Capnography in the Nonintubated Patient

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KEY POINTS

- Capnography can be performed in patients with and without airway devices.
- Capnography detects a change in ventilation up to 4 minutes before arterial desaturation, especially when supplemental oxygen is administered.
- In nonintubated patients, the precise value of partial pressure of end-tidal CO_2 is less important than any change from baseline in the respiratory pattern, rate, or end-tidal CO_2 reading.
- During procedural sedation, the addition of capnography greatly decreases the risk of hypoxia and hence is recommended by all major guidelines.

INTRODUCTION

The indispensable role of capnography in monitoring respiratory function has become increasingly evident in anaesthesia practice. This article focuses on capnography in nonintubated patients and will explore the place of capnography outside the operating room, including intensive care units (ICUs), nonoperating room anaesthesia, patient transportation, and the emergency department.

DEFINITIONS

Capnometry is the numerical measurement of CO_2 concentration or partial pressure in a gas sample. Capnography is the continuous monitoring of the concentration or partial pressure of CO_2 in respiratory gases plotted against time. Colorimetric capnography qualitatively determines the presence of CO_2 by means of a pH-dependent indicator.

Mainstream or nondiverting capnography measures the partial pressure of end-tidal CO_2 ($P_{ET}CO_2$) at the airway, providing a real-time measurement. Sidestream or diverting capnography transports the gas sample from the patient to a gas analyser located in the monitor, resulting in a lag of a few seconds. Sidestream analysers are less bulky than mainstream analysers, making them convenient to use in nonintubated patients, as the sample line can be fitted to any airway device, including a face mask.

HISTORY AND DEVELOPMENT

The Beer-Lambert Law, formulated in 1852, describes the logarithmic relationship of components of gas mixtures and solutions with light absorbed. Tyndall made the earliest measurement of CO_2 in exhaled air with a (room-sized) infrared analyser.

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TAKE ONLINE TEST

Introduction of the Luft cell in 1937 and development of "breathe through" CO_2 analysers resulted in the first clinical use in 1961. Capnography was "encouraged" in the 1986 American Society of Anesthesiologists guidelines and became a standard of care in 1991.

PRINCIPLES OF CAPNOGRAPHY

The 5 physical methods of measuring CO_2 concentration are infrared absorption spectrography, molecular correlation, Raman spectrography, mass spectrography, and photoacoustic spectrography. Infrared absorption spectrography is the most common technique because of its simplicity, accuracy, and reliability. It is based on the absorption of infrared light of a specific wavelength (4.27 μm) by CO_2. When a beam of infrared light is passed through the gas sample, any CO_2 in the sample absorbs some of the light and decreases the amount of light that reaches the sensor. The changes in light intensity are then converted into electrical signals and displayed on the monitor.

As seen in Figure 1, in mainstream monitors, the sample cell is directly in the path of the respiratory gases, with the infrared source and photodetector on either side. In sidestream monitors, the measuring mechanism is in the main body of the monitor and consists of a pump (to aspirate gas), the sample chamber, the infrared source, and photodetector.

Collisions with other molecules such as oxygen and nitrous oxide broadens the absorption spectrum of CO_2, causing a small error in measurement. A correction factor is applied by modern analysers, which monitor the other gases in the mixture. A further refinement is microstream technology, which is highly specific to CO_2 and hence is not affected by other gases. The sampling rate in these monitors is much lower, making it suitable for smaller patients.

CAPNOGRAPHY WAVEFORMS

The following 4 phases and 2 angles are shown in Figure 2:

- Phase I (expiration): reflects inspired gas, which is devoid of CO_2 and should be at 0.
- Phase II (expiratory upstroke): due to expiration of anatomical dead space gas mixed with some alveolar gas.
- Phase III (alveolar plateau): represents the exhalation of alveolar gas, rich in CO_2. The $P_{ET}CO_2$ is measured at the end of this phase.
- Phase IV (inspiratory downstroke): reflects the beginning of the next breath, with CO_2 content rapidly returning to 0.
- α Angle: the transition from phase II to phase III; normally 108°.
- β Angle: the transition from phase III to phase IV (the start of inspiration).

The $P_{ET}CO_2$ is an indirect measurement of the partial pressure of CO_2 in the arterial blood ($PaCO_2$). In healthy individuals, the $PaCO_2$ to $P_{ET}CO_2$ difference is very small (normal difference of 4 to 5 mm Hg) but increases with an increase in the alveolar dead space.

