PREHOSPITAL CARE

End tidal carbon dioxide monitoring in prehospital and retrieval medicine: a review

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End tidal carbon dioxide ($ETCO_2$) monitoring is the non-invasive measurement of exhaled CO_2. The Intensive Care Society guidelines include ($ETCO_2$) monitoring as one of the objective standards required for monitoring patients in transport, and the American Heart Association recommends that all intubations must be confirmed by some form of $ETCO_2$ measurement. The physiological principles and technology underlying $ETCO_2$ measurement and the clinical indication for its use in the prehospital environment are reviewed. $ETCO_2$ monitoring has been widely established in the prehospital environment and is of particular use for verification of endotracheal tube placement. It is non-invasive and easy to apply to breathing circuits. The units now available are compact and rugged, with extended battery operating times, which are ideally suited for prehospital use and should be considered as an essential item for advanced airway management.

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End tidal carbon dioxide ($ETCO_2$) monitoring is the non-invasive measurement of exhaled CO_2, first studied clinically by Smallhout and Kalenda in the 1970s.[1] It has been used extensively in operating theatres and intensive care units for the past 25 years and increasingly in emergency departments and the prehospital setting.[2–5] $ETCO_2$ monitoring is one of the objective standards set in the Intensive Care Society guidelines 2002 for the transport of the critically ill adult,[6] and is mandated by the American Heart Association in the new paediatric advanced life support guidelines, which state that all intubations must be confirmed by some form of $ETCO_2$ measurement.[7]

This article reviews the physiological principles and technology underlying $ETCO_2$ measurement and the clinical indication for its use in the prehospital environment.

PHYSIOLOGY

Aerobic cell metabolism produces CO_2, which diffuses out of the cell and into the tissue capillaries, where it is transported to the right side of the heart by the venous circulation.[2 8] The right ventricle pumps the venous blood to the lungs, where diffusion of carbon dioxide across the blood gas barrier of the alveolar wall, interstitial fluid, and pulmonary capillary endothelium is governed by Fick's law of diffusion (see definitions). The partial pressure of venous CO_2 is 46 mmHg (6.1 kPa) and the alveolar partial pressure of CO_2 is 40 mmHg (5.3 kPa) which gives a pressure gradient of only 6 mmHg (0.8 kPa).[8 9] This is a much smaller gradient than that for O_2 (65 mmHg/8.7 kPa), but the diffusion of both gases is almost equal, because CO_2 is much more soluble and has a diffusion constant 20 times greater than O^2.

When CO_2 diffuses out of the lungs in to the exhaled air it can be measured by a capnometer, which measures the partial pressure or maximum concentration of CO_2 at the end of exhalation. The graphic representation of expired CO_2 over time is termed capnography, and the waveform produced is a capnogram.[10]

$ETCO_2$ is a reflection of metabolism, circulation, and ventilation, and is usually equal to arterial CO_2 if there is no ventilation perfusion mismatch. The difference is usually 2–5 mmHg lower in $ETCO_2$ than arterial CO_2 ($PaCO_2$).[11] This difference can be markedly increased if there is a derangement of either the perfusion of the lung (as in compromised blood flow to the lung secondary to hypotension[12] or pulmonary embolus) or following the application of high levels of positive end expiratory pressure during mechanical ventilation, or in states that compromise ventilation of the alveoli, such as any of the lung diseases. Any conditions causing ventilation perfusion mismatch will cause the net $ETCO_2$ to underestimate the $PaCO_2$.[13] It is important to remember this, because the majority of patients in the prehospital environment will have significant physiological changes to their haemodynamic or ventilatory status as a result of trauma or anaesthetic agents used to aid tracheal intubation,[14] which may interfere with quantitative interpretation of $ETCO_2$.

