



Capnography in Dogs

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ABSTRACT:

Carbon dioxide (CO₂) is linked to a patient's perfusion, ventilation, and metabolism. End-tidal carbon dioxide (ETCO₂) is the measurement of CO₂ in exhaled respiratory gases and serves as an estimate of arterial CO₂. ETCO₂ is measured by a capnograph in a mainstream or sidestream method. A normal capnogram has four phases: phase 0, the inspiratory downstroke; phase I, the expiratory baseline; phase II, the expiratory upstroke; and phase III, the expiratory plateau. Complete evaluation of a capnogram includes determining the shape and value of the four phases and measuring the alveolar to end-tidal CO₂ gradient. Thorough evaluation gives a clinician information about a patient's state of perfusion, ventilation, and metabolism as well as equipment malfunction. Further veterinary studies are needed to determine the role of capnography in monitoring anesthetized patients, assessing response to treatment, diagnosing disease, and determining a prognosis.

Because of its many roles, carbon dioxide (CO₂) is one of the most important molecules in the body. CO₂ production and elimination is intrinsically linked with the body's state of perfusion, ventilation, and metabolism. Arterial blood gas analysis is considered the gold standard for analyzing a patient's arterial CO₂ and thus assessing its ventilatory status. Obtaining an arterial blood sample is not always possible in small animals. It is associated with a risk of thrombosis and infection and does not give continuous information. The ability to rapidly, noninvasively, and easily monitor CO₂ levels of intubated patients can aid in evaluating and treating them.

Capnography involves continuous measurement and recording of CO₂ in the respiratory gases. In 1943, Luft¹ developed the principle of capnography based on the fact that CO₂ absorbs infrared light. Capnography was first studied

clinically by Smallhout and Kalenda² in humans in the 1970s and has since been researched extensively. By 1985, capnography was considered the standard of care for basic anesthesia monitoring by the American Society of Anesthesiologists.³ In the mid-1990s, CO₂ monitors (capnographs) became small and inexpensive enough to be used in veterinary medicine (Table 1). Capnography minimizes the need for repetitive arterial blood gas sampling, thus providing an excellent noninvasive monitoring and diagnostic tool. This article discusses CO₂ physiology, the primary methods of measuring CO₂ in the respiratory gases using capnography, factors affecting CO₂ measurement, analysis of a capnogram, and the clinical applications of capnography.

CARBON DIOXIDE PHYSIOLOGY

CO₂ is produced as an end product of cellular metabolism. CO₂ diffuses from peripheral body cells into the venous system, where it is trans-

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Table 1. Capnography Equipment

Manufacturer	System
Nellcor	Capnograph NPB75 Capnograph and Pulse Oximeter NPB75/Oximax
SurgiVet	Capnograph 8200 Capnograph and Pulse Oximeter 90040
DRE Veterinary	Tidal 610 Capnograph Tidal 710 Pulse Oximeter and Capnograph
BCI International	3100A/70750/A3 71180A 9100 9400 Capnocheck Plus 58550A1
Bicore Monitoring System	CP100
Datascope	Multinex 4200
Datex-Ohmeda Medical Systems	5A Multicap Normocap 200 Capnomac Ii Capnomac Ultima Oscar Oxy, SCO-123-23-03 Capnomac Hypno ULT Cardiocap II 5200 5250RGM
Novamatrix Medical System	840 1265 Capnogard CO ₂ SMO CO ₂ SMO 7000 CO ₂ SMO 7100
Reister	5200
Spacelabs Medical Inc	90513-38 90518
Sullivan	Sullivan III
Smiths Medical PM, Inc	Capnocheck Capnocheck II/Oximeter

ported in three principal forms. Most (60% to 70%) CO₂ is transported as bicarbonate ion after conversion in the red blood cells by carbonic anhydrase. Another 20% to 30% is transported bound to proteins, and the remaining 5% to 10% is transported in physical solution in plasma.

This 5% to 10% is what is measured by blood gas analysis and reported as arterial partial pressure of carbon dioxide (PACO₂).⁴ Once CO₂ has been transported to the pulmonary circulation, the partial pressure difference between CO₂ in the alveoli (PACO₂) and pulmonary capillaries is the driving mechanism for CO₂ diffusion from the blood into the alveoli. With normal perfusion, equilibration between the pulmonary capillaries and alveolar CO₂ is reached in less than 0.5 seconds. Once the CO₂ has diffused into the alveoli, it is exhaled from the mainstem bronchi and trachea. The amount of CO₂ varies over the course of the breath because of several factors, including different parts of the lungs emptying at different rates and differing ventilation:perfusion ratios. Therefore, the portion of the breath that comes from and most closely resembles the composition of the air in the alveoli is the end-tidal portion. Capnography measures ETCO₂, which is reported as a partial pressure.

Capnography is a noninvasive method of measuring systemic metabolism, cardiac output, pulmonary perfusion, and ventilation.⁵ Changes in the ETCO₂ level reflect changes in one or more of these systems. If all but one of these systems stay relatively constant, the ETCO₂ level will reflect changes in the system that have not been constant.⁶ When CO₂ production remains relatively constant and cardiac output and pulmonary perfusion are normal, changes in ETCO₂ reflect changes in ventilation.⁷

The normal arterial CO₂ concentration in an awake healthy dog is 35 to 45 mm Hg.^{8,9} If ventilation and perfusion are well matched, the ETCO₂ value should nearly equal that of the PaCO₂.¹⁰⁻¹³ The ETCO₂ value is 2 to 5 mm Hg less than that of arterial CO₂.^{7,10-15} This difference is the gradient between CO₂ in the arterial blood and expired air [P(a-ET)CO₂] and can be accounted for by the fact that the PaCO₂ value represents all the perfused alveoli and the ETCO₂ value represents all the ventilated alveoli. The ventilation:perfusion ratio (V_A/Q) is usually 0.8 because of dead space ventilation.^{10,11,13} Alveolar dead space ventilation includes alveoli that are ventilated but not perfused. In cases of V_A/Q mismatch due to increases in alveolar dead space ventilation (i.e., low cardiac output states, hypovolemia, air embolism, shock, arrest, pulmonary embolism), the ETCO₂ level underestimates the PACO₂ level and hence that of the PaCO₂. The ETCO₂ level decreases because the nonperfused alveoli CO₂ concentration is zero, whereas the perfused alveoli concentration is normal. Virtually any condition that increases dead space ventilation can abruptly lower the