The anatomical and apparatus dead spaces combined cause rebreathing of CO_2 and thus decrease the alveolar ventilation for a given minute ventilation. A large apparatus dead space composed of an Heat and Moisture Exchanger filter, catheter mount, and other connections would lead to hypercapnia, which is reflected in a high $P_{ET}CO_2$. This is especially significant in infants and neonates.

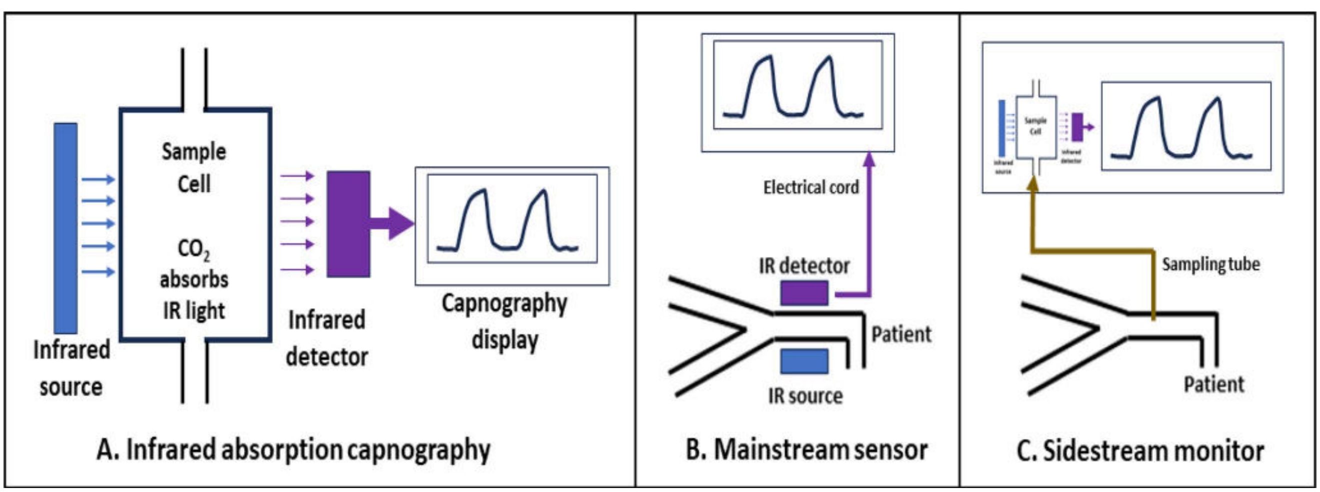

Figure 1. (A) Principle of infrared (IR) absorption capnography. (B) Mainstream capnography, where the sensor consisting of the infrared source and detector are located close to the patient. (C) During sidestream capnography, a gas sample is carried to the sensor located in the monitor.

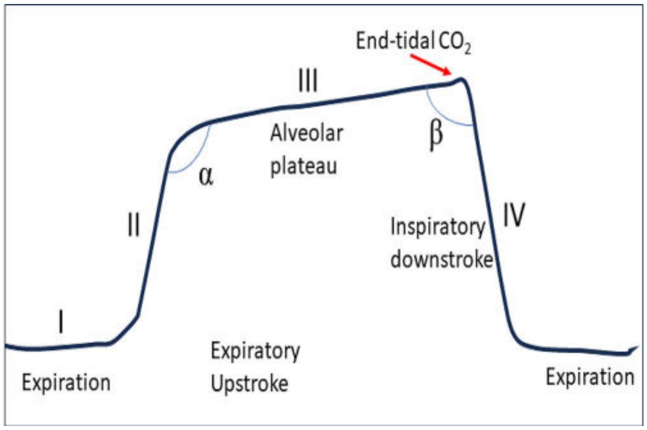

Figure 2. Capnography waveform.

Capnography has numerous applications, many of which are listed in Table 1.

CAPNOGRAPHY IN A PATIENT WITHOUT AN ENDOTRACHEAL TUBE

The normal capnography waveform of an intubated patient shows the 4 phases described above. By contrast, the sidestream sample in nonintubated patients consists of exhaled gas mixed with ambient air and any supplemented oxygen. As shown in Figure 3, the waveform is more rounded, and the peak CO_2 value does not represent the arterial CO_2 level. The displayed value also varies with the amount of dilution and distance from nose or mouth. The waveform, however, is confirmation that ventilation is taking place and allows us to determine the respiratory rate. Changes in the waveform pattern and rate are helpful in deciding whether any intervention is necessary. Thus, the nonintubated capnograph is a qualitative assessment of the ventilatory status, using exhaled CO_2 as a tracer gas.