TECHNOLOGY

There are several different methods for measuring CO_2 in respiratory gases but in the prehospital environment these are limited to two common methods: (*a*) monitors that incorporate infrared (IR) spectroscopy (either handheld or incorporated in to multimodal monitors) and (*b*) colorimetric detectors. IR spectroscopy works on the principle that infrared light is only absorbed by CO_2 and water vapour in the exhaled gases. The water vapour is removed by dehumidification, and in the sensor unit, light from the infrared measuring source is filtered to include

Abbreviations: CPR, cardiopulmonary resuscitation; $ETCO_2$, end tidal carbon dioxide; IR, infrared; $PaCO_2$, arterial carbon dioxide only the bandwidth corresponding to the absorption peak of CO_2. The amount of gas absorbed at the CO_2 bandwidth is compared with a known CO_2 concentration from a reference sample, and the partial pressure of $ETCO_2$ in the sample is determined.[15] IR spectroscopy monitor technology allows measurement of CO_2 qualitatively, semi-qualitatively, or quantitatively. The $ETCO_2$ is measured in pressure (torr) or volume concentration by dividing the $ETCO_2$ in torr by atmospheric pressure.

CO_2 sensors are located in line with the patient's breathing circuit (mainstream) or remote from the circuit (sidestream). Sidestream capnometers draw a continuous sample of gas from the respiratory circuit via tiny aspiration pumps for analysis. The major advantage of this method is that the patient does not require a closed breathing circuit to operate—that is, the patient does not need to be intubated and can monitored after administration of sedation or analgesia,[16] for example, during a prolonged entrapment. The disadvantages of this system are that the sampling tubing can become occluded with water and secretions, and gas analysis may take fractionally longer. Mainstream capnometers use specially designed airway adapters with windows, which allow the measurement head to be placed directly in line with the breathing circuit, usually attached to, or close to, the endotracheal tube. The major advantage of this technology is almost instantaneous gas analysis ("first breath analysis"), but the disadvantage is that it requires the patient to be intubated.

Modern IR capnometers are small handheld devices that have long battery operating times and tough rubberised shells, making them particularly suited to the prehospital environment. They have been shown to function effectively within the medical air transport setting.[17]

Colorimetric detectors are disposable devices that attach directly to the endotracheal tube. They incorporate a pH sensitive chemical that changes from purple ($ETCO_2$ 0.03%–<0.05%) to yellow ($ETCO_2$ 2–5%), and colour cycles can be observed during inspiration and expiration if the endotracheal tube is correctly placed in the trachea. The detector has a dead space of 38 ml, which precludes its continuous use in infants, but it can be safely used in patients weighing more than 2 kg to verify endotracheal tube position.[18] A dedicated paediatric device with a dead space of 3 ml does exist, which allows brief usage in infants up to 1 kg.[19] The advantages of the colorimetric devices are they are light and require no calibration or batteries. However, they can be difficult to read in poor lighting and give no indication of the quality of ventilation, and once soiled with blood, gastric contents, or tracheally administered drugs, they cease to function.

CLINICAL INDICATIONS FOR PREHOSPITAL $ETCO_2$ MONITORING

Determination of endotracheal tube placement

Intubation in the field is often performed in a less than ideal environment, with limitations on available equipment.[20] Unrecognised oesophageal intubation can prove rapidly fatal, and rates as high as 17–25% have been reported in emergency airway management of non-arrest patients.[21 22] Review of the literature is inconclusive for the actual incidence of missed and unrecognised oesophageal intubation in the prehospital setting in severely injured patients.[23–29] There are multiple methods for determining correct tube placement but no single method has been shown to be foolproof[30] (see Table 1). It is thus recommended that multiple methods are employed to confirm tube position, as no single method has perfect accuracy.[31] Capnography has proved a powerful adjunct, and in combination with auscultation has emerged as the gold standard in prehospital determination of tube position, as auscultation alone has not been sufficiently reliable.[23]

Table 1 Methods for confirming ETT placement in the prehospital setting

Clinical
Lateral/epigastric auscultation: equal and symmetrical breath sounds
Symmetrical bilateral hemi-thorax elevation on ventilation
Reservoir bag compliance and refilling
Direct inspection of tube passing between the cords
Mechanical
Lighted stylet
Oesophageal detector device
Colorimetric capnography
Electronic capnography (sidestream or mainstream)

