Capnography as a Clinical Tool

The capnography waveform is a key vital sign when determining treatment for patients in the field

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Carbon dioxide (CO\(_2\)) is a waste gas, so why do we care about it as long as we and our patients can get it out of the body? Just like an automobile's performance can be monitored by a probe put in the exhaust pipe, an evolving technology allows emergency providers to precisely monitor the performance of a number of critical human processes in an ill or injured patient. This article describes the use of technology to monitor metabolism, circulation and ventilation in the emergency patient.

The Relevance of CO\(_2\)

Long ago, Greek philosophers believed we had tiny internal combustion engines inside our bodies that produced "smoke," or capnos. It turns out, the Greeks were correct. Our internal combustion engines are really mitochondria that are fueled by hydrocarbons (sugars, fats and proteins) essential in the human diet. After eating and movement through the digestive processes, sugars enter the mitochondria, where they are "combusted" and carbon dioxide is "exhausted." Once CO\(_2\) is transported to the lungs via the circulatory system, it is exhaled with alveolar air.

The gases we breathe in are measured in partial pressure. So, a person standing at sea level under normal weather conditions would have 1 atmosphere of pressure being exerted by the gases in the air he breathes. An atmosphere of pressure is equivalent to 760 millimeters of mercury (mmHg). If the atmosphere contains approximately 79% nitrogen and 20% oxygen, the partial pressure of each is 600 mmHg nitrogen and 150 mmHg oxygen. The approximately 10 mmHg of air pressure remaining is composed of all of the other gases and vapors—mostly water vapor. Inhaled air contains essentially no carbon dioxide, while exhaled air is rich with CO\(_2\). The portion of pressure being exerted by carbon dioxide is called partial pressure and is typically 35-45 mmHg in the healthy person at rest. Partial pressure can be monitored on either the intubated or non-intubated patient. The monitoring process can be either discrete (one time or quick look) or continuous.

Capnography works by capturing exhaled air and redirecting it into the capnography device. The air then passes between a light and a detector that measures how much light is shining on it. As the concentration of CO\(_2\) increases, more light is absorbed by the CO\(_2\) and less light is transmitted onto the detector plate. This increased light absorption directly correlates with the percentage of carbon dioxide. The monitor presents the CO\(_2\) concentration to the capnographer as both a number and a waveform. The respiratory rate can be very accurately estimated and reported by measuring the tides between CO\(_2\) peaks.

Blood levels of carbon dioxide are as critically important as blood oxygen levels. In fact, oxygen loading onto
hemoglobin and transport to the tissues is highly dependent on the tight regulation of CO₂. Furthermore, CO₂ can act as a molecular signal affecting both nervous and smooth muscle tissues.

**Ventilation and Oxygenation**

Ventilation and oxygenation are interrelated, but represent distinct processes. Different diseases can affect the processes in different ways. Oxygenation involves loading hemoglobin with oxygen for delivery to the tissues, while ventilation addresses clearance of CO₂ from the blood. Technologies for monitoring oxygenation have been extraordinarily useful to EMS providers for the past 20 years. More recently, technologies are being developed to enhance EMS's abilities to measure the effectiveness of ventilation. Measuring exhaled CO₂ can provide valuable insight into metabolism and circulation. Take, for example, the moderately sick asthma patient demonstrating a "shark fin" pattern with an elevated EtCO₂ but 100% oxygen saturation. This patient is oxygenating well, but not ventilating effectively.

There are three physiological processes for human life: metabolism, circulation and ventilation.

1. **Metabolism** is the utilization of hydrocarbons to produce energy and power tissues, organs and the entire body. This process must be continuous for life to be sustained. It is important to note, however, that several hours after cardiac arrest, some residual metabolism (liver, skeletal muscles, skin, etc.) will continue to produce CO₂.

2. **Circulation.** Blood must be moving in order to deliver CO₂ from the tissues to the alveoli. Circulation requires blood, an effective heartbeat and blood pressure. Preload plus afterload equals circulation.

3. **Ventilation.** Air must move in and out of the alveoli effectively to get rid of carbon dioxide and other waste products, and to inhale fresh oxygen.

