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End-tidal CO_2 monitoring has many clinical uses: confirmation of endotracheal tube placement, monitoring of intubated patients, or monitoring of children undergoing procedural sedation.

The ability to provide continuous confirmation of airway stability is critical in today's medical and legal environment. The inability of the physical examination to detect subtle changes in patient ventilation makes the use of this modality particularly critical during periods when the patient must be moved from the emergency department (ED) for diagnostic testing, such as computerized tomography, or sedated for procedures.

Familiarity with the uses, advantages, and limitations of this technology enables the ED physician to recognize clinical scenarios where end-tidal CO_2 monitoring will provide a valuable adjunct to clinical care (e.g., endotracheal tube placement confirmation) and when the information provided must be interpreted cautiously (e.g., patients receiving cardiopulmonary resuscitation). The author provides a thorough review of the clinical indications, data interpretation, and limitations for end-tidal CO_2 monitoring.

— The Editor

End-tidal CO_2 Monitoring: Noninvasive Respiratory Monitoring for the Child in the ED

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Introduction

End-tidal carbon dioxide (E_TCO_2) is the carbon dioxide (CO_2) present in the airway at the end of expiration.[1] E_TCO_2 monitoring is the noninvasive measurement of exhaled CO_2.

Capnometry is the measurement and numerical display of the expired CO_2, and the *capnometer* is the machine that measures and displays the CO_2 in a numeric form without a graphic waveform.[2-3]

Capnography is the measurement and graphic waveform display of the expired CO_2 over time (e.g. throughout a given venti-

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latory cycle). The *capnograph* is the machine that measures and displays the CO_2 level in both a numeric and graphic waveform.[4] The graphic waveform displayed by a capnograph is called a *capnogram.*

There is a third type of CO_2 monitoring device, probably more familiar to emergency physicians, used to confirm correct placement of an endotracheal tube.[5] This is a *colorimetric detector*, which produces a color change in a chemically treated material in the presence of carbon dioxide.

Thus, there are three different techniques used to noninvasively monitor carbon dioxide during breathing or ventilation: 1) colorimetric qualitative devices (e.g., the Feneen or Nelcor disposable devices) and quantitative devices, 2) the capnometer, a device displaying a number, and 3) the capnograph, a machine that yields a waveform in addition to a numeric reading.

Clinical Uses of End-Tidal CO_2 Monitoring

Verification of Endotracheal Tube Placement. One of the most widespread uses of E_TCO_2 monitoring is to determine endotracheal tube placement because undetected esophageal intubation can have disastrous results.[6-8] Estimates of the incidence of misplaced or displaced oral endotracheal tubes range from 0-25% in prehospital intubations,[11,14-23] to 10.6 % in the ED.[11,12] Of anesthesia-related accidents resulting in brain injury or death, 15% were attributed to unrecognized esophageal intubation.[15] Certain populations (e.g., pediatric patients/neonates) may have an even higher likelihood of misplaced endotracheal tubes.[10,11,23-25] A 40-50% incidence of esophageal intubations has been documented in neonates in the neonatal intensive care unit.[24,25] Also, practitioners with relatively less experience in intubation are reported to have higher rates of missed intubation.[22,26-28]

More recent studies have reported on the intubation success rate (i.e., first-pass successful intubation versus multiple attempts).[24] Estimates of failed intubation vary greatly, but higher incidences of failed intubations occur with less experienced personnel (e.g., residents) and in high-risk populations (e.g., pediatric patients/ neonates).[22,24-28] The occurrence of failed oral intubations ranges from 47% for basic emergency medical technicians (first attempt only),[29] 13.2-16% for paramedics (includes multiple attempts),[30-32] 3-35% for air ambulance personnel (paramedics/nurses) (includes first attempt equals only 35%; other percentages are multiple attempts),[34-38] to 20-50% for residents (pediatric and emergency medicine specialties).[24-26, 28,39] The first-pass success rates for oral intubation has ranged from 43% to 90%.[26] Several recent anesthesia studies using various intubation techniques have noted a first-attempt successful intubation rate of 92% for American Society of Anesthesiologists' (ASA) class III or IV patients and 95.5% for ASA I or II patients.[41-42]

In summary, endotracheal intubation can be difficult, may not be successful on the first attempt, and if unsuccessful, can have catastrophic results. Therefore, a reliable method or technique for early detection of displaced or misplaced endotracheal tubes is highly desirable.

