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ESSENTIALS OF CAPNOGRAPHY

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ESSENTIALS OF CAPNOGRAPHY

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INTRODUCTION

During the administration of an anesthetic, continuous monitoring of a patient’s vital signs is a critical activity for ensuring patient safety. Advances in monitoring capability over the years have led to significant improvement in outcomes and reduction of morbidity and mortality in the operating room. Transferring this technology to the ambulatory oral surgery anesthesia practice has allowed more patients to undergo safer anesthetics in an outpatient setting. However, the open system in the oral surgery practice, in which the anesthetic is planned for the patient to maintain spontaneous respiration, is different from the operating room environment in which the patient is usually intubated and requires mechanical ventilation. Therefore, translating the technology that is present in the hospital operating room environment takes significant modification for ambulatory oral surgery anesthesia. Nonetheless, newer advances in monitoring should allow more parameters to be evaluated and potentially deleterious changes in the patient’s response to the anesthetic to be appreciated more rapidly.

A monitor is defined as a measuring device that includes an audible alarm that sounds when the measurement falls outside pre-set limits, usually set at the extremes of what a normal range should be for that parameter. Examples of cardiovascular monitors include continuous ECG monitoring with alarms for tachycardia and bradycardia (newer ECG monitors can also track ST wave changes in real time) and non-invasive blood pressure (NIBP) with alarms for high or low readings. Both of these examples are non-invasive monitors. Noninvasive monitors are ideal in that they are rapid to apply, require little training to apply and usually are cost effective because most of the hardware can be reused.

PHYSIOLOGY: VENTILATION AND GAS EXCHANGE

When discussing capnography it is important to understand the physiology of ventilation, perfusion and gas exchange. Ventilation refers to the amount of air within the respiratory tree, including the dead space. The average tidal volume of one breath is between 4-6 mL/kg. A 70 kg male with a respiratory rate of 12 breaths per minute (BPM) would therefore ventilate the lungs between 3.4L/min and 5L/min. In a healthy patient, perfusion is approximately equal to cardiac output, which is about 5L/min. The exchange of oxygen and carbon dioxide, and thereby the concentration of gasses in the blood depends on both ventilation and perfusion.
The total oxygen content in the blood (CaO₂) is calculated using the formula:

\[
CaO_2 = Hgb \times 1.36 \times \frac{SaO_2}{100} + PaO_2 \times 0.0031
\]

This formula demonstrates that 1.36 ml of O₂ is bound to each gram of hemoglobin (Hgb). Only a very small proportion of CaO₂ exists as free oxygen dissolved in the plasma (PaO₂).1-3 The oxygen bound to hemoglobin is delivered to the body’s cells for various life sustaining processes (i.e., metabolism), which in turn produce carbon dioxide. The carbon dioxide is then transported from the cell via the blood back to the alveoli where it is exchanged with oxygen and exhaled out of the lungs. (Fig. 1)

In anesthesia, and particularly in the setting of ambulatory oral surgery anesthesia, it is recognized that respiratory events usually are the cause of major morbidity and mortality, preceding the development of cardiovascular collapse in most cases. Hence, monitoring of the respiratory status is of critical importance.

The anesthetic-team concept in OMS practice is built around the surgeon along with two trained assistants. The role of one trained assistant is to monitor the vital signs using tactile, visual and aural senses, including applied monitors, to assess the patient and the mechanical devices in use.

In the past, patient oxygenation was verified by the observation of the movement of air (direct visualization of the chest rising and often a precordial stethoscope). However, quantitative data to assess this important aspect of the patient’s status under anesthesia was not available.

