mishaps. Monitoring ETCO$_2$ can alert the anesthetist to situations such as an inadequate seal or occlusion of the endotracheal tube, anesthetic circuit dysfunction and/or disconnects, ventilation abnormalities, or an impending respiratory and/or cardiac arrest.

Elevated ETCO$_2$ levels may occur as a result of hypoventilation (See Figure 2.), which may be due to airway obstruction, pneumothorax, body positioning, lung disease, or during periods of acutely increased metabolism (e.g., malignant hyperthermia, thyroid storm, or catecholamine release).
Significant disparities between PaCO\(_2\) and ETCO\(_2\) indicate an inefficiency of gas exchange (e.g., dead space ventilation), which may be secondary to pulmonary embolism, thromboembolism, decreased cardiac output, or perhaps as a result of mechanical ventilation (intermittent positive pressure ventilation).

Explanations for elevated ETCO\(_2\) and inspiratory carbon dioxide (See Figure 3.) may include faulty anesthetic equipment (e.g., malfunctioning valves within the breathing circuit), unsuitable fresh gas flow rates (e.g., non-rebreathing circuits), or exhausted soda lime absorber. Furthermore, end-tidal carbon dioxide measurements can at times be simply unreliable; such as when the PaCO\(_2\) is greater than 55 mmHg or during thoracotomy procedures when altered gradients occur due to an altered ventilation:perfusion ratio (V\(_A\)/Q). Therefore ETCO\(_2\) is best used as a trend study tool and must be analyzed in conjunction with an arterial blood gas sample to yield the most complete status of respiratory function.

Martin L. *All You Really Need to Know to Interpret Arterial Blood Gases*, Lippincott Williams & Wilkins Baltimore/Philadelphia, 1999; pp 15, 35, 37.
Kodall B. www.capnography.com
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