WHITEPAPER

Emerging Uses of Capnography in Emergency Medicine

INTRODUCTION

The Physiologic Basis for Capnography

Capnography is based on a discovery by chemist Joseph Black, who, in 1875, noted the properties of a gas released during exhalation that he called "fixed air." That gas—carbon dioxide (CO_2)—is produced as a consequence of cellular metabolism as the waste product of combining oxygen and glucose to produce energy. Carbon dioxide exits the body via the lungs. The concentration of CO_2 in an exhaled breath reflects cardiac output and pulmonary blood flow as the gas is transported by the venous system to the right side of the heart and then pumped into the lungs by the right ventricle.

Capnographs measure the concentration of CO_2 at the end of each exhaled breath, commonly known as the end-tidal carbon dioxide ($EtCO_2$). As long as the heart is beating and blood is flowing, CO_2 is delivered continuously to the lungs for exhalation. An $EtCO_2$ value outside the normal range in a patient with normal pulmonary blood flow indicates a problem with ventilation that may require immediate attention. Any deviation from normal ventilation quickly changes $EtCO_2$, even when SpO_2—the indirect measurement of oxygen saturation in the blood—remains normal. Thus, $EtCO_2$ is a more sensitive and rapid indicator of ventilation problems than SpO_2.[1]

Why $EtCO_2$ Monitoring Is Important

It is generally accepted that $EtCO_2$ monitoring is the practice standard for determining whether endotracheal tubes are correctly placed. However, there are other important indications for its use as well. Ventilatory monitoring by $EtCO_2$ measurement has long been a standard in the surgical and intensive care patient populations. Carbon dioxide monitoring should be regarded similarly in the pre-hospital setting: as a vital sign of a patient's ventilatory status, helping to guide immediate and future treatment. Increasingly, scientific evidence underscores the importance of monitoring both ventilation and oxygenation in the critically ill or injured patient and supports protocols that include this vital parameter. Yet, the applications of CO_2 monitoring in this setting have been limited despite data demonstrating its value.[2] That CO_2 monitoring is not as widely utilized as it could be in pre-hospital medicine is an issue that deserves new consideration.[3]

Capnography can be a life-saving modality because changes in $EtCO_2$ levels are an early indicator of several potentially dangerous conditions. Too much or too little exhaled CO_2 not only foreshadows deleterious physiological trends in critically ill or injured patients, but abnormal blood CO_2 in itself can have serious consequences. A sudden decrease can indicate hyperventilation or impending shock, while a sudden increase can indicate malignant hyperthermia in the absence of ventilatory changes. The absence of $EtCO_2$ in an intubated patient is an indicator of a misplaced endotracheal tube—a life-threatening situation.

Where is CO_2 Monitoring Underutilized?

The use of capnography could prevent serious problems in pre-hospital patient management as well as assist in triage after the patient arrives in the hospital emergency department, but it is not universally employed. One EMS director in a large US city estimates that only 75% of EMS systems have some form of $EtCO_2$ monitoring, meaning that 25% do not.[4] A 2005 study in Germany showed that capnographs were available to only 66% of emergency medical personnel,[5] and while this percentage has likely grown in the last several years, $EtCO_2$ monitoring is far from universal in EMS systems.

The most common reason in the pre-hospital emergency setting to use capnography is to ensure that endotracheal tubes are correctly placed, an important issue in an out-of-hospital setting. One study showed that unrecognized esophageal intubation is as high as 25%.[6] Another study showed unrecognized endotracheal tube misplacement is present in 3% of cardiac arrest patients and in 17% of trauma patients transported to a Level 1 trauma center.