The specific device used also makes a difference to the waveform, as can be seen in Figure 4, which shows a comparison of CO_2 waveforms between a face mask and a divided nasal cannula, where the nasal cannula reflected the $PaCO_2$ more accurately in this study by Loughnan.[1]

Confirmation of correct tracheal tube placement	Introduced into the American monitoring guidelines after several instances of hypoxic brain damage due to undetected oesophageal intubations. NAP4 report from the United Kingdom identified 9 cases of accidental oesophageal intubation over 1 year. “No trace = wrong place!”
Anaesthesia with a supraglottic airway device (SAD) or face mask	Good monitor of ventilation and correct positioning of the SAD (a well-positioned SAD has a similar waveform to an intubated patient, but the trace is more rounded if the SAD is poorly seated).
Transfer to and care of patients with SADs in situ in the postanaesthesia care unit	Good monitor of effective ventilation and correct positioning of the SAD.
Cardiac arrest	Confirmation of correct endotracheal tube or SAD placement; capnography trace attenuated but present since the lungs still contain CO_2. Prognostication (<10 mm Hg predicts a poor outcome). Adequacy of compression (10 to 20 mm Hg). Detection of return of spontaneous circulation (sudden increase). The trace is never completely flat unless the cardiac arrest has lasted several hours.
Detection of problems during anaesthesia	Equipment malfunction (eg, exhausted CO_2 absorber, stuck one-way valve, obstruction or kinking of breathing system, or endotracheal tube and ventilator or breathing system disconnection). Hypocarbia (overventilation or low cardiac output, pulmonary embolism, and cardiac arrest). Hypercarbia (CO_2 insufflation during laparoscopic surgery, hypoventilation, excessive dead space, and malignant hyperthermia). “Curare clefts” indicating that the muscle relaxant has worn off.

Table 1. Capnography Uses in the Operating Theatre Setting

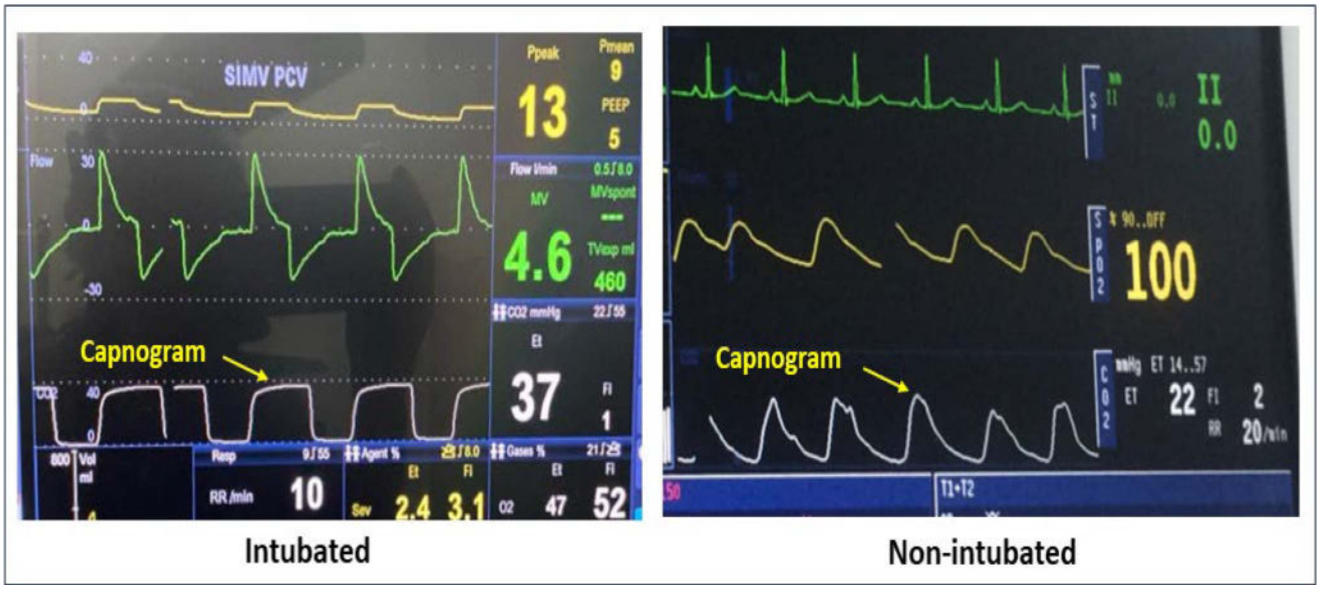

Figure 3. Comparison between intubated (left) and nonintubated (right) capnograph. The capnogram on the left is uniform and adheres to the waveform principles described in Figure 1. The capnogram on the right has variability amongst waveforms and deviates from the principles shown in Figure 1.