ETCO₂ concentration, thereby increasing the difference between the PaCO₂ and ETCO₂ levels. With severe decreases in cardiac output as in shock or cardiac arrest, ETCO₂ values reflect changes in pulmonary blood flow and cardiac output, not ventilation.^{11–13}

SAMPLING METHODS

The two primary methods used for measuring CO₂ in expired air are mass spectroscopy and infrared light absorption. The mass spectrograph separates gases and vapors of different molecular weights. These units are expensive and bulky and thus impractical for most veterinary practices. Infrared light absorption is the most common method for measuring CO₂ in respiratory gases. Polyatomic gases (i.e., nonelementary gases such as nitrous oxide and CO₂) and water vapor absorb infrared rays. CO₂ selectively absorbs infrared light at 4.3 μm. The amount of light absorbed by the CO₂ is directly proportional to the concentration of the absorbing molecules.

Capnometers and capnographs can be categorized based on the sensing device location. The two options for placement of the measuring device are mainstream or sidestream (Figure 1). In sidestream capnometers and capno-

graphs, the measurement device is located away from the sampler, which is placed between the endotracheal tube and breathing circuit. A sampling tube transmits gases to the measurement chamber located away from the breathing circuit. The rate at which respiratory gases are aspirated from the gas column varies from 50 to greater than 400 ml/min. In humans, the optimal rate is considered to be 50 to 200 ml/min.⁶ In mainstream capnometers and capnographs, the measurement device is placed between the endotracheal tube and breathing circuit. Infrared light rays within the sensor traverse the respiratory gases and are detected by a photodetector within a cuvette. Mainstream sensors are heated to prevent condensation of water vapor, which can lead to falsely elevated CO₂ readings.¹⁶

Advantages of sidestream analysis include a lightweight sampler, ease of manipulation near the patient, smaller sample chamber volume, and ability to sample other gases (i.e., inhaled anesthetics). Disadvantages include plugging of the sample line by secretions and condensation, a 2- to 3-second delay in determining the CO₂ concentration, and aspiration of extraneous air from leaks in the breathing circuit that dilute the sample. Low-flow systems and high respiratory rates can

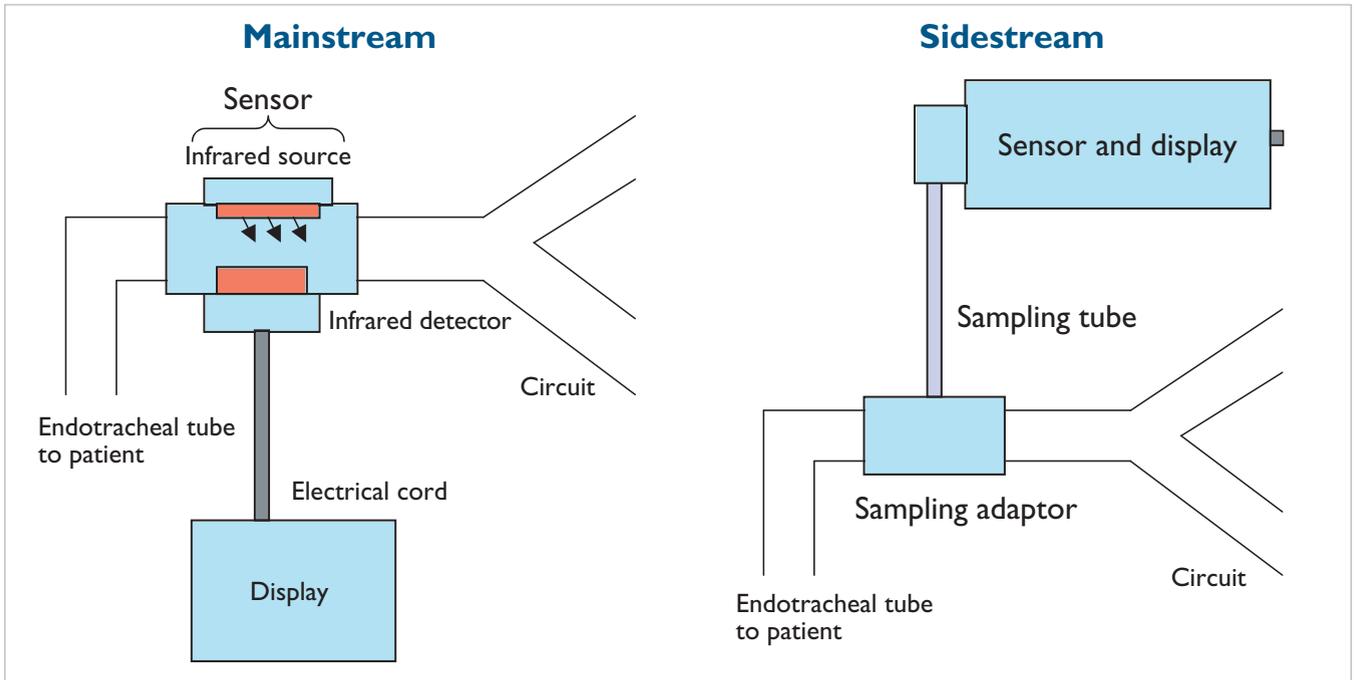


Figure 1. Comparing mainstream and sidestream capnography.

lead to inadequate flushing of the sample cell or line and yield falsely elevated values, thus changing the slope of the capnogram and ETCO_2 concentration.