Clinical tests to confirm tracheal intubation— including breath sound auscultation, chest rise visualization, auscultation over the stomach, and fogging of the endotracheal tube— have some limitations.[40-44] Unfortunately, none of these primary confirmation techniques are 100% reliable. Each has false-positive and false-negative findings in some patients.[40-44] For this reason, secondary confirmation of endotracheal tube placement with an exhaled CO_2 (end-tidal carbon dioxide) detection device and/or an esophageal detector device is recommended by the American College of Emergency Physicians,[45] the American Heart Association,[46-48] and the National Association of EMS Physicians,[49] while mandatory secondary confirmation of endotracheal tube placement is advocated by many clinicians.[44] There have been some studies indicating that the colorimetric E_TCO_2 devices are better than the esophageal detector device for secondary confirmation of endotracheal tube placement.[40,43,51]

Anesthesia, Procedural Sedation. The Society of Critical Care Medicine has recommended end-tidal CO_2 monitoring be available for ventilated patients in the intensive care unit, and during anesthesia, capnography is considered a standard of care.[52-56] Capnography is used to monitor patients undergoing procedural sedation and analgesia.[57-60] The result of hypoventilation/apnea with accompanying hypercarbia is hypoxia, detected by a decrease in pulse oximetry. Prior to the drop in pulse

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Figure 1. Capnograms in Ventilated Patients

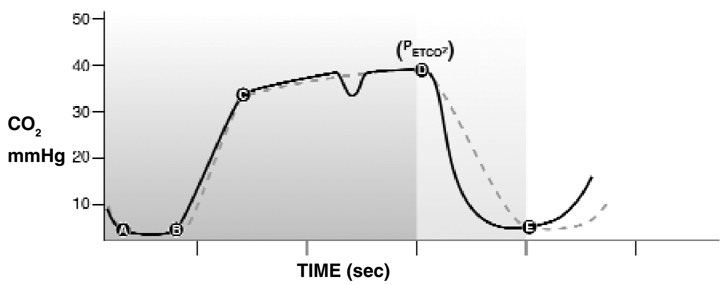

Figure 1A. Patient breathing spontaneously against or "fighting" the respirator = "Curare cleft" represents the patient's own breath.

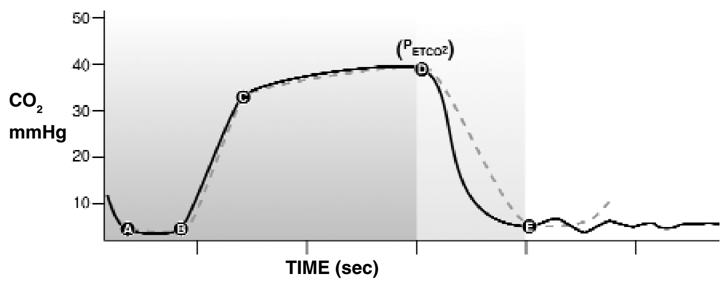

Figure 1B. Sudden Loss of Waveform – Airway Disconnect: Ventilator disconnected or patient accidentally extubated = sudden loss of waveform.

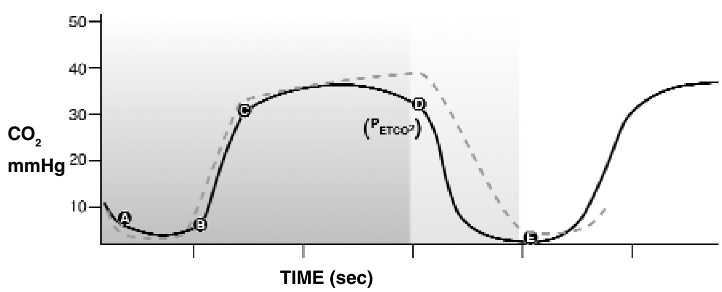

Figure 1C. Leak of Cuff of Endotracheal Tube = Rounded waveform with a normal height.

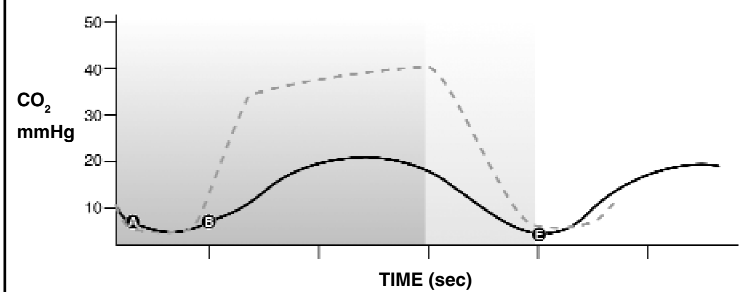

Figure 1D. Partial Airway Obstruction or Kinked Endotracheal Tube = dampened waveform with a low height and a rounded waveform.