**Capnography as a Tool for Measuring Metabolism, Circulation and Ventilation**

Capnography is a powerful tool for providing continuous real-time objective data to qualify and quantify the status of metabolism, circulation and ventilation. Metabolism is assessed by determining the quantity of CO₂ being exhaled and following this over time. Circulation is measured by the trends in delivery of CO₂ to the lungs. Capnography is the only technology able to display respiratory rate based upon the partial pressure of exhaled CO₂ while providing the unique pattern recognition of CO₂. Capnography quantifies patient ventilation in terms of transport of CO₂ from the pulmonary circulation across the alveoli for exhalation. It also provides a graphic picture of the patient's ventilatory status, presents an early warning of changes in the patient's cardiopulmonary status, supplies indisputable documentation of the patient's airway patency, and alerts clinicians to the presence of pulmonary pathology. Abnormal capnography values can be traced to diseases affecting ventilation, perfusion or metabolism.

Continuous waveform capnography is recommended to EMS for verification of endotracheal tube (ETT) placement.¹ The 2010 ACLS guidelines have elevated the role of capnography to recommending continuous waveform CO₂ monitoring during resuscitation.

Capnography can also provide valuable cardiopulmonary information to assist paramedics in caring for non-intubated patients.

**Capnography & Intubated Patients**

Capnography provides a reliable and objective method to confirm endotracheal intubation. The presence of a
waveform demonstrates proper placement, even during CPR. This has been well documented over the past few years.\textsuperscript{1,2}

Capnography can also be useful in detecting a change in position of the endotracheal tube. In EMS, this is important, as the endotracheal tube may be accidentally displaced while moving the patient. Given some of the untoward and noisy environments where cardiac arrest occurs, confirming ETT placement by lung sounds alone can be problematic and sometimes even deceiving, especially in smaller patients. A 2005 study compared prehospital intubations using continuous capnography to confirm tube placement with those not using capnography. The group using capnography achieved correct tube placement in 100\% of their patients. The group practicing without the benefit of capnography had a misplaced tube (unrecognized esophageal or supraglottic) in 23\% of their patients.\textsuperscript{1}

**Alternative Airways**

Recent studies have dulled the significance of endotracheal intubation, and many EMS providers are relying more on alternative methods of securing the airway.\textsuperscript{3} Capnography is just as easily applied to alternative airways like the Combitube, King airway or laryngeal mask airway (LMA). As with the endotracheal tube, proper and improper ventilation can be monitored with alternative airways and corrected where necessary. It is imperative to ensure the device is providing sufficient protection of the airway to allow effective rescuer ventilation.\textsuperscript{4}

The capnography waveform assists in determining proper ventilation with any device that securely attaches to a bag-valve mask. No matter which device is in use, capnography can provide immediate indication of the loss of proper position or function. As with endotracheal intubation, when using alternative airways it is critical to continuously monitor the airway and assess ventilatory status. Waveform capnography is able to support those clinical assessment needs and can indicate the need to adjust ventilatory support.\textsuperscript{2}

**Chest Compressions**

Capnography provides valuable information in the assessment of resuscitative efforts. In the cardiac arrest patient, $\text{EtCO}_2$ directly correlates with cardiac output. No carbon dioxide in exhaled air indicates either an improperly placed tube or no cardiac output. Systemic and pulmonary perfusion during cardiac compressions transports $\text{CO}_2$ to the alveolar space. Therefore, as long as the cardiac arrest victim has residual metabolic production of $\text{CO}_2$, $\text{EtCO}_2$ serves as a measure of the effectiveness of chest compressions.\textsuperscript{5-7}

Studies as early as the 1980s discuss how $\text{EtCO}_2$ can be used as a noninvasive measurement of cardiac output during cardiac arrest.\textsuperscript{6} During CPR, $\text{EtCO}_2$ production by cellular metabolism remains constant; therefore, $\text{EtCO}_2$ can assist in showing the paramedic the effectiveness of chest compressions. The AHA (American Heart Association) Guidelines call for quality compressions ("push hard, push fast, push deep")\textsuperscript{2} and direct rescuers to switch places every two minutes to maintain effective CPR. By analyzing the $\text{EtCO}_2$ waveform, a clinician can detect rescuer fatigue before the rescuer is aware of tiring.