In contrast to the controlled environment of the operating room or the ICU, the circumstances in which EMS personnel treat patients are unique. Patients are often in a high-motion, physically challenging environment in which monitoring equipment can malfunction and in which large, bulky devices are impractical. Yet, proper support and monitoring of ventilation are critical for successful outcomes for these seriously ill patients. Oxygen saturation, or SpO_2, can be measured as an indicator of ventilation, but hemoglobin oxygen saturation is not as rapidly sensitive to changes in ventilatory status as $EtCO_2$. Further, studies in ambulance settings have demonstrated that hypothermia and vasoconstriction might impair the ability of oximeter sensors to detect changes in SpO_2 even in the presence of respiratory distress. Capnography in the emergency setting can provide the data needed to monitor and correctly adjust ventilation parameters much more quickly and sensitively.

Thousands of patients are intubated or given bag-valve-mask (BVM) ventilation every year in the pre-hospital setting. It can be argued that even patients who are not intubated but are receiving BVM, should also have their CO_2 levels monitored. Although they are not subject to the potential disaster of a misplaced endotracheal tube, they are vulnerable to the consequences of over- or under-ventilation. In addition, tracking the $EtCO_2$ concentration of an artificially ventilated patient has predictive value in determining the efficacy of CPR.[7-10]

Current Methods of Measuring $EtCO_2$

There are three technologies currently available for CO_2 monitoring: colorimetric devices, cable-connected mainstream/sidestream, and self-contained mainstream. This last category is the newest entry in the armamentarium of available devices. Mainstream or sidestream devices can either display CO_2 as a digital readout (capnometer) or as a waveform (capnograph).

Colorimetric devices detect and present a range of $EtCO_2$ in a qualitative format rather than as a specific number. They display color changes indicative of the presence of CO_2. This type of device has a pH-sensitive chemical indicator visible through a clear dome that turns from purple to yellow when attached to a correctly intubated patient, indicating that CO_2 is in the expired breath and the tube is therefore in the trachea. If it is attached to a patient with the tube in the esophagus, it remains purple. While it is easy to use, it can give false positive readings caused by the presence of CO_2 in the esophagus if carbonated beverages are ingested by patients just prior to application or if certain gastric contents or drugs are present.[11] In addition, its sensitivity is markedly reduced in patients with cardiac arrest and low perfusion,[12] up to an incidence of 13% failure rate.[13] Finally, colorimetric indicators require six breaths before they can give an accurate reading. Colorimetric devices are placed on ambulances in the intubation airway bag and are used by ALS-trained personnel whenever an intubation is required. They are also widely available in hospital crash carts because of their ease of use and convenience. However, due to their unreliability, some countries in Europe have prohibited their use in both pre-hospital and hospital settings.[14]

Cable-connected mainstream or sidestream monitors measure CO_2 using a sensor with a source of infrared light, a chamber containing the gas sample, and a photo detector. When the expired CO_2 passes between the beam of infrared light and the photo detector, the light absorption is proportional to the concentration of CO_2 in the gas sample. The photo detector response is calibrated with known concentrations of CO_2 and stored in the monitor's memory. In sidestream designs, a portion of the patient's expired gases is transported from the airway through a sampling tube to the sensor. Measuring the concentration of a gas distant from the sampling site is, however, problematic, since the condition under which the sample is taken is subject to varying water content, humidity, pressure, and temperature. Mainstream designs have, by contrast, the source of infrared light and the photo detector located right at the airway. This arrangement results in an immediate measurement without delays and a precise CO_2 waveform.

Cable-based sidestream/mainstream CO_2 measurement is an optional feature in defibrillators or "all in one" patient monitors utilized by ALS-trained paramedics, accomplished by the addition of a sensor added to other sensors such as ECG, SpO_2, and non-invasive blood pressure. The CO_2 information is registered and displayed on the screen of the device.

An innovation in $EtCO_2$ monitoring technology is EMMA™ (Masimo Sweden AB), a hand-held, battery-powered, self-contained mainstream device. The EMMA monitor detects $EtCO_2$ values in every breath while also showing the respiratory rate and a continuous capnograph. EMMA is very lightweight, weighing only about two ounces and requires no calibration. It operates on two standard AAA batteries and takes virtually no warm-up time, with full accuracy in 15 seconds, to register accurate measurements on an LED display.