CAPNOGRAPHY PATTERNS IN A NONINTUBATED PATIENT

In otherwise healthy patients breathing at a normal minute ventilation, the waveform will resemble the intubated waveform, except for being more rounded at the corners (Figure 3). By contrast, hyperventilation would show as a faster rate and a lower plateau, reflecting the washout of CO_2 and a decrease in $PaCO_2$ and $P_{ET}CO_2$.

Hypoventilation, particularly in the perioperative setting, may be the result of sedative medication administration. Table 2 highlights some of the capnography patterns that may be associated with particular medications. One should also keep in mind that using these medications in combination can potentiate their individual effects. As shown in Table 3, the level of sedation is a continuum, and patients can easily drift into deeper sedation than intended, in which case intervention may be required to maintain cardiorespiratory function.

It can also be the result of upper airway obstruction due to decreased muscle tone; this results in a smaller capnogram plateau, showing a falsely low value for $P_{ET}CO_2$. Partial airway obstruction presents clinically with stridor or stertorous breathing along with distortion of the capnography waveform and low $P_{ET}CO_2$. Complete airway obstruction is clinically silent, with a flat waveform. Paradoxical movements of the chest and suprasternal retraction help to differentiate obstructive apnoea from central respiratory depression.

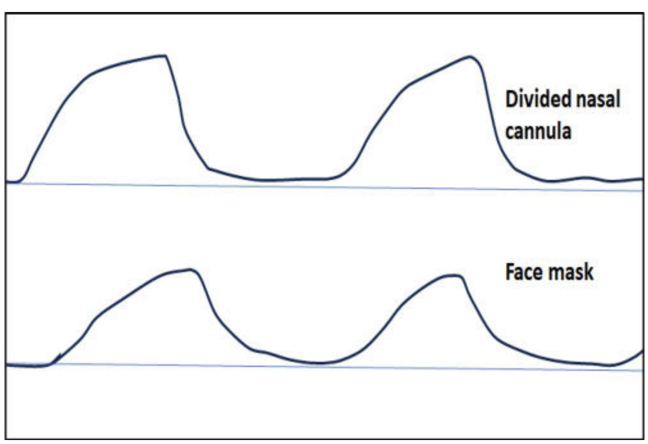

Figure 4. Comparison between facemask and divided nasal cannula capnograph. Sampling from the face mask is diluted by the administered oxygen; hence, the waveform is less well defined.

Drug	Tidal Volume	Respiratory Rate	$PaCO_2$	$P_{ET}CO_2$
Opiates	No change	Decrease	Increase	Increase
Inhaled anaesthetics	Decrease	Increase	Increase	Increase
Propofol, benzodiazepines	Decrease	No change	Increase	Increase
Ketamine, dexmedetomidine	No change	No change	No change	No change

Table 2. Sedative Drugs and Their Central Effects on Respiration; $PaCO_2$, partial pressure of CO_2 in the arterial blood; $P_{ET}CO_2$, end-tidal CO_2

Hypoventilation presents as high $P_{ET}CO_2$ if the airway is patent. It may also present as falsely low $P_{ET}CO_2$ if the tidal volume is decreased due to obstruction or drug effect. If the tidal volume is then increased by relieving the obstruction, the $P_{ET}CO_2$ increases, more closely approximating the $PaCO_2$.

DEVICES FOR CO_2 SAMPLING

CO_2 monitoring combined with oxygen delivery in the nonintubated patient can be achieved with modified face masks, nasal prongs, and mainstream analysers. As shown in Figure 5, Hudson-type facemasks can be modified by connecting a sampling port to the bowl of the mask. Because it is not possible to separate the exhaled air from the oxygen/air mixture in the mask, the measured $P_{ET}CO_2$ is not an accurate indicator of the actual partial pressure of alveolar CO_2. Some of these masks have a port to introduce an endoscope for monitoring during endoscopic procedures.

