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Uses of capnography in the critical care unit

Ian Kerslake BSc (Hons) MB ChB FRCA FFICM* and Fiona Kelly MA MBBS MRCP FRCA FFICM DICM

Consultant in Anaesthesia and Intensive Care Medicine, Royal United Hospital, Combe Park, Bath BA1 3NG, UK

*To whom correspondence should be addressed. Tel: 01225-825056; Email: ikerslake@me.com

Key points

- Capnography should be continuously monitored in all patients with an artificial airway
- Failure to use capnography in patients dependent on an artificial airway contributed to more than 70% of the ICU-related airway deaths in NAP4
- Education of medical and nursing staff is vital to ensure adequate understanding and appropriate interpretation of the capnography trace
- Capnography can be used in both intubated and non-intubated patients
- Uses of capnography are wide ranging and not limited to monitoring of the airway

The fourth national audit project (NAP4), a prospective study by the Royal College of Anaesthetists and the Difficult Airway Society, investigated major complications of airway management in the UK. It found that airway complications occurred in the intensive care unit (ICU) and the emergency department (ED) more frequently than in theatres, and that airway events in these areas were much more likely to lead to permanent harm or death.[1] In more than 70% of the deaths in these areas, failure to use capnography in patients dependent on an artificial airway was reported to be a contributory factor.[1] Following the publication of NAP4 in 2011, UK and European guidelines have been modified,[2–4] with the Association of Anesthetists of Great Britain and Ireland (AAGBI) issuing a safety statement in 2011: this stated that continuous capnography should be used in all anaesthetized patients, regardless of the airway device used or the location of the patient, and should be employed in all patients receiving advanced life support. Although the use of capnography in ICU has become more widespread since the modification of these guidelines, uptake is still incomplete with only 72% of UK ICUs routinely using capnography.[5] It is well recognized that capnography can be used to detect displaced tracheal tubes and tracheostomy tubes and to diagnose inadvertent oesophageal intubation. In addition, capnography has other uses in ICU relating to airway management and monitoring of respiratory and cardiovascular function.

Physical principles and physiology of capnography

Capnometry is the measurement of carbon dioxide (CO_2) in a sample of gas. Capnography is the continuous monitoring of the concentration or partial pressure of CO_2 in respiratory gases. This is represented in a graphical form, with time on the X-axis and expired partial pressure of CO_2 on the Y-axis: the result is a capnography trace or waveform (Fig. 1). The end tidal CO_2 (E'_{CO_2}) is the *maximal* partial pressure or concentration of CO_2 in the respiratory gases at the end of an exhaled breath. A capnometry monitor displays the E'_{CO_2} value alone, where as a capnography monitor displays the E'_{CO_2} value plus a continuous capnography waveform.

The capnography trace can be described in four stages (Fig. 1), and is divided into inspiration and expiration:

- Phase I (inspiratory baseline) represents inspiration, and therefore no CO_2 is detected. The end of phase I represents the beginning of expiration, but because the initial gases expired originate from *unventilated* dead space, the capnography trace remains at zero.

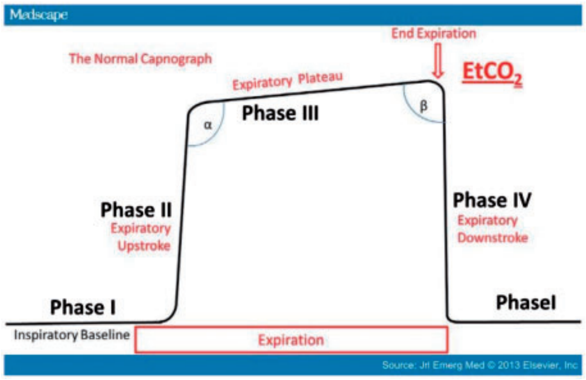


Fig 1 Normal capnography trace. Reproduced with kind permission from Elsevier (3616430770815).