The advantage of mainstream analysis is that it gives a real-time measurement (i.e., an immediate response rate of <100 milliseconds). However, there are several disadvantages to mainstream capnometry. The excessive dead space in the patient breathing circuit produced by the sensing chamber can lead to false readings. The weight of the device causes kinking of the endotracheal tube. The sensing chamber may be contaminated by secretions and condensation. In addition, patients may be burned by the heated cuvette.

The accuracy of infrared CO_2 monitoring can be affected by several factors. Water vapor can yield falsely high ETCO_2 values (a 1.5% to 2% increase in CO_2) because of condensation on the window of the sensor and in the sample tubing.¹⁶ Methods of decreasing this interference include positioning the sampling tube vertically upward from the patient and using water filters at both ends of the sampling tube. The atmospheric pressure does not affect the ETCO_2 reading because most capnometers have internal calibration devices that adjust for changes in atmospheric pressure. Halogenated anesthetics absorb infrared light at different wavelengths; however, their concentrations are so low that interference

is not considered important. High fresh gas flow rates in small patients can dilute the sample, causing falsely low ETCO_2 values and changes in the waveform. This occurs more often with sidestream than mainstream analysis. To decrease this inaccuracy, the fresh gas flow rate can be reduced to 10 to 30 ml/kg/min, which is currently considered a moderate flow rate for anesthesia maintenance. Higher respiratory rates cause underestimation of the ETCO_2 value because of inadequate emptying of the alveoli. Two keys to obtaining predictable ETCO_2 values and waveforms in animals with high respiratory rates are to program the response time of the analyzer to less than the respiratory cycle time of the patient and to ensure there is no leakage of respiratory gases.

A recent study compared sidestream and mainstream capnometers in mechanically ventilated dogs. This study found that mainstream analyzers were slightly more accurate than sidestream analyzers, but both analyzers satisfactorily reflected changes in the ventilatory status. In this study, PaCO_2 was compared with ETCO_2 . It was determined that the ETCO_2 value may underestimate the degree of hypercarbia at PaCO_2 values greater than 60 mm Hg.¹⁷ A second study showed that ETCO_2 values greater than 55 mm Hg may underestimate the degree of hypercarbia¹⁴ and the ETCO_2 value (at 30 to 55 mm Hg) is the best estimate of the PaCO_2 value.^{14,17,18}

In all situations, it is important to obtain a PaCO₂ reading from arterial blood gas analysis to verify the PaCO₂-ETCO₂ gradient.

NORMAL CAPNOGRAM

The capnogram is the graphic representation of the amount of CO₂ in the respiratory gases versus time. There are two different types of time capnograms: a slow speed to show CO₂ trends, and a fast speed that shows changes in each breath. The fast speed capnogram waveform is useful in determining causes of changes in ETCO₂. The shape of the waveform is altered in various situations, such as breathing circuit leaks, delayed alveolar emptying, and rebreathing expired CO₂. There is considerable variation in terminology describing the normal capnogram. Terminology representing various phases of the time capnogram based on logic, convention, and tradition was introduced by Bhavani-Shankar et al in 1992.¹⁹ The capnogram waveform has three phases of expiration and one of inspiration (Figure 2):

- **Phase I (expiratory baseline)** is the beginning of exhalation and corresponds to exhalation of CO₂-free dead space gas from the larger conducting airways. The CO₂ value during this phase should be zero.
- **Phase II (expiratory upstroke)** involves exhalation of mixed alveolar and decreasing dead space gas, which rapidly increases the CO₂ concentration.
- **Phase III (expiratory plateau)** occurs when all the dead space gas has been exhaled, resulting in exhalation of completely alveolar air. The highest point of phase III corresponds with the actual ETCO₂ value. The plateau has a slight positive slope because of the continuous diffusion of CO₂ from the capillaries into the alveolar space.
- **Phase 0 (inspiratory downstroke)**—Because of inhalation of CO₂-free gas, the CO₂ concentration rapidly declines to zero.

The alpha angle is between phases II and III. In humans, the average angle is 100° to 110°. The alpha angle increases as the slope of phase III increases. Thus the alpha angle is an indirect indication of the V_A/Q status of the lungs. The beta angle is between phases III and 0 and is usually 90°. The beta angle is used to assess the degree of rebreathing. During rebreathing, the beta angle increases as well as the response time of the capnometer compared with the respiratory cycle time of the patient. Normal values for these angles have not been published for dogs or cats.

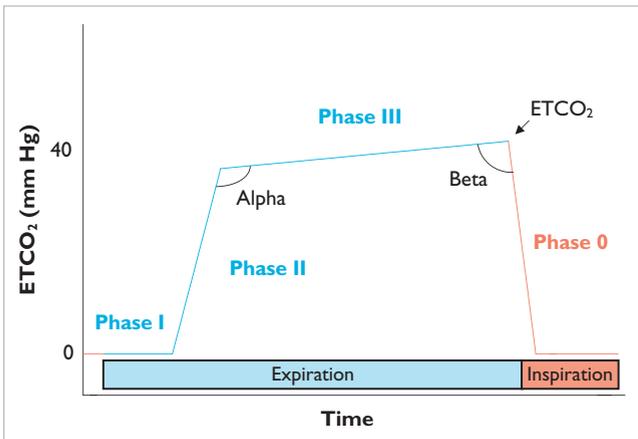
ANALYSIS OF CAPNOGRAM

Thorough examination and interpretation of the capnogram yields information about a patient's ventilation, perfusion, and metabolism. A suggested systematic approach to capnogram interpretation follows:

- Positively identify a waveform (absence of a waveform indicates cardiac or respiratory arrest, disconnection, improper intubation, apnea, or equipment malfunction).
- Determine the actual ETCO₂ and inspiratory CO₂ values.
- Evaluate the waveform.
 - Phase I (expiratory baseline): Is the absolute value zero?

