26

Capnography

Linda S. Barter

Terminology

A continuous plot of carbon dioxide (CO_2) 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 CO_2 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 CO_2 are called capnometry and capnography, respectively. Many monitors function as both capnometers and capnographs, displaying both numerical and graphical information about CO_2 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 CO_2 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 PCO_2. 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 CO_2 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 CO_2 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 can have 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 CO_2 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

Advanced Monitoring and Procedures for Small Animal Emergency and Critical Care, First Edition. Edited by Jamie M. Burkitt Creedon, Harold Davis.
© 2012 John Wiley & Sons, Inc. Published 2012 by John Wiley & Sons, Inc.

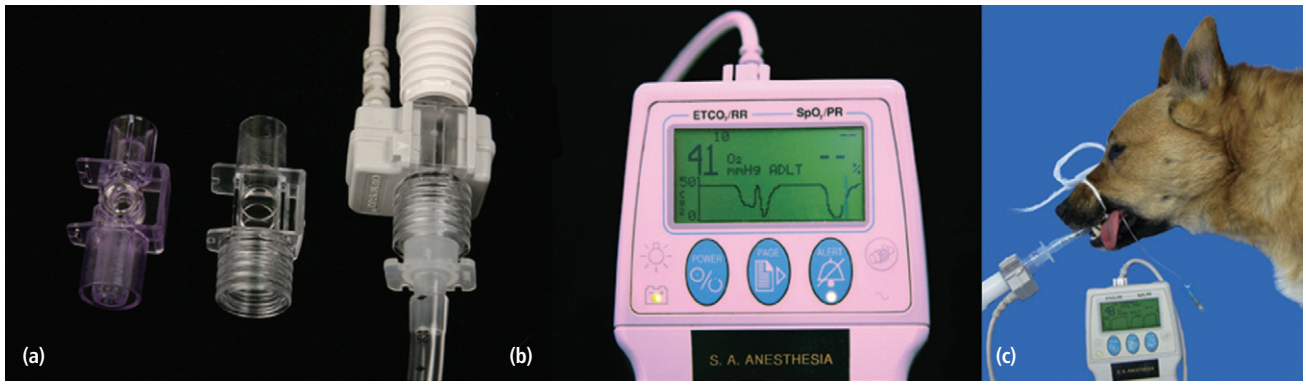

Figure 26.1 Mainstream capnography. (a) From left to right are micro cuvette, standard cuvette, and standard cuvette inside the infrared sensor connected between an endotracheal tube and the patient breathing circuit. (b) The display screen of a portable mainstream capnograph. (c) Mainstream capnograph in use on an anesthetized dog.

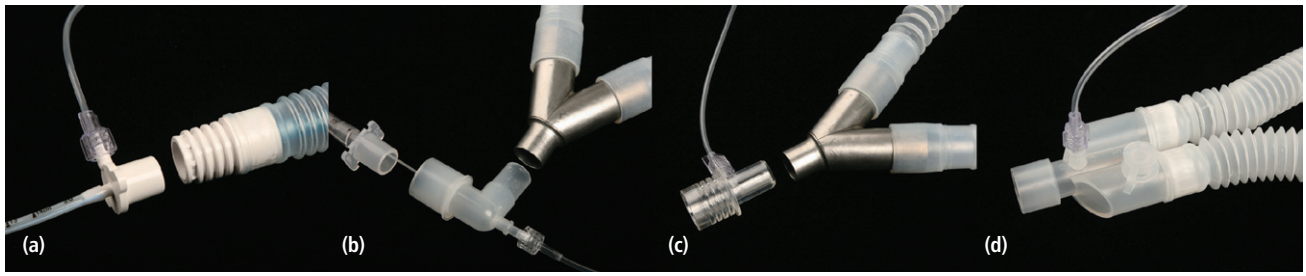

Figure 26.2 Different connection options for a sidestream capnograph gas sampling line. (a) Endotracheal tube adaptor with sample line adaptor. No additional apparatus dead space is added by attaching the capnograph in this way. (b) An elbow connector with adaptor port through which a small-bore catheter has been placed, which will be situated in the distal third of the endotracheal tube lumen to improve accuracy of sidestream gas sampling. (c) Short in-line connector between endotracheal tube and breathing circuit to which gas sampling line can be attached. (d) Some circuit Y-pieces have built-in sampling line connection ports.

designed to be inserted between the endotracheal tube or mask and the breathing circuit (see Fig. 26.2).