EMS providers can position the monitor so the compressors can view the $\text{EtCO}_2$ readings as well as the ECG waveform generated by their compressions. It is important to encourage prehospital personnel to perform quality chest compressions to keep the $\text{EtCO}_2$ number as high as possible. This represents effective cellular perfusion, allowing cells to metabolize and circulation to deliver carbon dioxide to the lungs.
Return of ROSC

A rapid rise in EtCO₂ during chest compressions can be the first indicator of return of spontaneous circulation (ROSC), possibly even before a pulse is detectable. This rapid rise is likely due to the recruitment of circulation of tissues that were not being circulated due to the inefficiency of chest compressions (approximately 25%-30%), as compared with intrinsic cardiac contraction.⁸ A recent study found the EtCO₂ increased on average 13.5 mmHg with sudden ROSC before returning to a normal range.⁹ If paramedics encounter a sudden increase in EtCO₂ during resuscitation, accompanied by a rhythm appearing capable of supporting perfusion, CPR should be briefly interrupted for a pulse check. If no pulses are present, CPR should be aggressively resumed, as ROSC may be near. It is important to note, however, that administration of sodium bicarbonate could also produce a "bump" in the EtCO₂ as a result of bicarbonate ion conversion to CO₂ during correction of acidosis.

Clinical Death Confirmation

While EtCO₂ can be used to gauge the effectiveness of resuscitation, it can also be used as a determining factor in the decision to cease resuscitative efforts. In 1997, a study in the New England Journal of Medicine established that an end-tidal carbon dioxide level of 10 mmHg or less measured 20 minutes after the initiation of advanced cardiac life support accurately predicts death in patients with cardiac arrest associated with electrical activity but no pulse. Patients with an EtCO₂ of less than 10 mmHg at the 20-minute interval had 100% mortality. The study suggests that cardiopulmonary resuscitation may reasonably be terminated in such patients.¹⁰ Caution must be taken, however, that rescuers are not hyperventilating the patient if capnography is used as a determinant for termination of efforts.

With the advent of induced hypothermia in the treatment of cardiac arrest patients, new research is now needed to set guidelines for the use of EtCO₂ in determining when to cease resuscitation efforts. In the induced hypothermia patient, the metabolic rate will be lowered, thus diminishing the production of cellular CO₂. A guideline for CPR termination based on an EtCO₂ of less than 10 mmHg for 20 minutes may not be adequately conservative for those patients receiving hypothermia treatment during CPR.

Head-Injury Patients

Capnography can help paramedics optimize ventilation in intubated patients with suspected increased intracranial pressure (ICP). Avoiding hypo- and hyperventilation in these patients is absolutely critical and difficult. Increased ICP may be caused by a head injury, intracerebral hemorrhage, a tumor or mass, or an infection. Hyperventilation of patients with increased ICP has been associated with increased mortality.¹¹ Hyperventilation decreases intracranial pressure by decreasing intracranial blood flow, thereby increasing the risk of cerebral ischemia. In a recent study of head-injury patients, those patients with EtCO₂ monitoring had a lower incidence of hyperventilation. A target EtCO₂ recommendation is outside the scope of this article, but ventilation should be tightly controlled in this patient population, using local protocol.

Non-Intubated Patients

Capnography can be used to differentiate between the varying causes of respiratory distress often seen by paramedics in the field, such as asthma, COPD exacerbation and CHF. It can also provide paramedics with early warning signs of hypoventilation, apnea, airway obstruction and hypercarbia before compensatory changes are seen in heart rate and/or blood pressure.

Patients with acute obstructive disease processes of the lung (asthma, COPD, bronchitis) may be identified using EtCO₂ monitoring. These patients, all of whom may experience bronchospasm in the lungs, can be identified by a unique characteristic change seen in the EtCO₂ waveform. Bronchospasm will produce a "shark fin" capnography waveform due to difficulty emptying alveoli. The characteristic shark fin appearance is a result of regional obstruction, which causes a turbulent mixing of dead space air with alveolar air. This mixing softens the rapid rise in CO₂ concentration of exhaled air. It is important to note that the shark fin appearance of the capnograph has a direct physiological cause and is characteristic of bronchospasm. In other words, shark-finning cannot be "faked" (see Figure 1).

