Terminology

A continuous plot of carbon dioxide (CO₂) in the respired gas versus time is called a capnogram and recorded by an instrument known as a capnograph. A capnometer detects the highest and lowest values for CO₂ in the respired gas and reports them as inspired and end-expired (also known as end-tidal) partial pressures or concentrations. The practices of measuring and recording CO₂ are called capnometry and capnography, respectively. Many monitors function as both capnometers and capnographs, displaying both numerical and graphical information about CO₂ in the respired gas. As with all monitoring tools, a capnogram is only a snapshot in time of one aspect of the patient’s respiratory system function and should be evaluated in light of each patient’s clinical condition.

Types of carbon dioxide analyzers

There are two types of CO₂ analyzers: mainstream and sidestream.

Mainstream

In mainstream analyzers, a sample cell or cuvette is inserted directly in the airway between the tracheal tube and the breathing circuit. An infrared sensor fits over the sample cell and emits light through windows in the sample cell (see Fig. 26.1). Light reaching the photodetector on the opposing side of the sensor measures PCO₂. Because the measurements are made directly in the airway, this technology eliminates the need for sampling tubes and scavenging but limits its use to the intubated patient. The capnographic waveforms generated by mainstream analyzers are crisper than those from sidestream analyzers because they reflect real-time CO₂ measurements and suffer no deformity due to dispersion of gases in a sample line.

To prevent condensation on the sample cell windows, which can cause falsely high CO₂ readings, the mainstream sensor is heated. Thermal injury to the patient is possible; however, newer analyzers now have limited upper temperatures to avoid such problems. Disadvantages of mainstream analyzers are that they can be bulky and have a relatively large internal volume. This bulk puts traction on the endotracheal tube, which may increase the risk of inadvertent extubation, and their internal volume adds to apparatus dead space. These factors are more troublesome in smaller patients. The sensor unit in older models was fragile and easily broken; however, newer models are of simpler design and are lightweight, increasing their durability and suitability to daily use in veterinary practice. Many models use disposable sensor windows, available in standard and pediatric sizes (see Fig. 26.1), which can be changed between patients, to prevent contamination and minimize apparatus dead space.

Sidestream

In sidestream capnography the CO₂ measuring unit (monitor) is remote from the patient. A small pump within the monitor aspirates gas from the patient’s airway through a long sampling tube. Ports onto which a sample line can be attached can be found on some endotracheal tube adaptors, some breathing circuit Y-pieces, or most commonly, lightweight connectors.
the airway and the monitor, the less mixing will occur and the more representative will be the capnogram of actual changes in respiratory gas composition. Slow rates of aspiration, long sample lines, and large-bore sample lines result in capnogram waveforms with slurred up- and downstrokes (see section on capnographic interpretation).

Sidestream analyzers remove gas from the patient’s breathing circuit. This must be accounted for when calculating fresh gas flow rates and also means that if patients are anesthetized with an inhaled anesthetic agent, then the gas must be appropriately scavenged or returned to the patient’s breathing system. Gas may pass through conduits within the analyzer that cannot be cleaned or sterilized. This may pose an infectious disease risk to subsequent patients if analyzed gas is returned to the patient. The small-bore sample lines used by sidestream analyzers can easily become obstructed with moisture or aspirated secretions, and methods must be instituted to collect moisture, such as the use of Nafion...
dead space. This can lead to rebreathing of CO₂ and either elevation in PaCO₂ or increased work of breathing and altered ventilatory patterns to maintain a normal PaCO₂.³ The size of the sampling cuvette relative to the tidal volume of the patient should be considered when choosing the type of analyzer to use on an individual (mainstream versus sidestream). Other considerations in making that decision would include whether there is any additional apparatus dead space as well as the length of time you intend to utilize the monitor. Routine mainstream capnography would not be recommended for long-term use in small patients.³ It is always good to minimize apparatus dead space; however, small internal volume connectors or cuvettes also have a small internal diameter. As such a compromise is made to avoid unnecessary increases in airway resistance due to reduced airway diameter. It would be generally recommended not to use a connector with an internal diameter any smaller than that of the endotracheal tube placed in the patient.