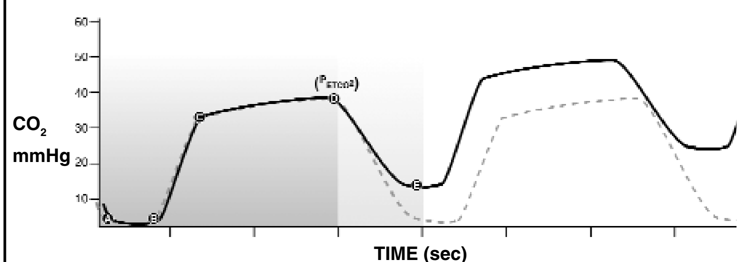

Figure 1E. Presence of CO_2 in inspired gas (e.g., rebreathing) = elevated baseline.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

oximetry, there is generally a rise in the end-tidal CO_2 level.[61] Use of capnography along with pulse oximetry should increase the safety of procedural sedation.[62,63] A prospective observational study in an ED found that capnography could detect subclinical respiratory depression not detected by pulse oximetry alone.[63] The criteria used were 1) an E_TCO_2 measurement greater than 50 mmHg, 2) an absolute change greater than 10 mmHg, or 3) an absent waveform.[63]

Cardiopulmonary Resuscitation (CPR). End-tidal CO_2 monitoring has been used to monitor the effectiveness of CPR, correlated with coronary perfusion pressure and cardiac output during CPR, used to detect the return of spontaneous circulation, and as a tool to predict the likelihood of successful CPR.[64-73] During CPR, decreased cardiac output results in decreased systemic and pulmonary blood flow with decreased delivery of CO_2 to the lungs and thus, decreased CO_2 elimination by the lungs resulting in a low E_TCO_2 level.[64,65] The adequacy of chest compressions during CPR can be assessed by capnography.[65] Several studies have used capnography to predict the likelihood of return of spontaneous circulation (ROSC) during CPR, with a rise in E_TCO_2 levels heralding ROSC.[67-70] In one study, no patients with an E_TCO_2 measurement less than 10 mmHg during CPR survived.[70] The survivors had an average E_TCO_2 level of 15 mmHg compared with an average E_TCO_2 level of 7 mmHg in the non-survivors group.[70]

Mechanical Ventilation. E_TCO_2 monitoring has been used to monitor ventilated patients.[74-77] The specific capnogram can indicate various problems that can occur during mechanical ventilation from a kinking of the endotracheal tube to disconnected equipment, airway leaks, rebreathing expired air, and a patient "fighting the tube" signifying a need for additional sedative/paralytic agents (*Figure 1*).[78-80] Capnography also has been used in ventilator management and to wean selected patients without parenchymal lung disease from mechanical ventilation in the intensive care unit or post anesthesia.[74-80]

Patients with Cardiopulmonary Disease. Capnography has been used to diagnose and monitor the response to therapy in patients with various cardiopulmonary diseases.[76,,80,81] Many respiratory diseases have characteristic capnogram waveforms (*Fig-*

Figure 2. Capnograms in Patients with Various Respiratory Diseases

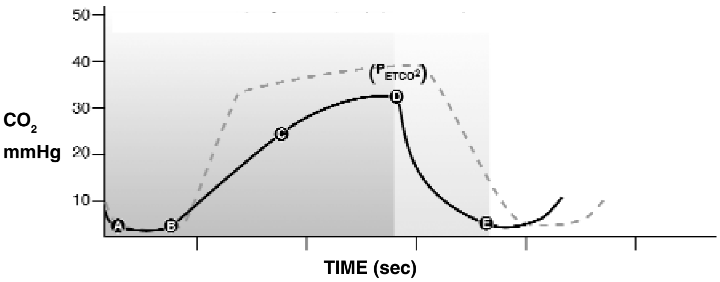

Figure 2A. Obstructive Airway Disease. A gradual rise from B to D, loss of sharp upstroke (no rapid rise from B to C), a steady gradual increase (from B to D), loss of flat plateau from C to D, (somewhat like a slanted bell-shaped curve)

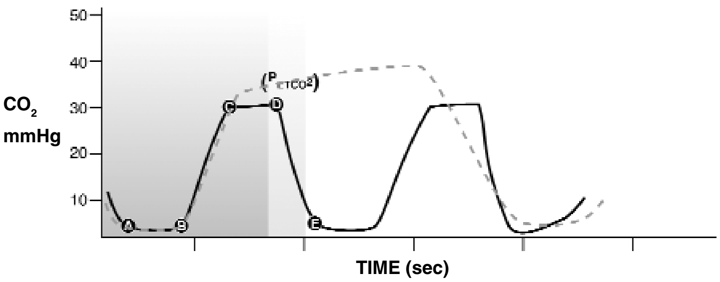

Figure 2B. Restrictive Airway Disease. Flat plateau (from C to D) is replaced by a gradual increase. A sharp upstroke fro B to C remains but is at a lesser height (from B to C).