Both cable-connected mainstream or sidestream devices and self-contained mainstream devices provide quantitative displays of $EtCO_2$. The results can be displayed as continuously varying digital readouts or a continuous waveform.

Different from colorimetric devices, quantitative capnographs display true readings of carbon dioxide usually expressed as a partial pressure of CO_2 in units of mmHg having a normal value between 35-45 mmHg. The use of quantitative capnographs is an advantage in pre-hospital medicine because it allows fast and reliable insight into ventilation, circulation, and metabolism. The availability of this technology may allow the wider use of capnography in EMS because of its ease of use and cost effectiveness. It could also lead to an expansion of applications within the emergency medicine spectrum that are not common now, but should be considered as the value of CO_2 monitoring is recognized well beyond its standard application as an endotracheal tube placement verifier. Capnography refers to the continuous, trend, and real-time CO_2 waveform display. These tracings have recognizable patterns that are helpful to advanced analysis of respiration, ventilation, and perfusion. Capnography is regarded as the ultimate form of CO_2 monitoring, includes a number of important parameters, and can be helpful in the differential diagnoses of a number of serious conditions.

The wide availability of CO_2 monitoring devices suggests that there is no technological impediment to its wider use. Some of the newer uses of capnography are evolving as its importance for the critically ill and injured patient are being recognized.

EMERGING USES OF CAPNOGRAPHY IN PRE-HOSPITAL MEDICINE

$EtCO_2$ Monitoring During Bag-valve-mask Ventilation

Bag-valve-mask ventilation (BVM) is one of the most common methods of ventilating patients during cardiac arrest, respiratory arrest, and trauma, and a frequently used procedure for those trained in Basic Life Support (BLS) since they are not certified to use devices that invade the airway. While other technologies may appear to have superseded it, there are clinicians who assert that BVM is at least as effective in ventilating patients as endotracheal intubation as demonstrated by survival rates. In fact, a large study concluded that the latter leads to longer pre-hospital times.[15] However, BVM is thought to be a difficult procedure to perform, sometimes requiring two operators who must remain focused on maintaining a seal on the patient's mouth while delivering ventilation. Studies have shown that varying BVM skill levels among EMS providers have led to poor patient outcomes.[16, 17] The use of capnography could improve these outcomes by providing real-time continuous feedback about adequacy of ventilation. However, the segmentation of levels of pre-hospital emergency care that EMS personnel are certified to provide has limited its use by more basic-level providers. In the United States, the levels consist of (1) Medical First Responder, (2) Emergency Medical Technician-Basic (EMT-B), (3) Emergency Medical Technician Intermediate (EMT-I), and Emergency Medical Technician-Paramedic (EMT-P). The latter two categories, comprising over 200,000 EMTs[18] of whom 25% are paramedics, are trained in Advanced Life Support (ALS), including the use of capnography. First Responders and EMT-Basic providers operate advanced medical devices such as bag mask resuscitators, facial masks, oxygen equipment and monitors, ventilators, and automated external defibrillators (AEDs). It is possible that they would be able to use portable mainstream $EtCO_2$ monitors but are not currently universally certified to do so.

$EtCO_2$ Monitoring During Transport

Several published studies have documented the importance of CO_2 monitoring of critically ill or injured patients during transport,[19-21] whether from an ambulance or a helicopter to an emergency department or from an emergency department to other areas of a hospital. These patients are commonly intubated, with some on mechanical ventilators. Both pediatric and adult advanced life support guidelines strongly recommend $EtCO_2$ monitoring during transport.[22]

A sudden change in CO_2 levels could indicate serious conditions such as endotracheal tube displacement, malfunction of the mechanical ventilator, or loss of pulmonary blood flow. However, even non-intubated patients may benefit from CO_2 monitoring, perhaps being an even more vulnerable population since they do not have an endotracheal tube in place and are subject to rapid changes in respiratory status. In two studies, capnography provided more reliable data than oximetry on patients during transport,[23, 1] leading the authors to recommend the use of CO_2 monitoring for victims of even minor trauma during transport to an emergency department.