By analyzing the CO₂ waveform over time, the paramedic can monitor the severity of asthma or chronic obstructive pulmonary disease (COPD) and the effectiveness of therapy provided. Capnogram analysis may be used to indicate airway obstruction in these patients, but further work is required to correlate curve indices to the degree of airway obstruction.

Carbon dioxide values in asthma will change depending on severity of the disease. Hyperventilation may occur early in an acute asthma attack, lowering EtCO₂ levels with a slightly abnormal waveform. As the attack progresses, the EtCO₂ may read in the normal range, with a more prominent looking shark fin waveform on the monitor. Finally, as the attack becomes severe, the EtCO₂ rises and the wave becomes indistinguishable in its shark fin form. Once treatment is decided upon and the bronchoconstriction decreases, the EtCO₂ number may increase initially as gas exchange improves. Recognize that the waveform will appear to be normalizing. The return of a normal waveform indicates resolution of the bronchoconstriction. The same concepts will apply with COPD patients; however, the initial numbers may be high due to retaining CO₂ in their disease process.

Congestive heart failure (CHF) patients have circulatory compromise, which results in changes in carbon dioxide delivery. This means that as the disease worsens, or as the patient approaches decomposition, EtCO₂ will continue to decline as alveolar perfusion decreases. Respiratory distress due to CHF does not typically result in bronchoconstriction, so the waveforms will not necessarily have a shark fin appearance unless the patient has a pulmonary comorbidity. Capnography can alert to early recognition in CHF, even before the onset of pulmonary edema is apparent. It is important to note that a patient with significant pulmonary edema may have a significant disparity (due to the relative solubility of O₂ vs. CO₂) between oxygenation and ventilation.

Medications

Paramedics frequently are required to administer medications that have a depressant effect on the central nervous system (CNS). This may include narcotic analgesics (morphine sulfate, fentanyl), benzodiazepines (Valium, midazolam, lorazepam) or other sedative agents (etomidate, ketamine). With any medication that depresses the CNS, there is a risk of hypoventilation. Capnography should be routinely used to monitor patients receiving pain management or sedation for evidence of hypoventilation and/or apnea.

At times, paramedics encounter patients who are "self-medicated" with CNS depressants, including alcohol, GHB, OxyContin, Xanax and many of the prescription compounds listed above. Overdose of alcohol and/or CNS depressants puts the patient at risk for hypoventilation. Capnography is invaluable and proven to be the earliest indicator of respiratory compromise due to medications with pain or sedative association. The EtCO₂ waveform dampens prior to a change in pulse oximetry due to the oxygen reserve in human anatomy. Capnography can be utilized in any patient who has ingested a significant quantity of CNS depressant, particularly those who are somnolent.
Diseases Affecting Metabolism and Acid-Base Status

Waveform capnography is a direct measure of the changes in elimination of CO₂ from the lung and indirectly indicates changes in the production of CO₂ at the cellular level. It reflects the delivery of CO₂ to the lungs by the circulatory system. With no pulmonary or circulatory disorders, EtCO₂ may indicate patient anxiety or a metabolic disorder. In diabetic ketoacidosis (DKA), Kussmaul's respirations result in hyperventilation as a means for patients to lessen their ketone load and attempt to correct metabolic acidosis. The increased rate of breathing causes EtCO₂ to decrease. End-tidal carbon dioxide is linearly related to bicarbonate (HCO₃⁻) in healthy subjects, and has been found to be significantly and chronically lower in children with DKA. Although more research is needed, in conjunction with clinical assessment, capnography may help discriminate between patients with hyperosmolar, hyperglycemic, nonketotic conditions and DKA.

Perfusion

Monitoring EtCO₂ can provide an early warning sign of shock. A patient with a sudden drop in cardiac output will show a diminished CO₂ waveform and a drop in the EtCO₂ number that may occur regardless of any change in breathing rate. Capnography should be used on all trauma and cardiac patients and any patient at risk for shock. Cardiac output and end-tidal partial pressure of carbon dioxide (PEtCO₂) were highly related in diverse experimental models of circulatory shock in which cardiac output was reduced by more than 40% of baseline values. Measurement of EtCO₂ is a noninvasive alternative for continuous assessment of cardiac output during low-flow circulatory shock states. A patient with low cardiac output from a shock state does not deliver as much CO₂ per minute back to the lungs to be exhaled, which results in decreased EtCO₂. It doesn't necessarily mean the patient is hyperventilating or has a reduced arterial CO₂ level. Reduced perfusion to the lungs and/or tissues alone can be the sole cause.