- Phase II (expiratory upstroke) represents expiration of both dead space gas and alveolar gas from the respiratory bronchioles and alveoli.
- Phase III (alveolar plateau) represents expiration of alveolar gases. At the end of phase III, the maximal value of CO_2 measured is equivalent to the E'_{CO_2}. Note that if the alveoli all contained exactly the same partial pressure of CO_2, phase III would be completely horizontal. In reality, CO_2 concentrations vary between alveoli as a result of varying ventilation to flow ($\dot{V}/\dot{Q}$) ratios. Generally those alveoli with lower $\dot{V}/\dot{Q}$ ratios and with longer time constants (containing relatively more CO_2 and emptying relatively slowly) contribute to the *later* part of phase III, leading to a slight upward slope of the capnography trace.
- Phase IV (expiratory downstroke) represents the beginning of the next breath, with the CO_2 content returning rapidly to zero. Healthy patients with normal respiratory function will produce a capnography trace with this form. Lung pathologies will change the appearance of the capnograph due to a number of different factors: bronchoconstriction and obstruction to airflow, destruction of alveoli, an increase in the range of alveolar time constants (alveoli that empty at different rates), and an increase in $\dot{V}/\dot{Q}$ spread (variation in CO_2 content of each alveolus). As a result, the slope of phase III is often markedly increased in respiratory disease.

Methods of capnography measurement

The CO_2 content can be measured by spectroscopy or mass spectrometry. Spectroscopy, usually infra-red spectroscopy, is the most commonly used method in clinical practice, and works on the principle that CO_2 absorbs infra-red radiation. A beam of infra-red light is passed across the gas sample to fall onto a sensor. The presence of CO_2 in the gas leads to a reduction in the amount of light falling onto the sensor, which then changes the voltage in a circuit. The analysis is rapid, allowing the production of an accurate real time waveform. Infra-red spectroscopy is incorporated into a side stream or mainstream analyser. There are advantages and disadvantages associated with both.

Side stream analysers

Sample gases are withdrawn from the main respiratory tubing, usually at the humidified moisture exchange filter, and into narrow tubing that is connected to a cuvette. The rate of gas withdrawal is usually between 50 and 500 ml/min. Side stream analysers are configured to use high-flow rates (greater than 100 ml/min) or low-flow rates (around 50 ml/min). Advantages of using side stream analysers are that they are less bulky than main stream analysers, and can be configured for use in non-intubated patients (e.g. with specially adapted nasal cannulae). Readings are prone to inaccuracy in smaller patients and in the presence of hypoventilation, particularly if high-flow rates are used. Disadvantages of side stream analysers include the need for a suction pump to draw the sample into the measurement chamber and inaccuracies caused by suction pump function. Side stream analysers can become blocked, especially on ICUs if a Heat and Moisture Exchanger is not used on the ventilator circuit, meaning that a water trap is essential. Additionally, the gas flow rates may cause auto-triggering of the ventilator particularly in neonates.

Main stream analysers

Main stream analysers have a measuring head which is placed directly into the ventilation circuit, and sends a beam of infra-red light through the respiratory gases in the circuit adjacent to the patient. The main stream technique therefore does not involve the removal of gases, eliminating associated errors in gas measurement and making the system simpler and less prone to malfunction. Disadvantages of such systems are that they are bulky (which may itself contribute to airway problems), relatively expensive, can be inaccurate if the sensor window is not kept clean and can only be used for intubated patients.

Capnography monitoring for non-intubated patients

The use of nasal cannulae with Microstream™ capnography has become more frequent over the past 5 years, and several devices are now available (Fig. 2). A surprisingly robust capnograph trace is generated, which can be used to monitor the respiratory rate and trends in exhaled CO_2. These nasal cannulae can be used for patients receiving non-invasive ventilation, and those sedated for a procedure such as transoesophageal echocardiogram or oesophageal gastroduodenoscopy.