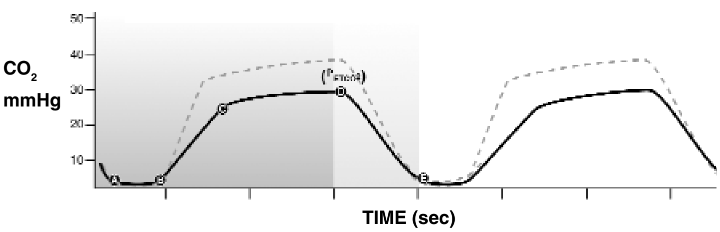

Figure 2C. Decreased Pulmonary Blood Flow. Decreased height (decreased E_TCO_2) while maintaining the "normal" wave form. Example: pulmonary emboli or cardiac arrest.

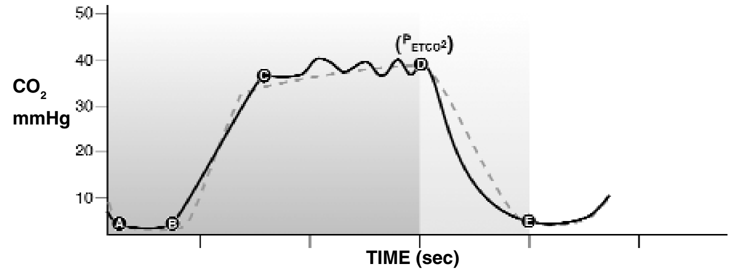

Figure 2D. Uneven Alveolar Emptying. Oscillations in plateau phase from differences in individual E_TCO_2 from various alveoli.

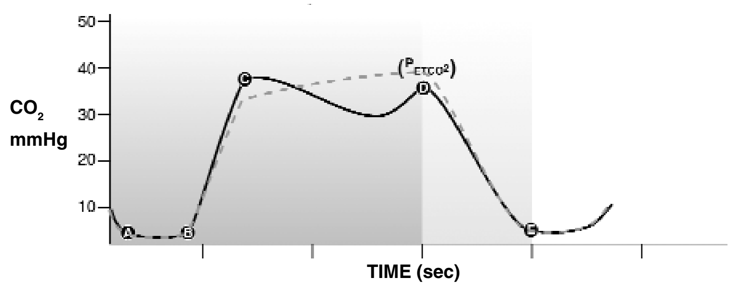

Figure 2E. Biphasic. Biphasic plateau phase due to markedly different alveoli. Example, single lung transplant.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

ures 2,3).[4,78-82] In a patient with respiratory distress/failure, the classic capnogram appearance may provide a clue to the underlying pulmonary disease (*Figures 2,3*). The capnogram also can indicate the severity of the disease as with asthma (*Figure 3*).[83] Capnography also has been used to monitor the response to treatment. As a patient improves, the appearance of the capnogram returns to a normal appearance. The capnograms of asthmatic patients have been noted to correlate with spirometry measurements.[83] Capnography may be especially helpful in pediatric patients; it is noninvasive, painless, effort independent, and may decrease the need for arterial blood gas measurements.[6,9,75,84]

Patients with Other Diseases. In pediatric patients with seizures, capnography correlates with the pCO_2 level and has been used to detect hypercarbia and the need for ventilatory assistance (*Figure 3*).[85] End-tidal CO_2 monitoring has been suggested as a way to help monitor head injured patients with increased intracranial pressure.[86,87] End-tidal CO_2 levels have been utilized successfully in the evaluation of sleep apnea patients, as recommended by the American Thoracic Society.[88] In patients who can not be monitored or visualized directly (e.g., during an MRI procedure), E_TCO_2 monitoring, in addition to pulse oximetry, may be a useful adjunct.[89]

During Transport. Because the patient's ventilatory state can change during transport, constant evaluation using end-tidal CO_2 monitoring may be extremely useful and has been recommended by the American Heart Association.[90,91]

Evaluation of Alveolar Dead Space in the Evaluation for Pulmonary Emboli. Interruption of pulmonary blood flow, as occurs with pulmonary emboli, will increase the alveolar dead space. Because there is less pulmonary arterial blood flow available for participation in gas exchange, the ventilation/perfusion (V/Q) ratio increases and less CO_2 is present in the exhaled breath as reflected in a decreased end-tidal CO_2. The larger the pulmonary emboli, the greater the V/Q abnormality, the greater the drop in perfusion, the greater the dead space increase, and the larger the drop in E_TCO_2 with a greater widening of the ($PaCO_2 - E_TCO_2$) gradient.