Table 2. Common Causes of Increased and Decreased ETCO₂ Values

	Metabolism	Pulmonary Perfusion	Alveolar Ventilation	Technical Errors
Decreased ETCO₂	Hypothermia Hypothyroidism Muscle relaxants	Decreased cardiac output Hypotension Hypovolemia Pulmonary embolism Cardiac arrest	Hyperventilation Apnea Partial airway obstruction Asthma Pulmonary edema	Disconnection Sampling leaks Sampling fresh gas flow Obstructed endotracheal tube
Increased ETCO₂	Fever Malignant hyperthermia Sodium bicarbonate Tourniquet release Seizures	Increased cardiac output Increased blood pressure	Hypoventilation Rebreathing	Exhausted CO ₂ absorber Inadequate fresh gas flow Leaks in the breathing circuit Faulty valves

**Figure 2. A normal capnogram.**

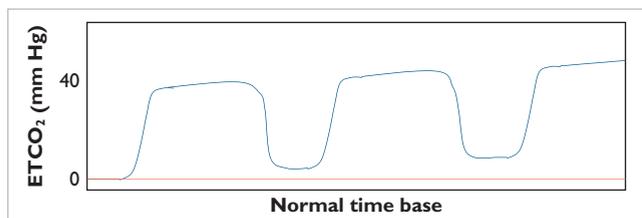
- Phase II (expiratory upstroke): Is it too steep, sloping, or prolonged?
- Phase III (expiratory plateau): Is it flat (compared with a slight positive upstroke), prolonged, or notched?
- Phase 0 (inspiratory downstroke): Is it prolonged?
- Measure the (a-ET)CO₂ gradient: Is it increased, decreased, or stable?

ANALYSIS OF ETCO₂ AND INSPIRATORY CO₂ VALUES

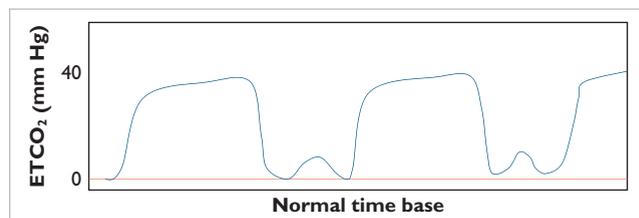
When there are abnormalities in ETCO₂ values or the waveform, it is helpful to consider the factors that affect them (i.e., metabolism, cardiac output/perfusion, ventilation, and mechanical problems). A sudden decrease in

the capnogram reading to zero or an abnormally low value should alert clinicians to a potentially catastrophic event, including failure to ventilate, complete circulatory collapse, cardiac or respiratory arrest, disconnection of the patient from the circuit or machine, or capnograph malfunction. Failure to ventilate could be caused by esophageal intubation, inadvertent extubation, obstruction of the endotracheal tube or breathing circuit, disconnection, or apnea. Circulatory collapse results in absence of a waveform; possible causes include massive pulmonary embolism, cardiac arrest, or exsanguination. Mechanical failures must also be ruled out. The anesthetic machine, ventilator, patient breathing circuit, sensor, and sampling lines should be routinely checked. An easy way to test for mechanical failure of a capnograph is to exhale into the sampling portion of the device. However, this requires that the patient be disconnected and is recommended only after ruling out cardiac or respiratory problems in the patient.

Another way to determine the most likely cause of a low or absent ETCO₂ value is to evaluate the rate of decline using the trend information versus the capnogram waveform. This allows observation of changes that occur in multiple waveforms over time. An abrupt decrease in the ETCO₂ concentration is more likely with inadvertent extubation, circuit disconnection, total obstruction of the endotracheal tube or breathing circuit, or ventilator malfunction. A rapid decrease in the ETCO₂ value occurs with loss of pulmonary blood flow or cardiac output, as in sudden hypotension, cardiac arrest, and pulmonary embolism. A gradual decrease in the ETCO₂ value may indicate decreased CO₂ produc-

Figure 3. Capnograms demonstrating changes in the inspiratory phase.

Capnogram demonstrating a gradual increase in baseline and ETCO₂. Rebreathing of exhaled gases is the primary reason that the inspiratory phase does not return to the zero baseline.



Capnogram of a nonrebreathing anesthetic system. During inspiration, a small rebreathing wave can result from inhalation of CO₂. The extent of rebreathing depends on fresh gas flow, the tidal volume, and the respiratory rate.

tion, as in hypothermia, or increased elimination, as in hyperventilation. Table 2 lists the causes of decreased ETCO₂ concentrations.

ETCO₂ levels greater than 45 mm Hg indicate hypercarbia. Elevated ETCO₂ values are seen primarily with increased CO₂ production or decreased CO₂ elimination. Increased production occurs with hypermetabolic states. Decreased elimination is caused by hypoventilation. Trend information can be used to determine the cause of hypercarbia. An abrupt transient increase in the ETCO₂ value can be seen with bicarbonate administration, release of a limb tourniquet, and transient increases in central nervous system activity. Gradual increases are seen with rising body temperature and hypoventilation. A high ETCO₂ value can also be due to an elevated baseline, as seen with malfunctioning rebreathing circuits and exhausted soda lime absorber.

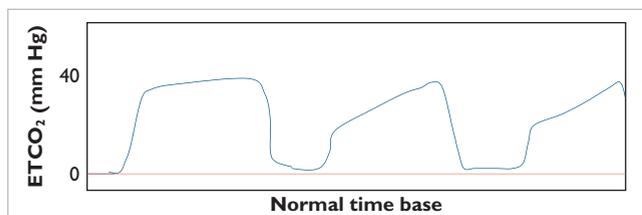
Elevated inspiratory CO₂ values distinguished by an elevated phase I can be seen with rebreathing circuits in which fresh gas flow rates are inadequate and soda lime absorber has been exhausted. Table 2 lists the causes of increased ETCO₂ concentrations. Acceptable inspiratory CO₂ values are 0.1% to 1% (up to 7 mm Hg).