Information derived from the capnograph

A capnography trace allows two pieces of information to be displayed: the E'_{CO_2} value and a continuous waveform. The E'_{CO_2} is a non-invasive estimate of the CO_2 concentration or partial pressure in the arterial blood (Pa_{CO_2}), with the E'_{CO_2} being 0.5–0.8 kPa lower than the Pa_{CO_2} in a healthy patient with normal lungs. This difference is increased if there is a mismatch between ventilation and perfusion of the lungs, as seen in patients with lung disease, pulmonary emboli (caused by thrombus, air or fat), low-cardiac output states, and hypotension.

Morphology of the capnography trace

The continuous waveform allows a visual breath-by-breath assessment of a patient's airway and ventilation, with the contour of the waveform giving considerably more information than the E'_{CO_2} value alone. A healthy patient with normal lungs will, when ventilated via a patent tracheal tube or tracheostomy, produce a typical 'square wave' capnography trace as shown in Fig. 1. A deviation from such a square wave trace (Figs 3 and 4) suggests one of the following problems:

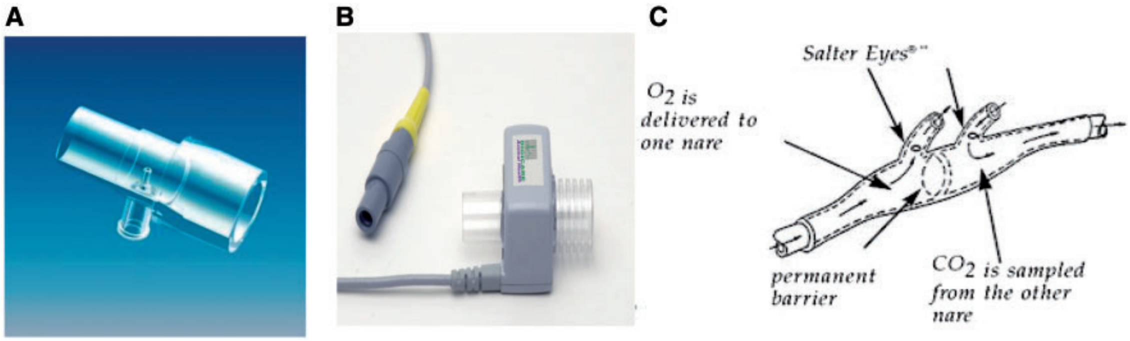


Fig 2 Methods of capnography measurement: (A) side stream analyser; (B) main stream analyser; (C) FilterLine™ capnography for non-intubated patients. Reproduced with kind permission from Salter Laboratories, USA.

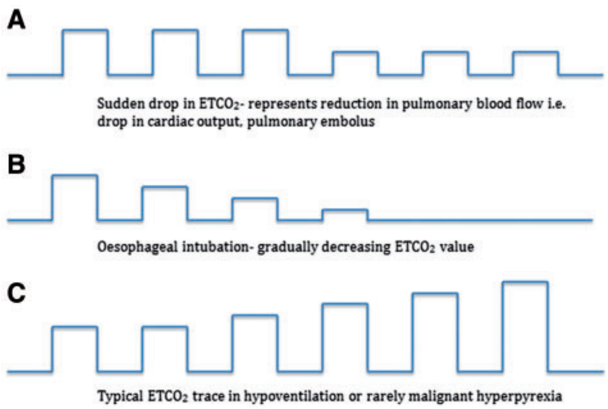


Fig 3 Different capnography traces: (A) sudden drop in E'_{CO_2}; (B) oesophageal intubtion; (C) steady rise in E'_{CO_2}.

(i) Capnography waveform with a dramatic up-sloping plateau phase: this suggests that the patient has bronchospasm, that the airway is partially blocked or that the endotracheal tube has migrated beyond the carina and into a main bronchus.

(ii) Capnography waveform with a peaked, triangular appearance: this suggests that there is a significant leak around the tracheal tube or tracheostomy.