With sidestream capnography, gas analysis is delayed because it takes time for the gas to reach the monitor and some time to make the measurement (depending on the technology used). The effect of this delay is that capnographic waveforms generated by sidestream analyzers do not appear synchronously with each breath as is the case with mainstream capnography. Additionally, capnographic waveforms produced by sidestream monitors tend to be more rounded than those produced by mainstream devices in the same situations (see Fig. 26.3). The delay due to transit time depends on the length and diameter of the tubing and the rate at which gas is aspirated (this can vary from 50 to 250 mL/min depending on the monitor). As gas aspirated from the airway travels through the tubing to the monitor, the gas molecules can move around and start to mix (i.e., the CO_2-containing gas starts to mix with non-CO_2-containing gas). The faster the transit time between 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

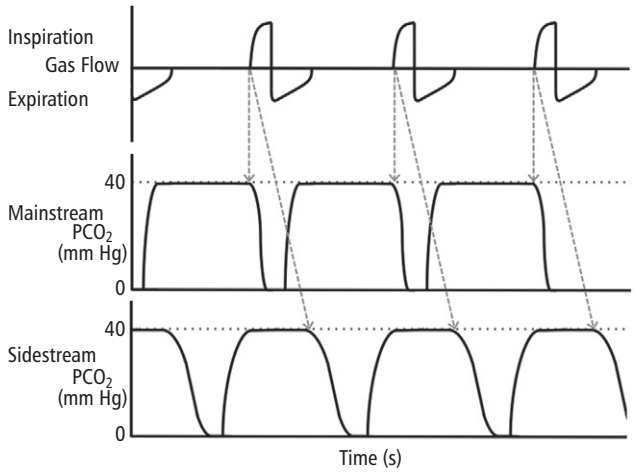

Figure 26.3 Comparison of capnograms obtained from mainstream and sidestream capnographs. The upper tracing depicts gas flow during the respiratory cycle, with gas flow above the line representing inspiration and gas flow below the line representing expiration. The middle tracing is a mainstream capnogram and the lower a sidestream capnogram recorded from the same patient at the same time. The dashed lines connecting the flow tracing with the capnograms illustrate the delay in registering changes in PCO_2 by capnography. The magnitude of this delay with a sidestream analyzer varies with the monitor settings and equipment (see text for details). A major difference between the two types of analyzers can be seen in the shape of the capnograms. Mainstream capnograms tend to record sharper changes in PCO_2, creating more vertical up-and-down strokes on the capnogram when compared with sidestream capnograms (see text for more details).

tubing (Nafion, E I du Pont de Nemours Company) or water traps.

Sidestream CO_2 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).

Equipment setup

In smaller patients mainstream CO_2 analyzers are technically superior to sidestream analyzers.[1,2] Due to their faster response time PCO_2 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 dead space. This can lead to rebreathing of CO_2 and either elevation in $PaCO_2$ or increased work of breathing and altered ventilatory patterns to maintain a normal $PaCO_2$.[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 CO_2 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 CO_2 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).

Physiology

Aerobic metabolism in tissues consumes oxygen, glucose, and other substrates and eventually produces energy, CO_2, and water. CO_2 produced in cells easily diffuses into the surrounding interstitial fluid raising local partial

pressure of carbon dioxide (PCO_2). Arterial blood entering the tissues has a lower PCO_2 than the interstitial tissue and thus CO_2 diffuses from the interstitial fluid into blood. Venous blood leaves the tissues with a PCO_2 higher than that of arterial blood but equal to that of interstitial fluid. Venous blood carries the CO_2 produced by metabolism to the lungs to be removed from the body by ventilation. The process of ventilation replaces CO_2-rich gas from the alveoli with CO_2-free gas from the atmosphere or breathing circuit.

Alveolar partial pressure of CO_2 reflects a balance between CO_2 delivery to the alveoli by the cardiovascular system and its removal by ventilation. In the steady state, alveolar partial pressure of CO_2 is directly related to the metabolic production of CO_2 and inversely related to alveolar ventilation. CO_2 is highly diffusible such that in perfused alveoli, alveolar and arterial partial pressures of CO_2 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 PCO_2.