ANALYSIS OF THE WAVEFORM

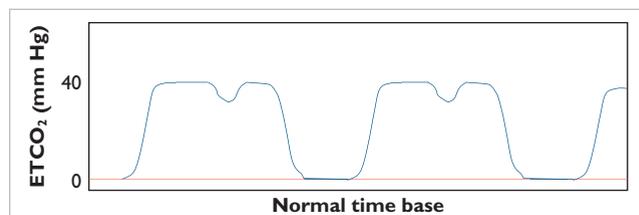
The normal baseline (phase I) is zero. An increase in the baseline represents rebreathing of expired CO₂. A rise in the baseline is seen with exhausted soda lime absorber, faulty one-way valves, or a nonrebreathing circuit when inadequate fresh gas flow rates are used. If both the baseline and ETCO₂ values rise precipitously, the sensor may be contaminated with secretions¹⁶ (Figure 3).

In a normal capnogram, the expiratory upstroke (phase II) is steep. If the upstroke slope is lessened, CO₂ delivery to the sampling site may be delayed. This delay could be physiologic or mechanical. Mechanical factors include obstruction of the breathing circuit with secretions, condensation, or kinking as well as a delay in the sampling rate with sidestream analyzers. Physiologic factors of a slow upstroke include uneven alveoli emptying typical of that found in asthma or bronchitis.

The expiratory plateau (phase III) should be nearly horizontal, with the highest point of the plateau representing the actual ETCO₂ value. The positive slope is due to the contribution of CO₂ from slow-emptying alveoli with a low V_A/Q , allowing accumulation of higher levels of CO₂.¹⁸ When evaluating the plateau, the

Figure 4. Capnograms demonstrating processes that affect the plateau phase.

Upward sloping plateau representing a bronchospasm or another expiratory obstructive process that prevents complete alveolar emptying.



Capnogram of a patient emerging from neuromuscular blockade and demonstrating a curare cleft.

slope, height, and shape should be considered. An increasing slope (increased alpha angle) is frequently seen in patients with obstructive lung disease (Figure 4). The rate at which the alveolus empties depends on airway resistance in the alveolus, compliance of the alveolus, and inflation pressure.¹⁹ A dip in phase III can occur in mechanically ventilated patients with spontaneous breathing (Figure 4). This dip results from spontaneous breath initiation after a ventilator-delivered breath. During this time, a small amount of fresh gas is drawn over the detector. This is known as a *curare cleft* because it occurs commonly when patients are emerging from neuromuscular blockade. This may also be a sign of hypoxemia, hypercarbia, or insufficient anesthesia. Plateau height should be evaluated. If the shape is normal but the plateau height is low, there may be a situation in which well-perfused and underperfused alveoli empty simultaneously (Figure 5). Decreases in pulmonary and systemic perfusion, hypothermia, hyperventilation, and increased dead space ventilation can cause low plateau height.

The inspiratory downstroke (phase 0) is a nearly vertical drop to baseline. Numerous cyclical irregularities in the downstroke that blend with the expiratory plateau are called *cardiogenic oscillations* (Figure 6). This is due to a small amount of gas flow produced after the lungs passively empty as the heart beats against the nearly gas-depleted lungs. If the slope is prolonged and blends with the expiratory phase, there may be a leak in the expiratory circuit (i.e., a loose-fitting endotracheal tube) or a cuff (Figure 6). A prolonged slope can also result from dispersion of gases in the sampling tube or a prolonged response time by the analyzer.

COMPARING THE ARTERIAL TO ET_{CO₂} GRADIENT

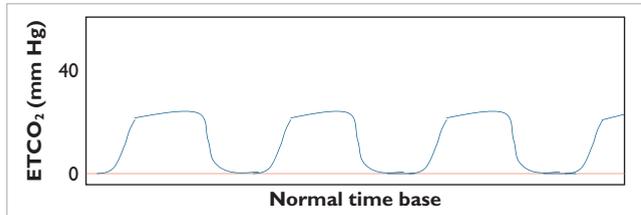
There is normally a 2 to 3 mm Hg difference between arterial and alveolar CO₂ values [P(a-ACO₂) gradient]. The PaCO₂ value is obtained via arterial blood gas analysis. The difference between PaCO₂ and ET_{CO₂} values is known as the P(a-ET)CO₂ gradient. The arterial to ET_{CO₂} gradient is usually less than or equal to 5 mm Hg in both humans and anesthetized dogs.^{7,10-15} The gradient results from the alveolar dead space, which results from temporal, spatial, and alveolar mixing defects in normal lungs. Changes in alveolar dead space correlate well with changes in the P(a-ET)CO₂ value only when phase III has a flat or minimal slope.¹⁸ To evaluate changes in the gradient, a P(a-ET)CO₂ baseline must first be calculated early in the course of events.

Causes of Increased (a-ET)CO₂

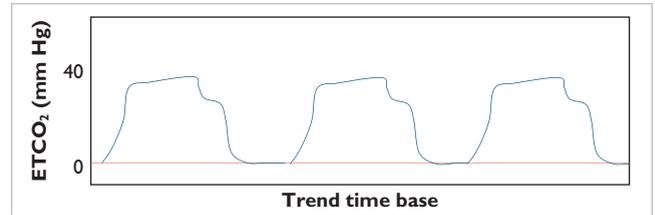
There are three main causes for increase of the (a-A)CO₂ gradient and hence increase of the (a-ET)CO₂ gradient, including V_A/Q abnormalities, respiratory patterns that cause incomplete alveolar emptying, and poor sampling techniques.

Ventilation:Perfusion Abnormalities

The overall V_A/Q in a normal lung is 0.8. Dead space ventilation is characterized as a high V_A/Q, resulting in less involvement of tidal volume in gas exchange. The portion of the tidal volume reaching the nonperfused or poorly perfused alveoli creates physiologic dead space. Any condition that

Figure 5. Capnograms demonstrating changes that can occur in the plateau phase.