(iii) Flat capnography trace: this suggests one of the following:
  a. the oesophagus has been mistakenly intubated instead of the trachea;
  b. the tracheal tube or tracheostomy has become displaced;
  c. the breathing circuit has become disconnected;
  d. the airway has become obstructed: the airway has become kinked or blocked with secretions, or the patient has bitten and occluded the tracheal tube;
  e. the expiratory limb of the breathing circuit has become blocked;
  f. Monitor failure, e.g. the presence of liquid in the tubing of a side-stream capnograph.

(iv) A sudden drop in E'_{CO_2}, but with a square wave capnography trace still seen, suggests a sudden drop in lung perfusion, either caused by an obstruction to blood flow through the lungs (caused by thrombus, air or fat) or by a reduction in cardiac output. When E'_{CO_2} falls because of reduced pulmonary perfusion, the arterial CO_2 will rise due to the inability of the lungs to excrete CO_2. The clinician may need to give consideration to increasing alveolar ventilation in this circumstance.

(v) A steady increase in the E'_{CO_2} value, again with a square wave trace, suggests hypoventilation, but may rarely represent malignant hyperpyrexia if associated with rise in temperature.

(vi) A steady decrease in the E'_{CO_2} value may represent oesophageal intubation, with a maximum of six waveforms seen after intubation. The alternative picture seen after oesophageal intubation is a flat line trace as described above.

The different waveforms seen and their clinical implications have been described using the 'hats and caps' capnography training tool (Fig. 4).[6] This has been used very successfully to train nurses and junior doctors on our ICU, remembering that 'posh hats are best in Bath': the traces in the left hand column (the 'posh' hats) indicate that the tracheal tube or tracheostomy is patent, as opposed to the traces in the right hand column which should give immediate cause for concern.

The capnograph trace is flat during untreated cardiac arrest due to the lack of cardiac output, but during c (CPR) there is an attenuated capnograph trace. Failure to identify a capnograph trace should raise the suspicion that the airway is incorrectly placed, but a flat line trace may be seen after very prolonged cardiac arrest.

Applications of capnography

Confirmation of tracheal intubation

Capnography is mandatory during intubation in theatre. NAP4 highlighted that failure to use capnography, or failure to

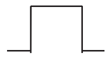
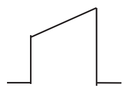
Good	Bad
 Top hat – good Indicates: • clear unobstructed airway	 Dunce hat – bad Indicates : • significant leak
 Ascot hat – OK Indicates: • bronchospasm • partially obstructed airway	No hat – very bad Indicates: • dislodged/displaced tracheal tube or tracheostomy • oesophageal intubation • lack of ventilation

Fig 4 'Hats and caps' capnography training tool.

correctly *interpret* a capnography trace, resulted in several oesphageal intubations going undetected in theatre, ICU and ED. In some cases, a flat capnography trace was misinterpreted as indicating lack of cardiac output due to cardiac arrest, and in other cases capnography was not used at all. Capnography during intubation, and for the period a patient remains dependent on an artificial airway, was cited as being the single most effective way of reducing morbidity and mortality surrounding airway and ventilator management.[1]

Confirmation of correct tracheal tube placement using clinical signs has been shown to be unreliable in numerous papers. The Anesthesia Closed Claim Project reported that oesophageal intubation was commonly not diagnosed until the patient suffered a cardiac arrest, and was usually preceded by misleading clinical checks which had suggested correct placement of the tracheal tube. Fogging of the tracheal tube occurs in 83% of oesophageal intubations, and chest wall movement can be produced by both correctly placed tracheal tubes and those incorrectly placed in the oesophagus. In one study, anaesthetists in ideal operating room conditions, using breath sounds as the sole means of verification, incorrectly identified tracheal tube location in 16% of cases.[7] The diagnosis of oesophageal intubation using capnography is not always straightforward. The capnopgraph trace classically associated with oesophageal intubation is a flat line trace. However, CO_2 can be present in gas in the stomach, especially if face mask ventilation has been difficult prior to intubation, and this can result in a confusing picture. A capnograph trace *may* be seen initially: oesophageal intubation often results in a series of waveforms, of decreasing height, and not usually more than six in total, before becoming a flat line trace. Oesophageal intubation may be harder to detect in patients in cardiac arrest or with low-cardiac output states. The sensitivity in cardiac arrest depends on the time since cardiac output was lost and the type of CO_2 monitoring used, with sensitivities quoted to be in the region of 62–100%.