Portability may be an important factor in the choice of capnographs, especially when patients are connected to other space-occupying monitors. In some cases, time to transport patients for in-hospital treatment is a factor and, thus, a reliable, portable device that does not need routine calibration is an advantage.

$EtCO_2$ Monitoring to Guide Ventilation Parameters

Much has been published about the importance of monitoring ventilation to avoid hyperventilation in particular. It is well recognized that hyperventilation is harmful to patient outcomes, yet it continues to be common during resuscitation. Excessive ventilation rates result in significantly increased intrathoracic pressure and decreased coronary perfusion pressures and survival rates.[24, 25] The goals for patients receiving artificial ventilation are controlled ventilation, optimized inspiratory time, and airflow.[26]

The problem of hyperventilation is particularly relevant in patients with severe head injuries in whom its negative effects have been studied extensively. In fact, the use of pre-hospital intubation has been challenged on the grounds that it predisposes to hyperventilation.[27] Careful monitoring of CO_2 and respiratory rate is required for the prevention of hyperventilation and is paramount to achieving improved outcomes in the field.[28]

Hyperventilation is an issue as well with the use of paramedic rapid sequence intubation (RSI) in patients with severe head injuries. There are mixed reports on whether or not RSI protocols increase intubation success in patients who cannot be easily intubated without the use of medications.[29, 30] Two San Diego studies were conducted to look specifically at the traumatic brain injury population in whom the risks of hyperventilation are well known. The first was a multi-agency ground transport study designed to explore the impact of hypoxia and hyperventilation on outcome. One of the study participants used portable digital CO_2 monitors with ventilation parameters modified to target $EtCO_2$ values of 30 to 35 mmHg. Patients in the $EtCO_2$ monitored group had a lower incidence of inadvertent severe hyperventilation than those without $EtCO_2$ monitoring; those who were monitored also had a reduced mortality rate. The authors concluded that the use of $EtCO_2$ monitoring is associated with decreased inadvertent severe hyperventilation and those patients who were not hyperventilated had a lower incidence of mortality.[31]

The second study was conducted in an air medical transport setting. It showed a different outcome: patient clinical parameters improved with pre-hospital RSI. There was a statistically significant decrease in patient mortality with air transport compared with ground transport. Air medical crews used capnography to guide ventilation on all study patients. The authors concluded that better outcomes may be attributed to the use of capnography to guide ventilation.[32]

Spot Checking $EtCO_2$ Throughout the Spectrum of Emergency Care

Another application of capnography is to spot check $EtCO_2$ levels and respiratory rates in patients as they progress through the emergency management system. Spot checking cannot practically be performed by equipment requiring time consuming setup or calibration. With a portable capnograph connected to a properly sealed face mask, any EMT or First Responder could ascertain $EtCO_2$ and respiratory rate in only 15 seconds. The results of spot checking could suggest a change in medical management or verify that current procedures are working.

$EtCO_2$ Monitoring During Emergency Department Delays

Because of the overcrowding of emergency departments especially during multiple trauma incidents, patients in the emergency department may experience delays until the appropriate specialists can be found to decide upon diagnosis and/or treatment. In such cases, fundamental to the appropriate care of these patients is the use of monitoring devices to ensure that patients remain stable until definitive treatment. In addition to monitoring of oxygenation and perfusion, ventilation should be monitored via capnography as well.[33]

$EtCO_2$ Monitoring for Assessment of the Efficacy of CPR and for Prediction of Survivability

A number of animal and human studies have shown an excellent correlation between $EtCO_2$ and cardiac output during cardiopulmonary resuscitation and during states of low blood flow,[33, 34] making capnography an effective tool to assist in evaluating the efficacy of cardiopulmonary resuscitation efforts. Reductions in $EtCO_2$ are associated with comparable reductions in cardiac output; increases in $EtCO_2$ are associated with return of spontaneous circulation (ROSC). The interpretation of $EtCO_2$ in the field has to take into account that controlled ventilations may be difficult or impossible when manual CPR is interrupted by patient movement or a change in rescuer position. However, several studies have concluded that certain changes in $EtCO_2$ levels are associated with successful CPR. A key study found that a rapid increase in CO_2 levels within 30 seconds of ROSC, followed by a decrease four minutes later that remained stable, is an almost immediate indicator of successful resuscitation.[7]