Sidestream analyzers can be connected to the patient airway with the addition of minimal to no apparatus dead space (see Figure 26.2d). The cost of making this choice is reduced accuracy. A general figure for total minute ventilation is 200 mL/kg/min. Gas aspiration rates of the monitor must be considerably lower than total minute ventilation of the patient to prevent dilution of expired gas with fresh gas during sampling. If not, the capnograph waveform would be deformed and end-expired CO₂ underestimated. However, slow aspiration rates mean a long delay before gas is analyzed and distortion of the capnographic waveform. The sampling line should thus be as short as possible to minimize this delay time. Microstream aspiration technology with miniaturized sample chambers should be used if expired CO₂ is to be measured on spontaneously breathing small patients (<3–4 kg) for any length of time for improved accuracy and reduced deadspace.⁴ ⁵

The closer to the alveolus that respiratory gas is sampled, the more faithfully the capnogram represents alveolar gas. However, a major problem with sampling from within the airways as is required with the sidestream technique is machine aspiration of secretions and water vapor. In intubated patients, sampling catheters placed within the lumen of the endotracheal tube reduce mucus aspiration (see Fig. 26.2b).

**Equipment setup**

In smaller patients mainstream CO₂ analyzers are technically superior to sidestream analyzers.¹² Due to their faster response time PCO₂ measurements are more reliable, especially when tidal volumes are small and respiratory rates are elevated. The main disadvantage of mainstream measurements is the addition of apparatus
tubing (Nafion, E I du Pont de Nemours Company) or water traps.

Sidestream CO₂ analyzers may be single-purpose monitors or part of a larger monitoring unit with capabilities to analyze other respiratory gases as well as inhaled anesthetic agents. A unique advantage of sidestream capnographs is the ability to use them to monitor nonintubated patients. For example, expired gases may be sampled from the nasal cavity using nasal cannulas, or these monitors may be connected to feeding tube to obtain information to ensure correct placement (see indications section for more detail).

**Physiology**

Aerobic metabolism in tissues consumes oxygen, glucose, and other substrates and eventually produces energy, CO₂, and water. CO₂ produced in cells easily diffuses into the surrounding interstitial fluid raising local partial
pressure of carbon dioxide (PCO₂). Arterial blood entering the tissues has a lower PCO₂ than the interstitial tissue and thus CO₂ diffuses from the interstitial fluid into blood. Venous blood leaves the tissues with a PCO₂ higher than that of arterial blood but equal to that of interstitial fluid. Venous blood carries the CO₂ produced by metabolism to the lungs to be removed from the body by ventilation. The process of ventilation replaces CO₂-rich gas from the alveoli with CO₂-free gas from the atmosphere or breathing circuit.

Alveolar partial pressure of CO₂ reflects a balance between CO₂ delivery to the alveoli by the cardiovascular system and its removal by ventilation. In the steady state, alveolar partial pressure of CO₂ is directly related to the metabolic production of CO₂ and inversely related to alveolar ventilation. CO₂ is highly diffusible such that in perfused alveoli, alveolar and arterial partial pressures of CO₂ are considered equivalent. Gas sampled at the end of expiration (end-expired or end-tidal gas) is representative of alveolar gas and is thus used as an estimate of arterial PCO₂.

Under the control of both the central and peripheral chemoreceptors, the body normally maintains arterial PCO₂ within a tight range by adjusting ventilation to the amount of CO₂ produced. Normal range for arterial PCO₂ is from 35 to 45 mm Hg, with some slight variations between species.

Hyperventilation describes the situation where alveolar ventilation is in excess of metabolic CO₂ production resulting in alveolar (and thus arterial) PCO₂ levels below the normal range (hypocapnia). Low PaCO₂ values are associated with respiratory alkalosis and reduced cerebral blood flow. Hypoventilation describes the opposite situation where alveolar ventilation is insufficient to remove the metabolically produced CO₂, causing alveolar (and arterial) PCO₂ levels to rise above the normal range (hypercapnia). Most anesthetic and sedative drugs result in dose-dependent respiratory depression and respiratory acidosis. A PaCO₂ > 60 mm Hg is generally considered respiratory depression significant enough to warrant positive pressure ventilation in small animal patients.

**Technology of carbon dioxide measurement**

A number of techniques are available for measuring CO₂ including infrared absorption, Raman scattering, and mass spectrometry.

**Infrared absorption**

Infrared (IR) absorption is the most popular technique for CO₂ measurement. Monitors utilizing IR technology are typically the most compact and least expensive. IR absorption is the only technique used for CO₂ measurement in mainstream analyzers. Polyatomic gases like CO₂ have specific and unique absorption spectra of IR light. The amount of light absorbed in a specific spectrum is proportional to the concentration of the absorbing molecule. The concentration of gas can then be determined by comparing the measured light absorbance with that of a known standard. Infrared absorption can be used to measure any polyatomic gas (e.g., nitrous oxide and the halogenated anesthetic agents), which may be advantageous if purchasing a single monitor for use in anesthetized patients.