Assessing tracheal tube and tracheostomy patency and position

Capnography monitoring for patients dependent on an artificial airway gives real time, continuous and 'at a glance' information on airway patency. A change in capnography waveform should alert staff to potential problems with the airway, and trigger an immediate assessment and response. Capnography has a fast response time, with changes in the capnography wave form usually seen before a change in oxygen saturations.

Monitoring adequacy of ventilatory support

Monitoring the adequacy of mechanical ventilation with capnography is well described. It can be used to detect hypercapnia due to hypoventilation, hypocapnia due to hyperventilation and can be useful when weaning patients from ventilatory support. It gives information about trends and efficiency of ventilation (and perfusion), but its use in determining absolute values for Pa_{CO_2} is limited, for the reasons previously described.

Use during percutaneous tracheostomy placement

Capnography can also improve safety when performing percutaneous tracheostomy by confirming that the tracheostomy is correctly placed in the trachea at the end of the procedure. Capnography monitoring is likely to become a standard of care for this potentially high-risk procedure.[5]

Monitoring patients with raised intracranial pressure

Capnography monitoring is especially useful for patients with raised intracranial pressure (ICP). Cerebral blood flow varies considerably depending on the Pa_{CO_2} in the blood: if the Pa_{CO_2} rises, cerebral blood flow rises, resulting in increased ICP. Low Pa_{CO_2} causes vasoconstriction of the cerebral blood vessels, reducing cerebral blood flow, which may also have detrimental effects. E'_{CO_2} monitoring can therefore be used as a surrogate but continuous monitor of the stability of Pa_{CO_2} during ICP management.

Monitoring response to the treatment of bronchospasm

A patient with bronchospasm usually has a capnography trace with an exaggerated up-sloping plateau phase, as discussed above, and with a prolonged phase II representing slow expiration of respiratory gases. Capnography has been used for many years to assist in the diagnosis of bronchospasm. In addition to conventional methods of assessing response to bronchodilator treatment, observing the steepness of the plateau phase slope on the capnography trace can be monitored.

Estimation of cardiac output

Provided ventilation remains constant, the E'_{CO_2} provides a continuous trend of pulmonary blood flow and therefore an estimation of the cardiac output. A number of studies have shown that the E'_{CO_2} can be useful in estimating a change in cardiac output. Changes in E'_{CO_2} in response to a fluid challenge or passive leg raise test (PLR) have also been studied, however, any rise in E'_{CO_2} in response to a PLR has been found to be small, meaning that E'_{CO_2} should not be used alone in this way to assess fluid responsiveness.

Use during cardiac arrest

Capnography has several roles at cardiac arrest:

(i) Confirmation that the airway is patent and present within the trachea
(ii) Monitoring ventilation rate during CPR and avoiding hyperventilation
(iii) Assessing adequacy of chest compressions during CPR
(iv) Identifying return of spontaneous circulation (ROSC) during CPR
(v) Prognostication during CPR.[8]

Arguably the most important role of capnography in cardiac arrest (with ongoing CPR) is to confirm that the airway is patent. As early as the 1980s, studies on animals showed that the effectiveness of CPR was reflected in levels of expired CO_2. During cardiac arrest, if the alveolar ventilation and metabolism can be assumed to be constant, then the E'_{CO_2} reflects the pulmonary blood flow. The more effective the CPR, the higher the cardiac output will be and therefore the higher the E'_{CO_2}. This was first shown to be the case in humans in 1988. More recently, it has been suggested that E'_{CO_2} can be related to outcome,[9] with low E'_{CO_2} values during CPR being associated with lower ROSC rates and increased mortality, and high values with better ROSC and survival However, the 2015 European Resuscitation Council[8] Guidelines emphasize that E'_{CO_2} values should be considered only as part of a multi-modal approach to decision making for prognostication during CPR.[8]