It is important to note the effect on ventilation/perfusion (V/Q) mismatch while using EtCO₂. V/Q mismatch occurs when there is an injury or disease process that affects normal blood circulation and/or lung function. For example, V/Q mismatch is often seen in pulmonary embolism, in which the alveolar tissue is capable of gas exchange. However, a vascular blockage prevents blood flow to areas of the lungs, so the EtCO₂ decreases because there is essentially fresh air being exhaled from the non-perfused portion of the lung. This V/Q mismatch results in increased CO₂ in the systemic circulation, with decreased exhaled CO₂.

Seizure Management

For patients who breathe during a seizure, capnography is a powerful tool to determine the aggressiveness of seizure management. If capnography reveals ventilatory failure, this will require aggressive airway and pharmacologic intervention. If a seizure patient has moderate elevations in EtCO₂ with an unalarming respiratory rate, perhaps less aggressive ventilatory support with or without medications would be indicated until the seizure approaches the end of its "cycle." If capnography indicates that a patient's ventilatory status is sufficient, then only supportive measures are required.

Patient Management Based on Capnography

To properly assess ventilation, it is important to understand what determines respiration and ventilation in the human body. Factors such as metabolic rate, acid-base status, central CO₂ respiratory drive, physiologic dead space and lung mechanics all play a role. There are factors that increase ventilatory demand, such as arterial
hypoxemia, increased metabolic rate, increased physiologic dead space, metabolic acidosis, pulmonary edema, increased work of breathing, confusion and central nervous system stimulation. Changes in any of the latter factors affect EtCO₂. Waveform capnography provides further insight into caring for your patient in many clinical states and is a tool paramedics should not be without. Table 1 lists some of the causes of both increased and decreased CO₂.

Conclusion

Capnography has a clinical utility in EMS with many types of disease states. It assists the EMS provider in measuring and monitoring metabolism, circulation and ventilation. Used with pulse oximetry, it provides insight into the management of many emergencies involving the pulmonary and circulatory systems. This includes not only respiratory compromise but factors also affecting perfusion and metabolism. The capnography waveform is a key vital sign when determining treatment for patients in the field. Capnography sampling devices are useful in all types of airways, whether or not the patient is intubated.

<table>
<thead>
<tr>
<th>Causes of Elevated EtCO₂</th>
<th>Causes of Decreased EtCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metabolism</td>
<td>Metabolism</td>
</tr>
<tr>
<td>Pain</td>
<td>Hypothermia</td>
</tr>
<tr>
<td>Hyperthermia</td>
<td>Metabolic acidosis</td>
</tr>
<tr>
<td>Shivering</td>
<td></td>
</tr>
<tr>
<td>Respiratory System</td>
<td>Respiratory System</td>
</tr>
<tr>
<td>Respiratory insufficiency</td>
<td>Alveolar</td>
</tr>
<tr>
<td>Respiratory depression</td>
<td>Hyperventilation</td>
</tr>
<tr>
<td>COPD</td>
<td>Bronchospasm</td>
</tr>
<tr>
<td>Analgesia/sedation</td>
<td>Mucus plugging</td>
</tr>
<tr>
<td>Circulatory System</td>
<td>Circulatory System</td>
</tr>
<tr>
<td>Increased cardiac output</td>
<td>Hypotension</td>
</tr>
<tr>
<td></td>
<td>Sudden hypovolemia</td>
</tr>
<tr>
<td></td>
<td>Cardiac arrest</td>
</tr>
<tr>
<td></td>
<td>Pulmonary emboli</td>
</tr>
<tr>
<td>Medications</td>
<td></td>
</tr>
<tr>
<td>Bicarbonate administration</td>
<td></td>
</tr>
</tbody>
</table>

References


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