Under the control of both the central and peripheral chemoreceptors, the body normally maintains arterial PCO_2 within a tight range by adjusting ventilation to the amount of CO_2 produced. Normal range for arterial PCO_2 is from 35 to 45 mm Hg, with some slight variations between species.[6,7]

Hyperventilation describes the situation where alveolar ventilation is in excess of metabolic CO_2 production resulting in alveolar (and thus arterial) PCO_2 levels below the normal range (hypocapnia). Low $PaCO_2$ 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 CO_2 causing alveolar (and arterial) PCO_2 levels to rise above the normal range (hypercapnia). Most anesthetic and sedative drugs result in dose-dependent respiratory depression and respiratory acidosis. A $PaCO_2 > 60$ 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 CO_2 including infrared absorption, Raman scattering, and mass spectrometry.

Infrared absorption

Infrared (IR) absorption is the most popular technique for CO_2 measurement. Monitors utilizing IR technology are typically the most compact and least expensive. IR absorption is the only technique used for CO_2 measurement in mainstream analyzers. Polyatomic gases like CO_2 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 CO_2 measurement, allowing them to measure inspired and expired concentrations. Water vapor absorbs infrared light and thus can spuriously increase measured CO_2. 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 CO_2. Most newer monitors that measure nitrous oxide in addition to CO_2 are able to correct for the effect of nitrous oxide on CO_2 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 CO_2 and eliminates interference with other gases. The high CO_2 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 CO_2, 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 CO_2 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 CO_2 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 PCO_2) suggest the presence of ventilation. It is theoretically possible to sample CO_2-containing gas from the stomach, but the values for end-expired partial pressure of CO_2 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 PCO_2 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 PCO_2 and a dampened waveform because little CO_2 is being delivered to the lung for expiration.

Table 26.1 Clinical indications for capnography

- Ensuring correct placement of endotracheal tube
- Detection of apnea
- Monitoring adequacy of ventilation
- Monitoring pulmonary perfusion during cardiopulmonary resuscitation
- Ensuring correct placement of nasogastric tube
- Detection of equipment problems

Detection of apnea

If a patient becomes apneic, the capnograph or capnometer typically sounds an alarm when CO_2 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 PCO_2 is representative of alveolar PCO_2. Due to the high diffusivity of CO_2, alveolar and arterial PCO_2 equilibrate and end-expired PCO_2 is used to estimate arterial PCO_2. 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 PCO_2. Therefore, very low or precipitously dropping PCO_2 should lead the operator to suspect cardiovascular collapse. Capnography may be useful in monitoring cardiopulmonary resuscitation efforts. End-expired PCO_2 has been used to predict the survivability from cardiac arrest. A successful outcome from cardiopulmonary resuscitation is more likely if expired PCO_2 levels are >10–15 mm Hg during resuscitation efforts.[8–10]

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 CO_2 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

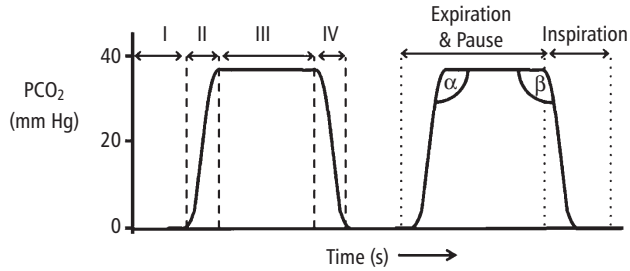

Figure 26.4 The normal capnogram. The capnogram can be divided into four phases, I through IV, and forms two angles, the alpha (α) and beta (β) angles. The phases of the respiratory cycle have been superimposed on the capnogram to the right side of the figure.

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°.

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°.

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 nonrebreathing 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