Advances in respiratory monitoring, namely the use of pulse oximetry, gave the practitioner quantitative information on the oxygen saturation of the patient. The amount
of oxygen bound to hemoglobin (reported as \( \text{SaO}_2 \) if measured by direct arterial sampling or \( \text{SpO}_2 \) if measured via the pulse oximeter) is proportional to partial pressure of oxygen. The oxygen-hemoglobin sigmoid-shaped dissociation curve depicts the amount of oxyhemoglobin associated with a certain partial pressure of oxygen. (Fig. 2, on P. 2)

Several factors determine the affinity of oxygen for hemoglobin, as described by the Bohr Effect. Acidosis or a decreased pH and high carbon dioxide level will shift the oxygen dissociation curve to the left, releasing oxygen more readily from being bound to hemoglobin and allowing the oxygen to diffuse rapidly to the surrounding tissues. Decreased 2,3-DPG (a metabolic byproduct of erythrocytes) and hypothermia will also cause a leftward shift in the oxyhemoglobin dissociation curve. An elevation in temperature or pH, low carbon dioxide, or increased 2,3-DPG will shift the oxyhemoglobin dissociation curve to the right. This results in a higher affinity of oxygen to hemoglobin. When the saturation of hemoglobin (\( \text{SaO}_2 \)) drops to approximately 90% to 92% there is a precipitous decrease in the \( \text{PaO}_2 \) due to the sigmoid shape of the dissociation curve. This abrupt drop in oxygen saturation of hemoglobin very rapidly leads to hypoxemia.

**RESPIRATORY MONITORING INSTRUMENTS**

**Pulse Oximetry**

Pulse oximetry has traditionally been used in the outpatient setting for adjunctive monitoring of the patient’s oxygenation status and has been part of the standard monitoring for deep sedation for many years. Pulse oximetry uses light-emitting diodes (LEDs) to transmit red and infrared wavelengths of light (600-750nm and 850-1000nm, respectively) through a vascular bed. A sensor then detects the amount of light absorbed, which in turn is then used to calculate the oxygen saturation. Oxyhemoglobin absorbs much more infrared light than red light, and through a series of calculations a processor determines the amount of hemoglobin and oxyhemoglobin in the blood, which correlates to oxygen saturation.\(^{2,4-7}\)

A limitation of pulse oximetry is that it does not monitor respiration, only oxygenation. Because most outpatient anesthetics in oral surgery include the administration of supplemental oxygen (often in combination with nitrous oxide) a decrease in oxygen saturation levels is a later occurrence in the presence of apnea or other forms of respiratory distress. The lungs maintain a volume of oxygen that continues to be transferred to the hemoglobin molecules even if the patient is no longer breathing. Although this provides some modicum of safety during temporary periods of apnea, once the oxygen saturation decreases it will drop precipitously, requiring rapid and aggressive management to get the oxygen saturation levels restored. Thus, the search for a rapid quantitative monitor that can detect respiratory changes led to the development of capnography, the measurement of carbon dioxide levels of expired breaths.

**Capnography**

Capnography is used routinely in the
hospital anesthesia setting and has been proven a safe, low-cost and effective means of monitoring patients undergoing anesthesia. For over 25-years it has been used to monitor patients in the operating room, and now capnography is being used with increasing frequency in the intensive care setting, emergency department, pediatric population and for outpatient sedation/anesthesia. Like pulse oximetry, it also is a non-invasive monitor that directly gives information on the respiratory status of the patient in real time. Breath-by-breath changes in a patient are immediately documented on the unit.

In 2010, the House of Delegates of the American Society of Anesthesia amended the Standards for Basic Anesthesia Monitoring to include mandatory exhaled end-tidal carbon dioxide monitoring. This was made effective by the ASA in 2011 for all patients undergoing general anesthesia and deep sedation. Recognizing the value of end-tidal carbon dioxide monitoring the American Association of Oral and Maxillofacial Surgeons has amended its standards as well.

The routine use of capnography in the oral and maxillofacial surgery office has become a requirement for anyone performing outpatient anesthesia. In 2014, the American Association of Oral and Maxillofacial Surgeons Board of Trustees guidelines took effect, requiring capnography equipment in oral and maxillofacial surgery offices. These guidelines state:

“During moderate or deep sedation and general anesthesia the adequacy of ventilation shall be evaluated by continual observation of qualitative clinical signs and monitoring for the presence of exhaled carbon dioxide unless precluded or invalidated by the nature of the patient, procedure or equipment; and improvements in monitoring exhaled CO₂ during anesthesia continue to evolve.

Beginning in 2014, AAOMS Office Anesthesia Evaluations will require capnography for moderate sedation, deep sedation and general anesthesia unless precluded or invalidated by the nature of the patient, procedure or equipment.”