Capnogram demonstrating a normal shape but decreased plateau height. This can be the result of hypovolemia, hyperventilation, hypothermia, and increased dead space ventilation.



Capnogram demonstrating dilution of ETCO₂ by fresh gas flow, which produces a terminal dip in the plateau.

increases the physiologic dead space ventilation effectively lowers exhaled CO₂ and increases the gradient. Examples include low forward flow states, hypotension, hypothermia, bradycardia, cardiogenic shock, and pulmonary embolism. In addition, patients undergoing a thoracotomy have altered gradients due to an altered V_A/Q . In dorsal or sternal recumbency, the lungs receive approximately equal ventilation. With lateral recumbency, however, ventilation of the upper lungs increases and perfusion of the lower lungs increases. In addition to positional effects, opening the pleurae increases CO₂ elimination of the upper lung and thereby decreases the P(a-ET)CO₂ gradient. Retraction of the lung produces the exact opposite effects. The lower lung gradient is not affected by these maneuvers, but the combined ETCO₂ reading and hence the gradient can be altered.²⁰

Respiratory Patterns

Respiratory patterns that increase the gradient by incomplete lung emptying include hyperventilation with incomplete exhalation as well as ventilation with inadequate tidal volumes. Patients with asthma or obstructive pulmonary disease may develop an increased gradient

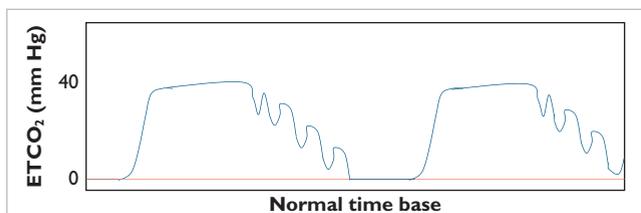
because of constricted airways and decreased chest wall elasticity, making complete lung emptying more difficult.¹⁰ To obtain a more accurate ETCO₂ in humans with restrictive diseases, a chest wall squeeze may be performed.²¹ This can be applied manually at the end of a patient's expiration, but the value of this has not been evaluated in veterinary patients.

Technical Errors

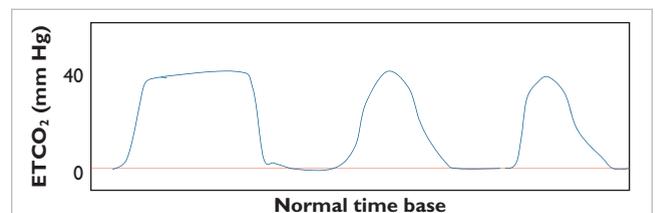
Sampling errors by capnography, such as sampling tube leaks and calibration errors, or blood gas analysis may also increase the gradient.

Causes of Low P(a-ET)CO₂ Gradients or Reverse Gradients

Shunt perfusion (normal to increased perfusion in less than normally ventilated alveoli) results in a low V_A/Q and, consequently, a low to normal P(a-ET)CO₂ gradient. This is a rare finding in dogs, cats, and humans. Situations that induce shunt perfusion are mucous plugging, atelectasis, and alveolar secretions. There are few reports of ETCO₂ values being greater than those of PaCO₂ (reverse gradients)^{22,23}; these are reported in humans, with a greater incidence during pregnancy²⁴ and exercise,²⁵ and

Figure 6. Capnograms demonstrating changes that can be equipment related.

Capnogram displaying oscillations during the inspiratory phase. They result from cardiac pulsations or fluttering of the inspiratory valve in a rebreathing circuit.



Capnogram with an abnormal plateau and inspiratory downstroke, representing endotracheal tube cuff leakage.

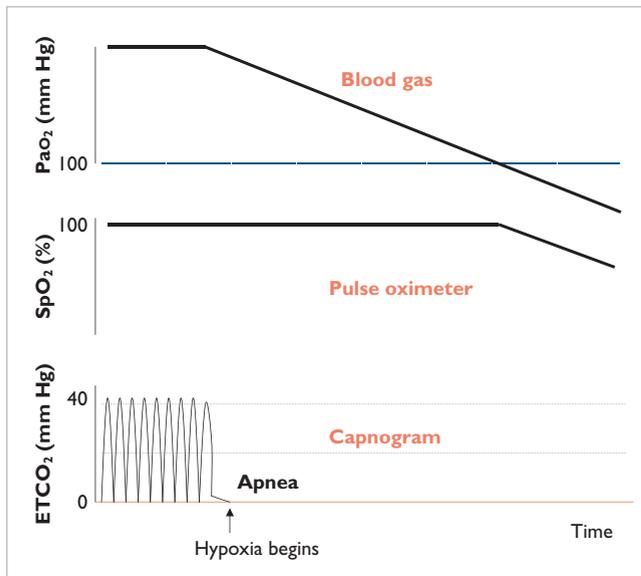


Figure 7. Demonstration of the superiority of capnography over pulse oximetry in detecting apnea.

in patients with large tidal volumes. A hypothesis for this occurrence involves patients with large tidal volumes and low respiratory rates, as seen in barrel- or deep-chested dogs. In this situation, highly perfused slow-emptying alveoli add additional accumulated CO_2 to the end of each breath, increasing the ETCO_2 .²⁵ The existence of such negative gradients further complicates the assumption of PaCO_2 from ETCO_2 values.

CLINICAL USES

Although some studies have shown that the ETCO_2 concentration does not always accurately reflect the PaCO_2 concentration in critically ill patients, it is valuable in detecting trends and sudden changes. A high or rising ETCO_2 concentration likely reflects high or rising arterial CO_2 , whereas a decreasing ETCO_2 value may indicate a decrease or rise or no change in the PaCO_2 value, depending on a patient's temperature, perfusion, and ventilation. Nevertheless, changes in the ETCO_2 should prompt the clinician to evaluate the patient's ventilatory and hemodynamic status.