IR monitors have a short warmup period and a fast response time for CO₂ measurement, allowing them to measure inspired and expired concentrations. Water vapor absorbs infrared light and thus can spuriously increase measured CO₂. Water must therefore be removed from the expired gas by use of water traps or Nafion tubing (Nafion, E I du Pont de Nemours Company). There is some overlap between the absorption of nitrous oxide and CO₂. Most newer monitors that measure nitrous oxide in addition to CO₂ are able to correct for the effect of nitrous oxide on CO₂ readings.

**Microstream capnographs** are based on a modified approach to IR absorption. Molecular correlation spectroscopy is used to generate a narrow band of infrared light that precisely matches the absorption spectrum of CO₂ and eliminates interference with other gases. The high CO₂ specificity and sensitivity allows for a very short light path, and measurements can be made on a very small gas sample. In turn this allows the use of low sample rates (50 mL/min compared with typical rate of 150 mL/min for conventional IR analyzers) without compromising accuracy or response time. This reduces entry of moisture into the sample line and also reduces the competition for tidal volume that may compromise measurement accuracy in small patients or those with high respiratory rates.

**Raman scatter**

Raman scatter is a technique able to measure CO₂, oxygen, nitrogen, nitrous oxide, and halogenated anesthetic agents. Gas is sampled into an analyzing chamber where it is illuminated by a high-intensity monochromatic argon laser beam. When the laser beam hits molecules with interatomic bonds, a fraction of the energy is absorbed and reemitted at various wavelengths characteristic of the particular molecule that absorbed it. These monitors have a short warmup period, fast response time, require little maintenance, and are very accurate.
**Mass spectrometry**

Mass spectrometry is not commonly used for CO₂ measurement in clinical practice because these machines tend to be expensive and bulky. A unique feature of mass spectrometers is that a single unit can be used to measure gas concentration from up to 30 different locations. As such, these are most commonly found in large hospitals. Gases are aspirated into a vacuum chamber where an electron beam ionizes and fragments the components of the sample. Ions are then accelerated through a magnetic field that separates them based on their mass-to-charge ratio. Individual detector plates allow for determination of the concentration of each component of the gas mixture. These analyzers typically measure only gases for which they have been preprogrammed to find. Adding the capability to measure new gases may require new hardware and/or software and may be costly. Because these units measure gases in concentrations (as opposed to infrared analyzers and Raman spectrometers that measure gases as partial pressures), they assume that the sum of the gases they can detect is 100%. If an unmeasured gas is present in significant concentrations, this may result in erroneously high measured CO₂ concentrations.

**Indications for capnography/capnometry**

Indications for performing capnography or capnometry are listed in Table 26.1.

**Confirming correct endotracheal tube placement**

Capnography or capnometry may be useful in to situations in which it is challenging to determine visually the correct endotracheal tube placement. Repeated upstrokes in the capnogram (repetitive increases in the PCO₂) suggest the presence of ventilation. It is theoretically possible to sample CO₂-containing gas from the stomach, but the values for end-expired partial pressure of CO₂ are likely to be much lower, reduce with time, and not fluctuate in a pattern consistent with respiration. Positioning of the endotracheal tube tip just inside the glottis may produce acceptable end-expired CO₂ levels and a normal capnogram. Such tube placement risks easy dislodgement and inadequate airway protection. In low perfusion states (e.g., cardiac arrest, shock) verification of correct endotracheal tube placement by capnography is complicated by the presence of abnormally low end-expired PCO₂ and a dampened waveform because little CO₂ is being delivered to the lung for expiration.

**Detection of apnea**

If a patient becomes apneic, the capnograph or capnometer typically sounds an alarm when CO₂ stays at zero for a given period of time. Such monitoring is easily achieved if the patient is intubated. The sampling line of a sidestream analyzer can be attached to nasal prongs for the detection of apnea in nonintubated patients.

**Monitoring ventilation**

The gas exhaled at the end of expiration should be primarily alveolar gas, and thus end-expired PCO₂ is representative of alveolar PCO₂. Due to the high diffusivity of CO₂, alveolar and arterial PCO₂ equilibrate and end-expired PCO₂ is used to estimate arterial PCO₂. Capnography and capnometry can therefore be used to assess the adequacy of ventilation in spontaneous or mechanically ventilated patients.

**Monitoring pulmonary perfusion**

Large drops in cardiac output (hypovolemic shock or cardiac arrest) result in exponential drops in expired PCO₂. Therefore, very low or precipitously dropping PCO₂ should lead the operator to suspect cardiovascular collapse. Capnography may be useful in monitoring cardiopulmonary resuscitation efforts. End-expired PCO₂ has been used to predict the survivability from cardiac arrest. A successful outcome from cardiopulmonary resuscitation is more likely if expired PCO₂ levels are >10–15 mm Hg during resuscitation efforts.