It is the standard of care for any oral and maxillofacial surgeon administering outpatient anesthesia to comply with these guidelines. This article will discuss some of the terminology and technology of capnography, as well as review ventilation physiology and gas exchange. At the end of the article there is a discussion and interpretation of a series of capnographic waveforms. These guidelines should serve to provide safe and effective treatment to our patients. It is always important to remember new technologies and monitoring should not replace sound clinical judgment.

TERMINOLOGY

Capnometry vs. Capnography

The two most commonly used methods to monitor end-tidal carbon dioxide are capnometry and capnography. Both obtain measurements from expired gas from the lungs. However, a capnometer simply shows numerical values. The normal amount of exhaled carbon dioxide is approximately

TERMINOLOGY
which correlates to somewhere between 35-45mmHg. These values would be similar to the display on capnometry for a healthy patient undergoing sedation or anesthesia. Capnography is both a numerical and graphical display of inhaled and exhaled carbon dioxide relative to volume or time. Time capnography is most commonly used and provides useful information regarding the patient’s ventilatory status, gas exchange and, therefore, any changes that occur.²,⁴,⁹-¹² Time capnography graphically displays both the expiratory and inspiratory pattern. During expiration, there are three main phases and an alpha and a beta angle (Fig. 3).²⁻⁴,⁹ It should be noted that the only “normal” waveform is the one depicted in Figure 3. Any changes from the pattern of this waveform indicate abnormalities that will be discussed below. It is also important to note that the waveforms are based on a closed, or intubated, capnography and therefore the open system will not always present with these classic patterns.

Capnography Phases

**Phase I** begins expiration. During Phase I there is no significant release of carbon dioxide because this air is being sampled from the dead space where there is no exchange of oxygen and carbon dioxide. Shortly after Phase I, there is a rapid increase in carbon dioxide release beginning Phase II as the dead space is diluted. As **Phase II** progresses the amount of carbon dioxide released plateaus, marking the transition into Phase III. The end-tidal carbon dioxide (ETCO₂) can be seen graphically at the end of **Phase III**, which is also at the peak of end expiration. This point correlates to the functional residual capacity (FRC) lung volume, i.e., the volume of air remaining in the lungs after a normal breath.

The quantitative difference in the height of the tracing, in addition to the shape of the graph, can give a great deal of information about the patient’s ventilation (V), perfusion (Q), and any V/Q mismatching, which are discussed later in this article.¹⁻³,⁸ The height of the curve along the Y-axis depends on the end-tidal concentration of carbon dioxide. The frequency depends on the respiratory rate and the rhythm is a function of the ventilator or patient’s respiratory center. At the end of **Phase 0**, which represents the inspiratory phase, the capnogram should return to a baseline of CO₂ that is equal to zero.

The ETCO₂ seen at the end of Phase III is not always reflective of the partial pressure of carbon dioxide (PaCO₂) in the patient’s blood. There will always be a slight difference between total PaCO₂ and ETCO₂ due to anatomical and alveolar dead space. (Fig. 4, on P. 6) Obtaining an arterial blood gas sample would give an accurate PaCO₂ measurement, but due to the high solubility of CO₂ capnography monitors are accurate and...
There are two types of capnography monitors used for measuring end-tidal carbon dioxide, mainstream and side-stream devices. Mainstream monitors are connected directly to the circuit on the endotracheal tube, and detect the end-tidal carbon dioxide using an infrared detector and sensor (infrared absorption spectrometry). Carbon dioxide absorbs light with a wavelength of 4.3 micrometers; allowing detection of carbon dioxide without interference from other gasses. These monitors give accurate, precise, real-time measurements of end-tidal carbon dioxide. The side-stream monitors, also very accurate, are connected to the main circuit via a sampling line. The side-sampling technique is used in the outpatient setting.

One disadvantage of pulse oximetry compared to capnography is the delayed recognition of low circulating oxygen. This is particularly true when there is concomitant oxygen administration, which maintains SaO₂ longer after periods of apnea. As seen in the oxygen-hemoglobin dissociation curve (Fig. 2, on P. 2) the delay in detection occurs at the upper flat portion of the curve. In this area of the curve a decrease in PaO₂ from 100 mmHg to 75 mmHg will not cause a significant drop in the SaO₂. Often, several minutes of poor oxygenation will have passed before being detected with pulse oximetry.