There have been no studies addressing whether colorimetric CO_2 detectors are superior to capnography for confirming endotracheal tube position exclusively in the prehospital environment; however, the current literature suggests that both are equally accurate at detecting tracheal intubation, but colorimetric detection is potentially less accurate at detecting oesophageal intubation.[32] It has been demonstrated that in emergency situations where air that contains CO_2 may be present in the oesophagus, colorimetric devices may falsely indicate correct tracheal intubations, due to their sensitivity to very low CO_2 values.[33] Animal studies have also indicated that a diet cola drink placed in the stomachs of piglets produces sufficient CO_2 to give false positive $ETCO_2$ readings when the oesophagus was intubated.[34]

Control of ventilation

Traumatic brain injury is a leading cause of death in young adults.[35] Interventions in the prehospital phase are critical for prevention of secondary brain injury. Positron emission tomography brain imaging studies have demonstrated that cerebral blood vessels are sensitive to changes in $PaCO_2$, and hypocapnia induced by hyperventilation ($PaCO_2$ <34 mmHg) can lead to vasoconstriction and a reduction in global cerebral blood flow with an increase in volume of hypoperfused brain tissue, thus worsening the secondary brain injury.[36] Hyperventilation strategies to reduce hypertension induced by traumatic brain injury are no longer used, and ventilation parameters should be aimed at achieving "normocapnia". This can be adequately achieved by utilisation of a capnograph after intubation to guide ventilation parameters and thus prevent inadvertent hyperventilation.[37 38]

Safety during transport

As mentioned previously, $ETCO_2$ monitoring is one of the objective standards set in the Intensive Care Society guidelines 2002 for transport of the critically ill.[6] A typical primary transfer may involve moving a ventilated patient from the scene to aircraft to ambulance to emergency department, with inherent risks of circuit disconnection at every stage. Endotracheal tubes have been shown to migrate as far as 50 mm during transportation.[39] Because of the high levels of ambient noise in the prehospital environment, the capnograph is a more reliable indicator of integrity of the breathing circuit than reliance on audible alarms.[14]

$ETCO_2$ as a prognostic indicator

The primary interventions of cardiopulmonary resuscitation (CPR) include establishing a patent airway, ventilation, and chest compressions. If these interventions are performed optimally, a cardiac output of 17–27% can be achieved.[40 41] Several animal studies have found that the higher the coronary artery perfusion pressure achieved during CPR,

DEFINITIONS

- **Fick's law of diffusion:** relates the flow of gas across a membrane to the area and thickness of the membrane, the partial pressure difference of the gas across the membrane, and the diffusion constant of the individual gas
- **End tidal CO_2:** measurement of CO_2 at the very end of expiration. This is the maximum concentration of expired CO_2.

the more likely the resuscitation is to be successful.[42 43] $ETCO_2$ has been shown to correlate linearly with coronary artery perfusion pressure, and hence this simple and non-invasive method can be used to measure blood flow during CPR and can indicate a return of spontaneous circulation.[44] It has been demonstrated that $ETCO_2$ values of <10 mmHg at the start of resuscitative efforts is associated with a high risk of death.[45] $ETCO_2$ measurements may have some value in decision making about when to terminate resuscitative efforts, given their prognostic value.

$ETCO_2$ as a reflection of cardiac output has also been applied to patients with blunt trauma to determine if there is an association with outcome from prehospital trauma. Patients requiring intubation following blunt trauma with low $ETCO_2$ values at 20 minutes had lower rates of survival, thus indicating that $ETCO_2$ is of value in predicting outcome.[46]

CONCLUSION

$ETCO_2$ monitoring has been widely established for a number of roles in the prehospital environment and is of particular use for verification of endotracheal tube placement in difficult and noisy environments. It is non-invasive and easy to apply to breathing circuits. Manufacturers have developed compact and rugged units with extended battery operating times, which are ideally suited for prehospital use, and should be considered as an essential item of kit for any prehospital care practitioners performing advanced airway management.

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