**Correct nasogastric tube placements**

Connection of a sidestream analyzer to gastric tubes may provide additional evidence for correct placement. Detection of any significant level of CO₂ should create suspicion of inaccurate placement.

**Equipment problems**

Capnography may be used to detect malfunctioning or incorrect assembly of breathing circuits, anesthetic machines, and ventilators. Problems such as malfunctioning
unidirectional valves, exhausted CO$_2$ absorbers, and inadequate fresh gas flows may be detected by alterations in the capnogram waveform (see next section).

**Interpretation of the capnogram**

The normal capnogram, seen in Figure 26.4, can be divided into four phases (I–IV).

**Phase I**

Phase I is the normally flat baseline segment of the capnogram. During the first part of this phase, inspiration is occurring. At the very end of this phase, the direction of gas flow reverses as expiration begins. During early expiration, expired gas comes from anatomic dead space. Anatomic dead space has not participated in gas exchange, and as such gas from these regions is identical in composition to inspired gas (normally CO$_2$ free).

**Phase II**

Phase II is the upstroke of the capnogram waveform. This corresponds to the period of expiration where CO$_2$-containing alveolar gas begins to be exhaled in a mixture with gas from anatomic dead space. As expiration proceeds the expired gas is composed of rapidly increasing proportions of alveolar gas, and the CO$_2$ levels quickly rise.

**Phase III**

Phase III is the plateau of the capnogram. During this phase PCO$_2$ is normally almost constant as alveolar gas, normally of nearly uniform composition, is expired. Expiration actually ends partway through this phase and is usually followed by a pause. During this pause PCO$_2$ typically remains constant on the capnogram even though no gas is flowing in or out of the patient. This occurs because there is expired alveolar gas remaining stationary within the region of breathing circuit from which the gas is being sampled by the capnograph. This part of the plateau may be cut short by small tidal volumes, high fresh gas flow rates, and/or high gas sampling rates (see abnormal capnograms for more details). The angle between phases II and III of the capnogram is known as the alpha angle and is normally close to $100–110^\circ$.

**Phase IV**

Phase IV is the rapid downstroke on the capnogram corresponding to inspiration. During this phase fresh normally CO$_2$-free gas passes the sampling port as it is inspired into the lungs. The angle between phases III and IV is known as the beta angle and normally close to $90^\circ$.

**Abnormal capnograms**

**Abnormal phase I**

If the capnogram fails to return to baseline during inspiration, then the shape of the waveform should be considered. If the response time of the analyzer is slow, particularly in the face of high respiratory frequencies, then the capnogram may adopt a sine wave formation (see Fig. 26.5a). This is a relatively common capnographic waveform in cats. Such a waveform has no distinct alveolar plateau, and erroneous values for inspiration and expiration may result (falsely elevated baseline and underestimated peak expired CO$_2$, respectively).

If the capnogram fails to return to baseline during inspiration and is not the result of a slow response time (i.e., the shape of the waveform is relatively normal), then there must be CO$_2$ in the inspired gas. Common reasons for this include exhausted CO$_2$ absorber in a circle system, malfunctioning inspiratory valve in a circle system, or inadequate fresh gas flow in a non-rebreathing system (see Fig. 26.5b).

Periodic elevations in baseline can occur if external pressure is applied to the patient’s chest during the inspiratory period. If this occurs, then gas is forced out of the lungs and a small rise in PCO$_2$ is registered on the capnogram during what would normally be the baseline period (see Fig. 26.5c).

**Abnormal phase II**

With sidestream capnographs, gas sampling rate affects the shape of the capnogram. Slow sampling rates decrease the slope of phase II, shorten the alveolar plateau, and decrease the slope of phase IV (see
or reduced delivery of CO$_2$ to the lungs (low cardiac output). Trends in peak expired CO$_2$ over time can be useful to demonstrate the effect of reduced pulmonary blood flow on the capnogram. Figure 26.6 displays tracings of a systemic arterial pressure waveform and corresponding capnogram recorded at slow paper speed. A period of hypotension can be seen to correspond to reduced alveolar plateau levels on the capnogram, which returned to previous levels when systemic pressure was restored.