**INTERPRETATION OF CAPNOGRAPHY**

Capnography displays a waveform that represents the CO₂ partial pressure over time and provides a great deal of information that can be used for diagnosis and management. For example, if the patient is to be intubated, either in the emergency room setting or in...
Figure 6: Placement of the endotracheal tube in the esophagus. Initially there may be a normal capnographic waveform from the residual CO₂ in the esophagus and stomach. However, the waveform will quickly taper off, indicating little or no CO₂ return to the circuit.

In the operating room, capnography verifies successful placement of the endotracheal tube. If intubation is unsuccessful (e.g., esophageal intubation) the capnographic waveform will be abnormal. (Fig. 6) An initial return of carbon dioxide may be noted due to residual gastric gas, but the ETCO₂ waveform is quickly lost and the CO₂ levels are reduced to baseline. In this situation immediate suctioning of the gas that was delivered to the stomach followed by correct placement of the tube is indicated.

After successful intubation there can be problems with the endotracheal tube itself. For example, a slow leak around the endotracheal tube balloon will display as a slow decrease in ETCO₂ because of dilution, with blunting of Phase II and Phase III (Fig. 7).

An increase in ETCO₂ seen on capnography (Fig. 8) can be caused by many different factors. The most frequently encountered cause of an increase in ETCO₂ is from hypoventilation. A similar pattern may be seen after drug administration (particularly respiratory depressants such as opioids). This should alert the practitioner to consider airway support or assisting respirations. Other causes may be increased muscular activity such as shivering. A steady increase in end-tidal carbon dioxide can also be a sign of malignant hyperthermia, especially if the respiratory rate remains constant.

A decrease in ETCO₂ is most commonly seen with increased minute ventilation/
(Figure 9: Potential causes of decreased end-tidal carbon dioxide)

(hyperventilation. (Fig. 9 on P. 8) Other causes of decreased end-tidal carbon dioxide include decreased muscle activity (i.e., muscle relaxant), hypothermia, and decreased cardiac output (i.e., cardiac arrest.)

Obstruction of the airway, or other V/Q mismatches, as seen with pulmonary emboli, can produce an initial change in the waveform shape. Although the end-tidal carbon dioxide may remain normal, the alpha angle becomes more obtuse because the rise in the carbon dioxide level is slower. (Fig. 10) This is the classic presentation of early bronchospasm and can also be used to verify the effectiveness of bronchodilator therapy as the alpha angle returns to a more right angle pattern.

Endotracheal tube malposition or malfunction (i.e., in the mainstem bronchus, mucous plugging or foreign body airway obstruction) will present with a similar pattern. Finally, a complete loss of ETCO₂ waveform may be due to acute apnea, disconnection of the circuit or obstruction of the sampling line.

It is also important to understand that ETCO₂ may not always reflect PaCO₂. There is always a gradient between the two, and this gradient can increase with an increase in dead space. An increase in dead space can be seen in V/Q mismatches, as in patients with emphysema or other chronic lung diseases.² (Fig. 11)

CLINICAL APPLICATION IN ORAL SURGERY
Figure #12: utilization of end tidal carbon dioxide monitoring with conventional nitrous oxide/oxygenation administration system. The side stream sampling port penetrates both layers of the double lined nasal mask and permits scavenging of the gases. Note Luer-type adapter (arrow).

Patients are not routinely intubated for outpatient anesthetics by oral and maxillofacial surgeons. In this setting the side-stream sampling technique of nasal airflow is used. (Fig. 12) However, this technique has limited usefulness if the patient is mouth breathing, has a nasal obstruction or is phonating.

The sampling line is placed in the nasal mask or nasal cannula. With a conventional dual-layer nitrous oxide nasal hood an adapter with a sharp point is used to penetrate the mask. The side-stream sampling tubing is attached to this via a Luer-type adapter. Although there can be 10 feet of tubing between the patient and the monitor, the narrow diameter of the sampling tubing permits rapid recognition of the ETCO₂ levels.