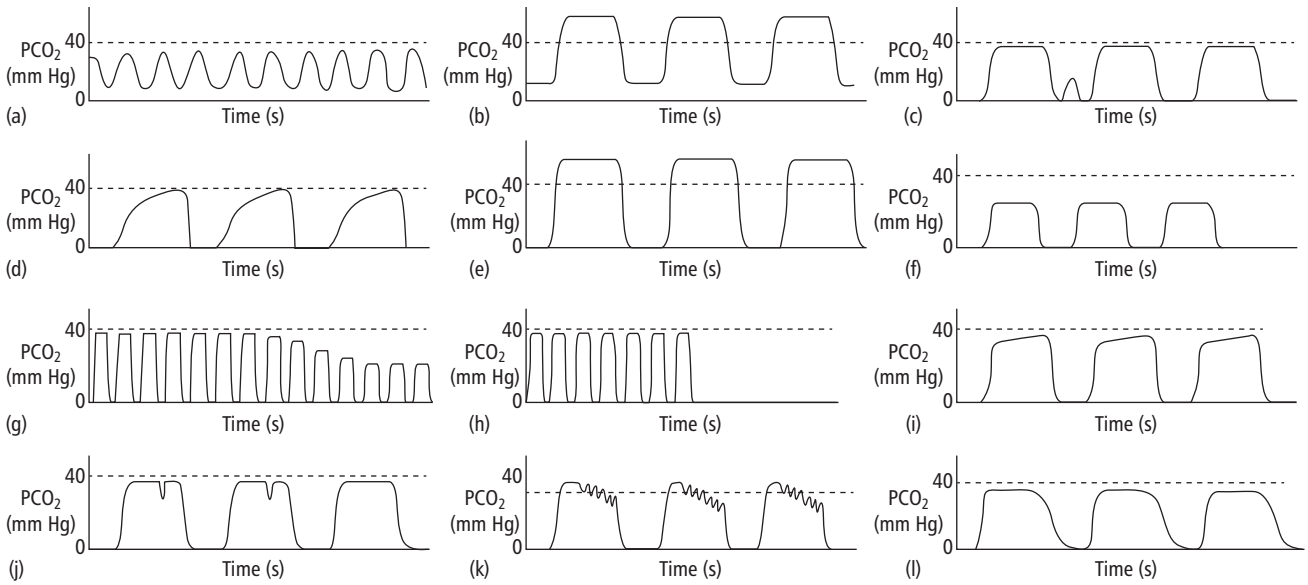

Figure 26.5 Examples of common capnogram waveforms. (a) Sine wave form common with sidestream analysis on small patient with high respiratory rate; (b) rebreathing of CO_2-containing gas; (c) expiratory effort between regular breaths; (d) bronchoconstriction/airway obstruction; (e) hypoventilation; (f) hyperventilation; (g) slow-speed capnogram suggesting reduced pulmonary blood flow; (h) slow-speed capnogram indicating accidental extubation, patient disconnection, or sudden apnea; (i) uneven alveolar emptying; (j) spontaneous inspiratory efforts during mechanical ventilation; (k) cardiogenic oscillations; (l) faulty inspiratory valve.

Fig. 26.3). This delayed equipment response time typically results in increases in both the alpha and beta angle of the capnogram. If the slope of phase II is decreased in the absence of delayed equipment response time, it suggests slow expiration. Such an abnormality is often also associated with a sloped alveolar plateau and increases in alpha angle but normal beta angle (see Fig. 26.5d). Important causes of slow expiration are patient conditions causing airway narrowing or external conditions such as a partially obstructed or kinked endotracheal tube.

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) 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 PCO_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