Figure 6 shows how nasal oxygen prongs are modified to combine oxygen delivery with CO_2 sampling. The divided type has a partition in the middle so that 1 prong can be used for sampling and 1 prong can be used for delivering oxygen. These types of devices are likely to have the least dilution with inspired/ambient air. However, mouth breathing or blockages at the end of the sampling orifice impede effective sampling. Others have a scoop, or oral guide, so that exhaled air from both the mouth and nose can be sampled, but dilution is greater than the divided type of sampling device.

Figure 7 shows mainstream CO_2 sensors (cap-ONE), which have been modified for nonintubated patients by using a small lightweight sensor that can be fitted to a mask or a nasal/oral adaptor. A bite-block for endoscopy combined with mainstream capnography is also available.

Comparison of Devices

An early comparison by Loughnan showed that the divided nasal cannula was more accurate at reflecting $PaCO_2$ than a modified mask, with an arterial-to-expired CO_2 difference of 5 mm Hg versus 14.7 mm Hg.[1] Pekdemir et al compared $P_{ET}CO_2$ values obtained from mainstream and sidestream devices with $PaCO_2$ in 114 nonintubated patients and found mean differences of 13 and 9.7 mm Hg, respectively, with correlation coefficients of 0.55 and 0.41.[2]

Kasuya found that mainstream capnometers reflected the arterial PCO_2 more closely than sidestream capnometers in 60 patients recovering from anaesthesia.[3] The presence of an oral guide improved the accuracy of sidestream capnometers in predicting $PaCO_2$, which was not affected by obesity or obstructive sleep apnoea. In a paediatric postanaesthesia care unit population of 58 children, a mainstream capnography device performed with more precision and less variability than a nasal cannula despite widely varying oxygen flow.[4] With both devices, the waveform was lost during mouth breathing or crying.

	Minimal Sedation (Anxiolysis)	Moderate (Conscious Sedation)	Deep Sedation	General Anaesthesia
Responsiveness	Normal response to verbal stimulation	Purposeful response to verbal or tactile stimulation	Purposeful response after repeated or painful stimulation	Unarousable, even with painful stimulus
Airway	Unaffected	No intervention required	Intervention may be required	Intervention often required
Spontaneous ventilation	Unaffected	Adequate	May be inadequate	Frequently inadequate
Cardiovascular function	Unaffected	Usually maintained	Usually maintained	May be impaired

Table 3. Continuum of Sedation

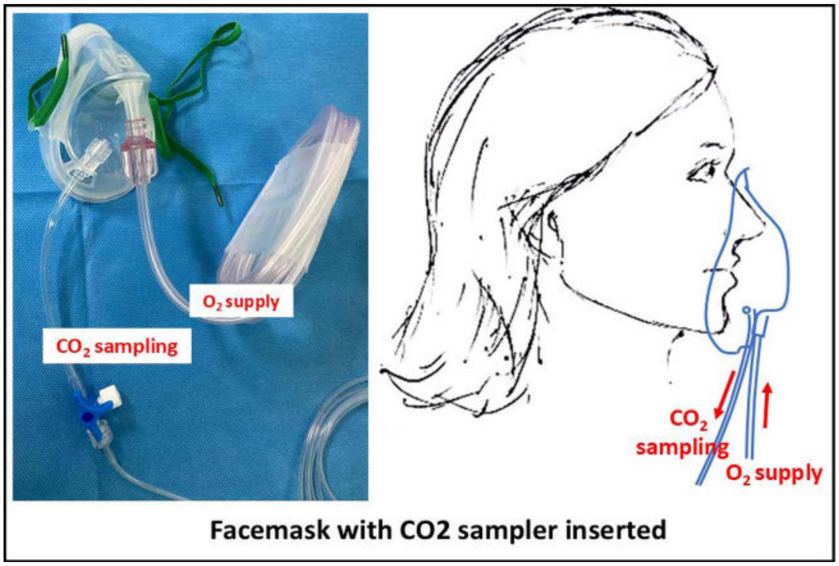

Figure 5. Hudson-type facemask with CO_2 sampling port. Modified masks are commercially available, some of which have access for endoscopy.

In these studies, which have had mixed results, the arterial-to-expired CO_2 difference has been used as an indicator of performance. However, in many of the situations where nonintubated capnography is used, the precise value of $P_{ET}CO_2$ is not of interest. It is more important to establish that adequate ventilation is taking place by observing a regular, normal-looking capnography waveform.