**Capnography and ACLS**

The American Heart Association (AHA) and Advanced Cardiac Life Support (ACLS) have adopted the use of waveform capnography and CO₂ detection for confirmation of endotracheal (ET) tube placement and monitoring during cardiac resuscitation. According to the AHA, continuous waveform capnography along with clinical assessment is the most reliable method of confirming and monitoring correct placement of the ET tube.

At the minimum, once intubation is performed, colorimetric end-tidal CO₂ detectors can be used for confirmation of ET tube placement into the trachea. Proper placement of the ET tube should be confirmed with a color change, indicating detection of CO₂. Color-change detection of CO₂ can sometimes be misleading. For example, esophageal intubation with a distended stomach may initially give false color change as noted above. If there is no color change after ET tube placement, then incorrect placement should be assumed. For these reasons, the AHA and ACLS protocol also include clinical confirmation (auscultation of both lungs and verification of no ventilation into the stomach).

Ideally, capnography should be initiated during ACLS. This can provide useful information regarding the effectiveness of
cardiopulmonary resuscitation (CPR) and return of spontaneous circulation (ROSC). 13-16 As previously discussed the normal waveform capnography ETCO₂ should be within the range of 35 mmHg to 45 mmHg. The expected waveform during adequate chest compressions in cardiac arrest should be approximately 20 mmHg. (Fig. 13 on P. 10) Lower readings should direct the code leader to reassess the effectiveness of the CPR or search for other causes of ineffective CPR (blocked airway, gastric distension).

ROSC can also be detected using waveform capnography. 14,15 An ETCO₂ less than 10 mmHg is associated with a low chance of successful ROSC. In most cases, however, ETCO₂ has been shown to increase approximately 10 mmHg higher after ROSC. 14,15 (Fig. 14) This increase in ETCO₂ may indicate a ROSC and may provide an indication to hold CPR and assess the patient for pulses. 14,15

CONCLUSION

The AAOMS guidelines now require clinicians to monitor patients using capnography when providing anesthesia, and for good reason. Capnography has been proven to be a safe and effective tool for monitoring patients during anesthesia. It can recognize airway obstruction, hypoventilation and apnea in real-time, all of which precede hypoxia seen with pulse oximetry. The trained clinician with an understanding of physiology and capnography should be able to interpret the information and better manage their patients.

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Stuart E. Lieblich, DMD, graduated from University of Pennsylvania School of Dental Medicine (1981). He completed his residency in oral and maxillofacial surgery at Kings County/Downstate Medical Center in New York. In 1984 he assumed a full-time position on the faculty of the University of Connecticut until 1988. Currently, he is in private practice in Avon, CT and maintains a part-time teaching appointment at the university as a clinical professor. At the University of Connecticut he lectures to the medical and dental students on head and neck anatomy (with special focus on the temporomandibular joint and the anatomy of orthognathic surgery) and also to the various postgraduate residency programs.

Dr. Lieblich has been a contributor to over 19 textbooks and published over 45 peer reviewed papers and abstracts. He is an invited speaker at conferences throughout the United States and has presented his research at international scientific meetings with focuses on ambulatory anesthesia, dental implants, dentoalveolar surgery and periapical surgery. Previously he has served as president of the American Dental Society of Anesthesiology and, following a six-year term, as a member of the examination committee of the American Board of Oral and Maxillofacial Surgery (chair of the medicine and anesthesia sections) he was elected to an eight-year term of the ABOMS board of directors (President 2009-2010). Dr. Lieblich is on the editorial boards of the journals Anesthesia Progress, Oral Surgery, Oral Medicine Oral Pathology (“Triple O”) and the Journal of Oral and Maxillofacial Surgery. He regularly reviews articles for the International Journal of Oral and Maxillofacial Surgery, and General Dentistry. Dr. Lieblich serves on many local, state and national committees in his specialty and currently is a member of the American Dental Association’s Commission on Accreditation (oral and maxillofacial surgery) and the American Association of Oral and Maxillofacial Surgeons Parameters of Care Committee (chair, Dentoalveolar surgery section).
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