ETCO_2 has been shown to be superior to pulse oximetry in early detection of airway mishaps, both technical and pathophysiologic (Figure 7). It takes a longer time for oxygen saturation to drop and hence the percentage of oxygenation of hemoglobin (SpO_2) to change compared with changes in ETCO_2 , where the absence of CO_2 is detected instantaneously when the

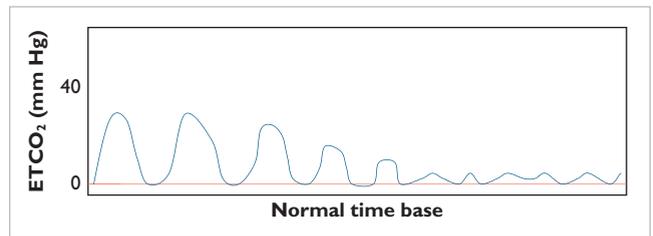


Figure 8. Normal time base capnogram demonstrating the waveform after a patient has been mask ventilated with esophageal intubation.

next breath fails to occur.^{26–29} In this manner, capnography is superior to pulse oximetry in detecting apnea. In addition to monitoring patients during anesthesia, capnography can be used to confirm correct endotracheal tube and nasal esophageal feeding tube placement, guide cardiopulmonary cerebral resuscitation (CPCR), and assist treatment planning for patients receiving mechanical ventilatory support.

Endotracheal Tube Position and Feeding Tube Placement Confirmation

ETCO_2 monitoring for the verification of correct endotracheal tube placement has been studied extensively in humans³⁰ and animals^{31,32} in both arrest and nonarrest settings. The theory behind this involves the fact that CO_2 is normally exhaled through the trachea and not through the esophagus or gastrointestinal tract; hence CO_2 should be detected only from a correctly placed endotracheal tube. Mask ventilation and aerophagia cause the stomach to insufflate with air and may initially result in a false-positive ETCO_2 reading when used with esophageal intubation. In humans, recent ingestion of an antacid may also cause false-positive ETCO_2 readings when using esophageal intubation (Figure 8). To avoid a false-positive ETCO_2 value after suspected inappropriate intubation, the ETCO_2 reading should be interpreted after six breaths.^{33,34}

Capnography can be used as an adjunct to radiography to determine correct placement of nasal-esophageal feeding tubes. The same principles used to determine correct endotracheal tube position are applied. The partial pressure of CO_2 in the stomach and esophagus is considered to be negligible. The ETCO_2 value should be zero in correctly placed feeding tubes.³⁵

Cardiopulmonary Cerebral Resuscitation

Capnography is a valuable tool during CPCR. At the onset of cardiac arrest, the ETCO_2 values fall abruptly

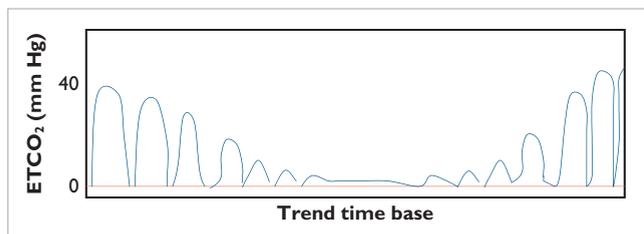


Figure 9. Trend capnogram showing a progressive decrease in ETCO_2 associated with onset of cardiopulmonary arrest followed by a progressive increase in ETCO_2 with successful CPR and ROSC.

because of decreased cardiac output and subsequent pulmonary perfusion. The levels increase slightly with effective CPR and transiently overshoot prearrest values with return of spontaneous circulation (ROSC)^{36,37} (Figure 9). During effective CPR, ETCO_2 values have been shown to correlate with cardiac output,^{38,39} coronary perfusion pressure,⁴⁰ efficacy of cardiac compression, ROSC, and even survival.^{41,42} A clinical human pediatric and an experimental canine pediatric model of asphyxial arrest showed that the higher the initial ETCO_2 value following arrest, the greater was the short-term survival.^{43,44} Ventricular fibrillation is the most commonly researched mode of arrest

and animal studies, an ETCO_2 value greater than 10 mm Hg is highly predictive of successful resuscitation; this value is achieved when coronary perfusion pressure exceeds 30 mm Hg.⁴⁹ To date, the ETCO_2 value is the only noninvasive monitor of the effectiveness of CPR.

Several investigators⁵⁰⁻⁵² have noted a transient decrease in expired ETCO_2 tension after administering epinephrine in patients with nontraumatic prehospital cardiac arrest and in an experimental setting of canine ventricular fibrillation. This finding was marked with high-dose (0.2 mg/kg) epinephrine administration in a porcine model of cardiac arrest.⁵² In human clinical trials, 82% of patients with ROSC had a decreased ETCO_2 value after receiving epinephrine compared with 25% of patients who did not regain a pulse.⁵³ It has also been reported that the greatest accuracy in predicting prognosis is achieved by evaluating an ETCO_2 reading taken after several minutes of initial resuscitation but before epinephrine administration. However, in one clinical human study, epinephrine administration did not significantly affect the ability to predict ROSC based on the ETCO_2 value.^{53,54}

Mechanical Ventilation

The ETCO_2 value can be used to estimate the PaCO_2 value in critically ill, mechanically ventilated, hemody-

Capnography can be used to evaluate a patient's perfusion, ventilation, and metabolism as well as anesthetic and ventilator equipment.

in animal and human studies of CPR. Ventricular fibrillation has a characteristic ETCO_2 pattern of a sudden drop followed by an increase with effective CPR. Respiratory arrests followed by cardiac arrest have an initial markedly elevated CO_2 level, which decreases to low levels with CPR and finally increases with ROSC.⁴³ This increase is due to accumulation of CO_2 in the lungs after respiratory arrest and before cardiac arrest.⁴⁵ Multiple studies have shown that ETCO_2 values of 10 mm Hg or less after 20 minutes of CPR predicted death in humans.^{46,47}