CLINICAL APPLICATIONS IN NONINTUBATED PATIENTS

Evidence for Capnography in Procedural Sedation

Table 4 summarizes relevant studies on the use capnography during procedural sedation. The following are the main conclusions:

- Procedural sedation is associated with adverse events, such as oxygen desaturation, bradycardia, hypotension, and even cardiac arrest.
- Incidence of adverse events is higher with deeper sedation. The likely sequence of events in these cases is hypoventilation due to airway obstruction and/or respiratory depression, leading to desaturation and then cardiovascular problems.
- Patients may drift into a deeper level of sedation than intended.

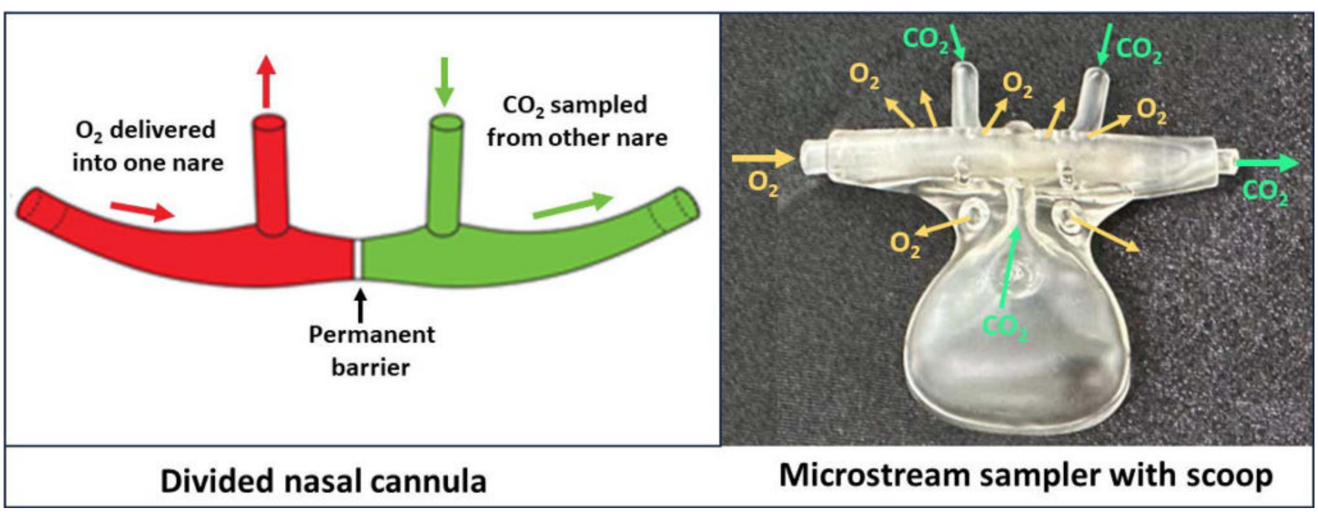

Figure 6. Nasal cannula with capnography sampling. The divided cannula has a barrier in the middle so that oxygen is delivered into 1 nostril while expired air is sampled from the other nostril. The microstream sampler has a more complex coaxial design. Exhaled air is sampled from both nostrils and the mouth (via the scoop, or oral guide). Oxygen is delivered via multiple holes in front.

Figure 7. Mainstream sensors for nonintubated capnography. These can be combined with oxygen delivery via nasal prongs or face mask. It also has an option for monitoring during endoscopy. Reproduced with permission from Nihon Kohden India.

- Capnography indicates airway and breathing problems earlier than pulse oximetry.
- Supplementary oxygen without capnography may delay the recognition and management of respiratory depression.

Assessment and Management during Procedural Sedation

Figure 8 illustrates a management plan for safe procedural sedation. The shape of the capnography curve, respiratory rate, and baseline $P_{ET}CO_2$ should be recorded before the start of sedation. The presence of a regular capnography waveform is evidence of continuing ventilation.