Carbon dioxide monitoring has also been used to predict out-of-hospital cardiac arrest survival. A 1985 study looked at this question in 34 patients, of whom 9 survived resuscitation. These 9 patients had higher average $EtCO_2$ levels during CPR than the 25 who did not.[7] Other studies confirmed these findings via different methodologies.[34] One of them was performed in 150 consecutive victims of cardiac arrest outside the hospital who had electrical activity but no pulse. The patients were intubated and evaluated by mainstream $EtCO_2$ monitoring. The authors' hypothesis was that an $EtCO_2$ level of 10mm Hg or less after 20 minutes of CPR would predict death. Of the 150 patients, 35 patients survived to hospital admission, and, in fact, the study showed that after 20 minutes of CPR, an $EtCO_2$ value of 10mmHg or less was predictive of death.[10]

Other studies confirm the 10 mmHg threshold. One found that initial, final, maximum, minimum, and mean $EtCO_2$ values were all higher in patients who were resuscitated than in those who were not. No patient with a reading below 10 mmHg survived.[9]

The data from multiple studies confirm that capnography appears to offer an effective tool to evaluate the progress and results of cardiopulmonary resuscitation and should be more widely used for this purpose by both ALS and BLS providers.

THE FUTURE OF CAPNOGRAPHY IN EMERGENCY MEDICINE

Based on the abundance of published studies, the value of $EtCO_2$ monitoring in emergency medicine is increasingly clear. Used in the past primarily for verification of correct endotracheal tube placement, its utility in monitoring ventilation in both intubated and critically ill non-intubated patients is being recognized. It is particularly effective in patients in whom inadvertent hyperventilation can cause a secondary injury and in assessing the efficacy of cardiopulmonary resuscitation. Its value in monitoring critically ill and injured patients during transport not only by ambulances or helicopters to hospitals but also within hospitals has resulted in practice standards adopted by a number of professional organizations worldwide.

It is likely that $EtCO_2$ is underutilized in resuscitation, perhaps because its critical importance in verifying correct endotracheal tube placement has overshadowed its utility in other clinical circumstances. It is recognized that pulse oximetry values can remain high for a considerable time while respiratory compromise remains undetected: in the pre-hospital, emergency setting, only $EtCO_2$ monitoring can consistently indicate impending respiratory deterioration. Monitoring $EtCO_2$ levels when respiratory compromise is suspected should be part of routine emergency department protocols. Finally, making capnography a standard for BLS providers is the next positive step in patient care. The difficulty of BVM ventilation and studies confirming poor outcomes for BLS personnel attributed to their varying skills argue for using capnography whenever bag-valve-mask ventilation is performed.

Cost is universally a consideration when the adoption of new technology is considered. Recently, advances in sensor design and miniaturization have made $EtCO_2$ monitoring more economical. Patients are often in physically inaccessible locations, time is always of the essence, and low light often makes attaching monitors to patients and reading the display a challenge. Having a rugged, portable, mainstream capnograph that can give both CO_2 measurements and make respiration rate accessible in an EMS "grab bag" is a clinical advantage.

Resuscitation medicine is at an exciting time in its development as a specialty. Not only does it attract people whose dedication to quality patient care is superior, it is innovative in adopting new technologies from clinical areas outside EMS for its unique patient population. Capnography has long been considered essential in the surgical suite and intensive care unit, but is just emerging as essential in pre-hospital medicine. Scientific evidence strongly supports more widespread application. The availability of portable, quantitative capnographs makes it cost effective and convenient to carry out in a time-sensitive, geographically challenging field of medicine.

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