One of the most important factors that determines successful resuscitation of a patient in cardiac arrest is coronary perfusion pressure; in a porcine ventricular fibrillation model, coronary perfusion pressure was shown to be highly correlated with ETCO_2 concentration.⁴⁸ In human

namically stable patients and in patients without rapidly progressive lung pathology. It is most useful to have initial paired PaCO_2 and ETCO_2 values. The P(a-ET)CO_2 gradient can be used to determine optimal levels of positive end-expiratory pressure.¹⁸ The gradient should be smallest when there is maximal recruitment of perfused or functional gas exchange units without overdistention of alveolar areas contributing to dead space. To ensure the smallest P(a-ET)CO_2 gradient, patients should be breathing synchronously with the ventilator. The P(a-ET)CO_2 gradient is also useful in detecting and delineating mechanical failure, including breaks in the breathing circuit, and CO_2 rebreathing; in monitoring patient progress during weaning from the ventilator; and in noting the clinical consequences of changes in mechanical support.^{3,53-57}

Resources

SurgiVet.com

Contains the following articles:

Let's Talk About Capnography by Keith Simpson, MRCVS

Capnography in Veterinary Medicine by Deborah Wilson, DVM

Capnography.com

Contains extensive information and examples of various pathologies

VIN.com

Posts discussions on setup and troubleshooting of capnographs

FUTURE OF ETCO₂ MONITORING

Capnography is being used and studied in diagnosing pulmonary embolism and measuring cardiac output using volume capnograms. Future study of ETCO₂ will include assessing the degree of physiologic dead space in patients with lung pathology. As this monitoring methodology is increasingly used in veterinary medicine, further research will be needed to evaluate its multiple uses, reliability, and cost effectiveness.

CONCLUSION

ETCO₂ monitoring provides clinicians with a valuable tool to assess and monitor patients. Because the physiology of CO₂ production, metabolism, and excretion is so intricately linked to proper cardiopulmonary function, ETCO₂ monitoring can provide information concerning the status of patient ventilation, circulation, and metabolism. ETCO₂ is best analyzed in a systematic fashion, in which the actual value, waveform, and trend of waveforms over time are evaluated. Capnography can be used to identify potentially life-threatening situations such as esophageal intubation, circuit disconnection, a defective anesthetic system, hypoventilation, hypotension, and airway obstruction. Most of the data presented in this review are from the human literature. The ease and practicality of this monitoring tool make it useful in veterinary medicine. Additional research and clinical studies are needed to correlate its multiple uses in humans to animals as well as identify species and breed differences unique to veterinary medicine. As additional studies are conducted, the diagnostic and monitoring capabilities of capnography will be further defined.

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ARTICLE #1 CE TEST



This article qualifies for 2 contact hours of continuing education credit from the Auburn University College of Veterinary Medicine. Subscribers who wish to apply this credit to fulfill state relicensure requirements should consult their respective state authorities regarding the applicability of this program. To participate, fill out the test form inserted at the end of this issue. To take CE tests online and get real-time scores, log on to www.VetLearn.com.

1. Which of the following does not cause a low ETCO₂ value?
 - a. hypothermia
 - b. hypotension
 - c. sampling leaks
 - d. hypoventilation
2. Which of the following does not cause a high ETCO₂ value?
 - a. rebreathing
 - b. soda lime exhaustion
 - c. sodium bicarbonate administration
 - d. cardiac arrest
3. The normal arterial CO₂ concentration in an awake healthy dog is _____ mm Hg, and the ETCO₂ value is usually _____ mm Hg less than arterial CO₂.
 - a. 25 to 35; 2 to 5
 - b. 30 to 40; 5 to 10
 - c. 35 to 45; 2 to 5
 - d. 35 to 45; 2 to 8
4. To confirm correct placement of an endotracheal tube, the ETCO₂ value should be interpreted after _____ breaths.
 - a. two
 - b. four
 - c. six
 - d. eight
5. Rapid loss of a capnogram waveform has been associated with
 - a. hypothermia, inadvertent extubation, and ventilator malfunction.
 - b. pulmonary embolism, acute hypotension, and cardiac arrest.

- c. hypothermia, hyperventilation, and ventilator malfunction.
 - d. circuit disconnection, pulmonary embolism, and hypothermia.
- 6. The positive slope of the expiratory plateau is due to**
- a. slow-emptying alveoli with a low V_A/Q .
 - b. fast-emptying alveoli with a low V_A/Q .
 - c. fast-emptying alveoli with a high V_A/Q .
 - d. slow-emptying alveoli with a high V_A/Q .
- 7. Which aspects should be considered when thoroughly evaluating the expiratory plateau?**
- a. slope, shape, height, $ETCO_2$ value, duration
 - b. slope, shape, height
 - c. $ETCO_2$ value, shape, duration
 - d. slope, height, $ETCO_2$ value
- 8. Which of the following is not one of the three main causes of an increased arterial $ETCO_2$ gradient?**
- a. V_A/Q abnormalities
 - b. respiratory patterns that cause incomplete alveolar emptying
 - c. respiratory patterns that cause complete alveolar emptying
 - d. poor sampling technique
- 9. If a sensor becomes contaminated with secretions, a capnogram will show**
- a. an abrupt rise in the baseline and $ETCO_2$ values.
 - b. a gradual rise in the baseline and $ETCO_2$ values.
 - c. an abrupt rise in the baseline value and no change in the $ETCO_2$ value.
 - d. no change in the baseline value and an abrupt rise in the $ETCO_2$ value.
- 10. A disadvantage of sidestream analysis is _____, and an advantage is _____**
- a. a 2- to 3-second delay; smaller sample chamber volume.
 - b. plugging of the sample line by secretions; real-time measurement of the $ETCO_2$ concentration.
 - c. the bulk and weight of the device; real-time measurement of the $ETCO_2$ concentration.
 - d. facial burns on the patient due to the heated cuvette; a lightweight sampling port.