Reference	Study	Findings
Gangi 2004[5]	Endoscopy over a 2-year period	3.08% incidence of adverse events, including severe oxygen desaturation, bradycardia, hypotension, and even cardiac arrest. Risk of procedure-related complications was up to 70 times higher than previously reported.
Woodward 2017[6]	Closed claims analyses	NORA carries a higher risk of severe injury and death, most frequently related to excessive sedation. These claims involved monitored anaesthesia care and were judged to be preventable by better monitoring including capnography.
Patel 2005[7]	Conscious sedation planned for endoscopic procedures under intravenous sedation in 80 patients	Sixty-eight percent became deeply sedated, demonstrating the difficulty in maintaining patients at the intended level of sedation.
Burton 2006[8]	60 episodes of procedural sedation in 59 patients; sedation team blinded to capnography	Abnormal capnography findings in 36 episodes; low $ETCO_2$ levels in 32 and high levels in 5 (1 patient had high and low $ETCO_2$ during the same sedation episode). Twenty respiratory events were recognised by desaturation 12 to 271 seconds (median of 88 seconds) after the capnography change.
Deitch 2010[9]	132 adults undergoing procedural sedation	Capnography recognised respiratory depression 60 seconds (median, range of 5 to 240 seconds) before desaturation.
Parker 2018[10]	Meta-analysis including 3866 patients; also looked at potential harm from using capnography	Capnography had higher sensitivity (92%) at detecting adverse events and reduced risk of hypoxia by 31%. No evidence of alarm fatigue or unnecessary stimulation of patients, which might affect the quality of sedation.
Bisschops 2021[11]	Addition of capnography as a quality improvement intervention in a high-volume gastroenterology centre	Adverse events reduced from 11.45% in 1092 patients to 5.08% in 1044 patients after intervention.

Table 4. Capnography in Procedural Sedation; $ETCO_2$, end-tidal CO_2; NORA, nonoperating room anaesthesia

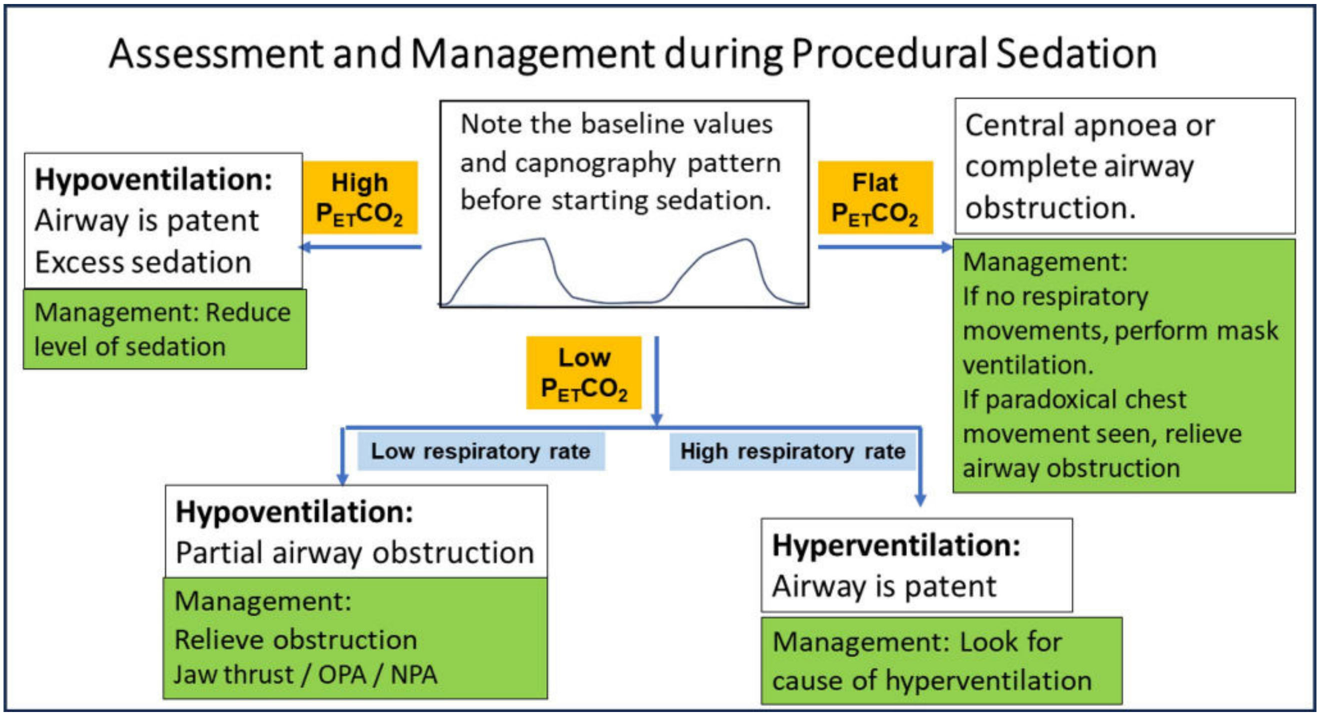

Figure 8. Assessment and management during procedural sedation. Abbreviations: NPA, nasopharyngeal airway; OPA, oropharyngeal airway; $P_{ET}CO_2$, end-tidal CO_2.