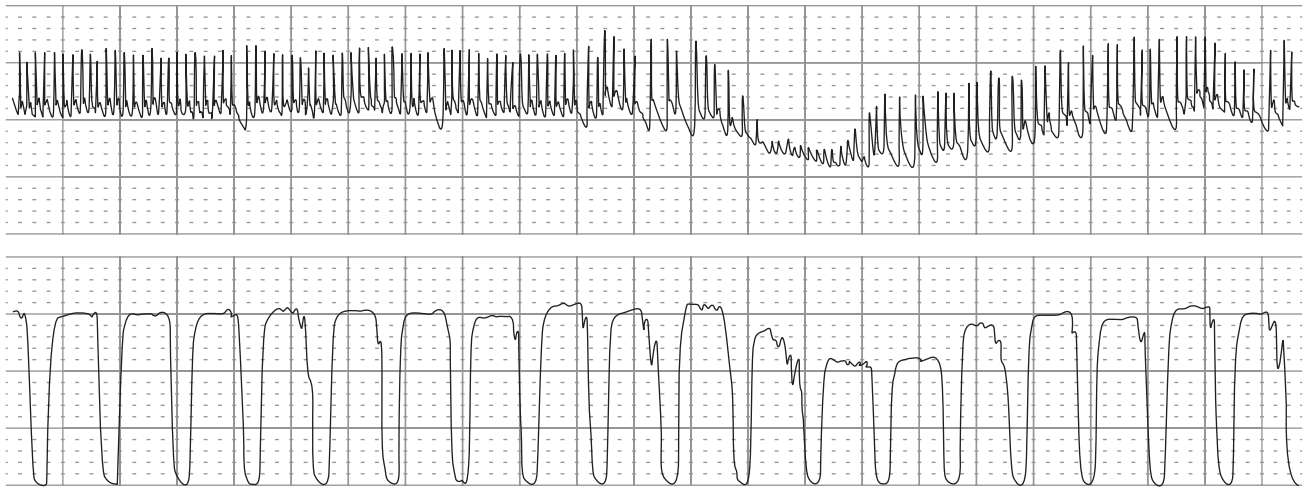

Figure 26.6 The effect of reduced pulmonary blood flow on the capnogram. The upper tracing is arterial blood pressure recorded from the dorsal pedal artery of an anesthetized dog. The lower tracing is a capnogram recorded concurrently from the same patient. Note that the period of hypotension results in a corresponding reduction in the height of the alveolar plateau on the capnogram.

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 PCO_2 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 PCO_2 levels may not be reached before inhalation occurs, and as such end-expired PCO_2 values will be below alveolar and thus arterial PCO_2 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 PCO_2 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 CO_2-containing gas at the sampling site. If the slope of this phase is reduced (i.e., the beta angle is increased; see Fig. 26.5l), 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 CO_2 in the inspired gas. This could occur with inadequate fresh gas flows on a nonrebreathing circuit or malfunctioning inspiratory valve on a circle system.

Protocol 26.1 describes a step-by-step approach to capnogram interpretation.

Summary

Capnography is a noninvasive method for continuous assessment of ventilation because $ETCO_2$ provides a very good estimate of PCO_2 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 PCO_2 monitoring. Finally, evaluation of

Protocol 26.1 Capnogram interpretation: a step-by-step guide

Procedure

1. Are there regular waves of CO_2 providing evidence of ventilation?
2. Does the baseline return to zero (normal) or is there evidence of rebreathing (elevated baseline)?
3. Is the upstroke steep (normal) or is there evidence of slow expiration (slanted upstroke)?
4. Is the alveolar plateau even (normal) or is there evidence of uneven alveolar emptying (slanted plateau) or interruption of the expiratory period by inspiratory efforts (clefts in plateau)?
5. Are end-expired PCO_2 values within an acceptable range, and are they consistent with the patient's respiratory parameters?
6. Is the downstroke steep (normal), or is there evidence of slow inspiration or rebreathing (slanted downstroke)?

capnographic waveforms can aid in the detection of patient or equipment abnormalities.

References

1. Badgwell JM, Heavner JE. End-tidal carbon dioxide pressure in neonates and infants measured by aspiration and flow-through capnography. J Clin Monit 1991;7:285–288.
2. Pascucci RC, Schena JA, Thompson JE. Comparison of a sidestream and mainstream capnometer in infants. Crit Care Med 1989;17:560–562.
3. Schmalisch G, Foitzik B, Wauer RR, et al. Effect of apparatus dead space on breathing parameters in newborns: "flow-through" versus conventional techniques. Eur Respir J 2001;17:108–114.
4. Kugelman A, Zeiger-Aginsky D, Bader D, et al. A novel method of distal end-tidal CO2 capnography in intubated infants: comparison with arterial CO2 and with proximal mainstream end-tidal CO2. Pediatrics 2008;122:e1219–1224.
5. Hagerty JJ, Kleinman ME, Zurakowski D, et al. Accuracy of a new low-flow sidestream capnography technology in newborns: a pilot study. J Perinatol 2002;22:219–225.
6. Middleton DJ, Ilkiw JE, Watson AD. Arterial and venous blood gas tensions in clinically healthy cats. Am J Vet Res 1981;42:1609–1611.
7. Haskins S. Monitoring the anesthetized patient In: Tranquilli WJ, Thurmon JC, Grimm KA, eds. Lumb & Jones' Veterinary Anesthesia & Analgesia. 4th ed. Ames, IA: Blackwell; 2007:533–558.
8. Sanders AB, Kern KB, Otto CW, et al. End-tidal carbon dioxide monitoring during cardiopulmonary resuscitation. A prognostic indicator for survival. JAMA 1989;262:1347–1351.
9. Trevino RP, Bisera J, Weil MH, et al. End-tidal CO_2 as a guide to successful cardiopulmonary resuscitation: a preliminary report. Crit Care Med 1985;13:910–911.
10. Gudipati CV, Weil MH, Bisera J, et al. Expired carbon dioxide: a noninvasive monitor of cardiopulmonary resuscitation. Circulation 1988;77:234–239.