The existence of alveolar dead space (ventilated but unperfused areas of the lung), such as would occur secondary to pulmonary thromboembolism, creates a situation in which peak expired CO$_2$ levels are substantially lower than arterial PCO$_2$ measurements. Unperfused alveoli will not have participated in gas exchange and so contain gas identical in composition to inspired gas, which is normally CO$_2$ free. During expiration this gas mixes with the gas from perfused alveoli diluting the PCO$_2$ in the expired alveolar gas. When examining a capnogram recorded at slow paper speed, the alveolar plateaus of each wave are typically fairly uniform in a stable patient (see early part of Fig. 26.5g). Sudden reductions in pulmonary blood flow, such as occurs with pulmonary thromboembolism, typically result in exponential decreases in the peak alveolar plateau as long as ventilation continues (see progression of Fig. 26.5g) as

**Abnormal phase III**

Normally, peak expiratory PCO$_2$ values are only a few mm Hg lower than PaCO$_2$. A normally shaped capnogram with an elevated alveolar plateau (see Fig. 26.5e) reflects hypoventilation. This is very common in anesthetized or sedated patients. If the patient is not receiving supplemental oxygen, hypoventilation is a common cause of hypoxemia.

A normally shaped capnogram with lower than normal alveolar plateau (see Fig. 26.5F) may reflect hyperventilation. In this instance end-expired and arterial PCO$_2$ levels are close in value. If the patient is being mechanically ventilated, ventilator settings should be evaluated. Other causes for lower than normal alveolar plateau include reduced CO$_2$ production (hypothermia)
Capnography

Volume of gas from the lungs with each beat. In combination with gas aspiration by a sidestream analyzer, oscillations in PCO₂ during the respiratory pause may become evident. This is a common and inconsequential finding in dogs.

Abnormal phase IV

Normally the capnogram returns briskly to baseline from the alveolar plateau, creating a beta angle of almost 90° as fresh gas is inspired thus replacing the CO₂-containing gas at the sampling site. If the slope of this phase is reduced (i.e., the beta angle is increased; see Fig. 26.5i), then either inspiration is occurring abnormally slowly (not common because it does not take much gas to replace the small volume of exhaled gas at the sampling site) or there is CO₂ in the inspired gas. This could occur with inadequate fresh gas flows on a nonrebreathing circuit or malfunctioning inspiratory valve on a circle system.


Summary

Capnography is a noninvasive method for continuous assessment of ventilation because ETCO₂ provides a very good estimate of PCO₂ in most cases. Gas sampling can be either mainstream or sidestream, each of which has advantages and disadvantages. Capnography is most accurate in intubated patients but can also be used in awake, nonintubated patients for continuous noninvasive PCO₂ monitoring. Finally, evaluation of opposed to an abrupt disappearance of the capnogram waveform as would occur with disconnect or accidental extubation of a patient (see Fig. 26.5h).

An abnormally low alveolar plateau could also be seen if a sidestream analyzer were to have a leak in the gas sampling line and constantly aspirate room air, thus diluting the exhaled gas and creating falsely low PCO₂ measurements.

Conditions causing uneven filling and emptying of alveoli (ventilation perfusion mismatch) result in a slanted plateau phase of the capnogram (and an increased alpha angle) (see Fig. 26.5i). If exhalation is particularly slow, then peak PCO₂ levels may not be reached before inhalation occurs, and as such end-expired PCO₂ values will be below alveolar and thus arterial PCO₂ values.

The normal alveolar plateau is roughly horizontal (see Fig. 26.4). Artifactual dips and bumps in the plateau phase may result from pushing on the thorax of an anesthetized patient causing gas to move out and into the lungs. In an animal being mechanically ventilated, spontaneous ventilatory efforts may be interspersed among mechanical breaths and cause dips or clefts in the alveolar plateau (see Fig. 26.5j). Reasons for these respiratory efforts should be investigated including insufficient anesthetic depth, inadequate mechanical ventilation, hypoxemia, inadequate analgesia, and hyperthermia.

Cardiogenic oscillations are undulations in the capnogram that are synchronous with cardiac contractions (see Fig. 26.5k). Contraction of the right ventricle and filling of the pulmonary vasculature expels a small volume of gas from the lungs with each beat. In combination with gas aspiration by a sidestream analyzer, oscillations in PCO₂ during the respiratory pause may become evident. This is a common and inconsequential finding in dogs.

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Summary

Capnography is a noninvasive method for continuous assessment of ventilation because ETCO₂ provides a very good estimate of PCO₂ in most cases. Gas sampling can be either mainstream or sidestream, each of which has advantages and disadvantages. Capnography is most accurate in intubated patients but can also be used in awake, nonintubated patients for continuous noninvasive PCO₂ monitoring. Finally, evaluation of
capnographic waveforms can aid in the detection of patient or equipment abnormalities.

References