E'_{CO_2} also identifies ROSC. There is often an incremental increase in the E'_{CO_2} at the point of ROSC.[8] This has been reported to precede a palpable pulse if there is a sudden increase in cardiac output.[10] The guidelines describe the use of capnography to 'enable ROSC to be detected without pausing continuous chest compressions thereby improving quality of resuscitation and preventing the potential harm caused by administering a further boluses of adrenaline after ROSC'.[8]

Other uses of capnography

Volumetric capnography (VCap) measures the kinetics of CO_2 elimination on a breath-by-breath basis (e.g. the NM3, Philips, Connecticut, USA). It can do this by simultaneously measuring the expired CO_2 and the tidal volume, using a pneumotachograph. If ventilation is kept constant, the VCap becomes a sensitive monitor of pulmonary blood flow, allowing cardiac output to be estimated non-invasively and fluid responsiveness to be assessed. VCap can also be used to measure physiological and alveolar dead space, and to assess any response to a change in ventilation. A volumetric capnogram contains physiological information about metabolism, the effectiveness of the circulation and CO_2 elimination within the lungs. VCap is also a clinical tool to measure dead spaces allowing an accurate analysis of the functional components of each tidal volume. If the arterial concentration of CO_2 is known and one measures the exhaled tidal volume, the physiological dead space can be calculated [Vd (phys) = anatomical (+apparatus) + alveolar dead space]. VCap can then be used to track changes in lung mechanics in response to a change in either tidal volume or application of PEEP. In addition, if ventilator conditions are kept constant, the VCap becomes a very sensitive monitor of pulmonary blood flow. This enables rapid detection in cardiac output or intravascular volume responsiveness.[11] Similarly, it can also be used to differentiate deficits in lung perfusion as a result of embolic events (i.e. pulmonary embolus) or central hypovolaemia.

A meta-analysis performed by Chau and colleagues[12] looking at the use of capnography in the placement of nasogastric tubes (NGs), showed that there is evidence capnography can be used to detect misplacement with a sensitivity of 0.88–1.0 for misplacement. Although this method was first described over 10 years ago, it cannot be used as a sole method for confirmation of NG tube placement at present.

Provision of capnography in the UK

Although the use of capnography for all patients with a tracheal tube or tracheostomy in ICU is increasing, there are still many UK ICUs who do not routinely use such monitoring. Many reasons have been postulated for such resistance to change, including lack of suitable monitors and the cost involved in establishing this level of monitoring, costs of capnography tubing, concerns that capnography tubing may cause an airway to become displaced, lack of time to train ICU nursing staff, and an opinion amongst some intensivists that such monitoring is not necessary. Capnography monitoring in theatre is judged to be essential by the AAGBI, and many hold the view that failure to use continuous capnography in ICU is similarly negligent.[13,14]

Conclusion

Capnography has multiple uses on the ICU, where its use can significantly improve patient safety and quality of care. UK and European guidelines recommend that all ICU patients dependent on an artificial airway should have continuous capnography monitoring, and its use in UK ICUs is becoming more frequent. In addition to assessing the patency and position of a tracheal tube or tracheostomy, capnography can give additional information regarding respiratory and cardiovascular function, in both ventilated and non-ventilated patients. Capnography use is mandatory for patients anaesthetized in theatre; many would say that it is now indefensible for ICU patients, dependent on an artificial airway, to be cared for without continuous capnography monitoring.[13,14]

Declaration of interest

None declared.

MCQs

The associated MCQs (to support CME/CPD activity) can be accessed at https://access.oxfordjournals.org by subscribers to *BJA Education*.

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