Capnography in the Postoperative Period

Mask-based capnography has been useful in monitoring adequacy of ventilation in the postoperative period after abdominal surgery. Capnography identified 198 apnoea alert events on 80 women who had received 150 mcg intrathecal morphine for analgesia following caesarean section under spinal anaesthesia. None of these were detected during the 2 hourly observations by nursing staff.[12]

Several meta-analyses of postoperative patients receiving opioids found continuous pulse oximetry to be superior to intermittent nursing observations. Additionally, they showed that capnography provided early warning of respiratory depression before desaturation, especially when oxygen was administered. Four of the 9 studies in the meta-analysis by Lam et al included patients with patient-controlled analgesia.[13] Another study involving 194 paediatric patients in the postanaesthesia care unit found that nearly half the patients had apnoea or hypopnoea detected by capnography but not by pulse oximetry.[14]

Addition of capnography is therefore useful in both paediatric and adult patients at risk of respiratory compromise in the postoperative period.

Capnography in Critical Care

An important application of capnography in the ICU is to confirm the correct position of an artificial airway at insertion and for as long as it is used for airway maintenance. Other uses are to detect disconnection from the ventilator, monitor adequacy of ventilation, and detect potential respiratory problems early. It is useful in monitoring patients on noninvasive ventilation and during procedural sedation.[15] It was also found useful in 70 nonintubated trauma victims during transport, as the capnography reading was more stable and reliable than pulse oximeter.[16]

GUIDELINES AND RECOMMENDATIONS

Capnography was first introduced as part of mandatory monitoring in the operating theatre in 1986, and recommendations for its use have expanded since then.[17] The Association of Anaesthetists of Great Britain and Ireland statement of 2009 also recommended that capnography should be considered for moderate and deep sedation. This was upgraded in the 2015 statement that “Capnography monitoring is essential at all times in patients with endotracheal tubes, supraglottic airway devices and those who are deeply sedated.” The American Society of Anesthesiologists Practice Guidelines of 2018 recommended continuous capnography in addition to observation and pulse oximetry in patients undergoing moderate or deep sedation.

CAPNOGRAPHY IN LOW-RESOURCE SETTINGS

Acknowledging the great disparity in perioperative mortality rates and access to monitoring between high-income countries and low- and middle-income countries, the Global Oximetry Project was initiated by the World Federation Society of Anaesthetists and Lifebox Foundation in 2010, and, to date, over 33,000 pulse oximeters have been distributed in 116 countries.

Recognising the gap in access to capnography between high-income countries and low- and middle-income countries, the Smile Train-Lifebox Capnography Project was launched in 2020, aiming to provide a capnography solution for low-resource settings. This has resulted in the selection of a device made by Zug Medical Systems, which combined pulse oximetry with sidestream capnography.[18] An analysis of the impact of the introduction of capnography monitoring in these settings is ongoing.

SUMMARY

- Capnography is the continuous monitoring of the concentration or partial pressure of CO_2 in respiratory gases, plotted against time, most commonly measured by infrared absorption spectrography, with sidestream (diverting) or mainstream (nondiverting) sensors. It is a mandatory monitor in a patient with an airway device (endotracheal tube, supraglottic airway device, or tracheostomy) both in and out of the operating theatre.
- In the nonintubated patient, CO_2 monitoring can be achieved with modified face masks, nasal prongs, and mainstream analysers. The peak CO_2 value varies with the amount of dilution and distance from the nose or mouth. The waveform does, however, confirm that ventilation is taking place. Changes in the respiratory rate and the height and shape of the waveform are helpful in deciding whether any intervention is necessary.
- During procedural sedation, the addition of capnography decreases the risk of hypoxia by detecting any change in ventilation before the onset of hypoxia. Capnography is useful in both paediatric and adult patients at risk of respiratory compromise, for instance in the postoperative period or in the ICU. All major guidelines now recommend continuous capnography in addition to observation and pulse oximetry in patients undergoing moderate or deep sedation.

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