These principles have been used to diagnose pulmonary emboli. The dead space (V_D) to tidal volume (VT) ratio or V_D/V_T

Figure 3. Capnograms in Patients with Other Diseases

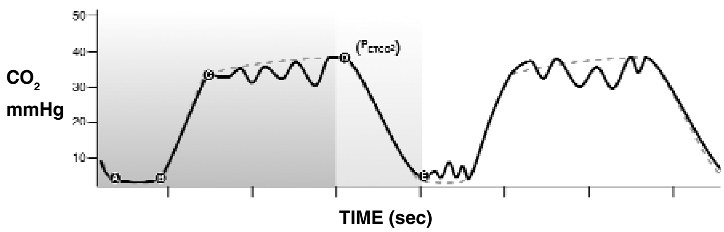

Figure 3A. Distortions throughout ventilator cycle occur during all phases, both inspiration and expiration. Example: hiccups, diaphragmatic contractions, intermittent chest compressions during CPR.

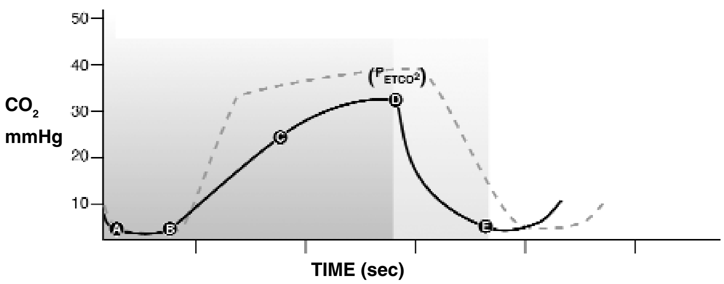

Figure 3B. Mild Asthma with Hyperventilation. Decreased E_TCO_2, prolonged expiratory phase, gradual rise from B to C, loss of sharp upstroke from B to C.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

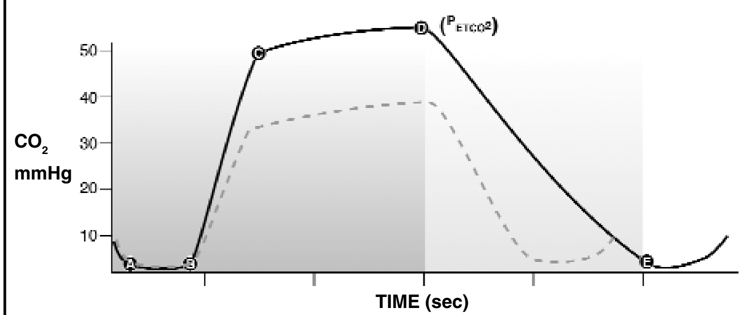

Figure 3C. Hypoventilation. Increased E_TCO_2, normal waveform. Example: CNS depression.

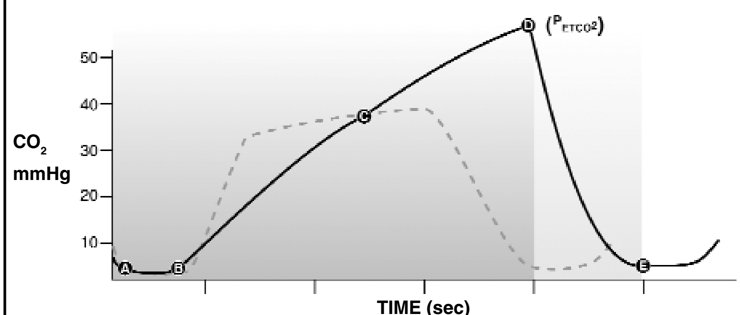

Figure 3D. Asthma-Severe. Hypoventilation (tiring), increased E_TCO_2 and abnormal waveform, no sharp upstroke from B to C, prolonged expiratory phase, gradual rise from B to C.

is calculated using the Bohr equation:

$$V_D/V_T = (PaCO_2 - E_TCO_2)/PaCO_2.$$

The physiological dead space is computed from the mixed expired CO_2 tension or E_TCO_2. A dead space less than 0.4 in a patient with previously normal lungs (e.g., no pulmonary disease such as COPD) has a negative predictive value of 96.7% for pulmonary emboli.[92]

Feeding Tube Placement. Capnometry has been used to verify feeding tube placement.[93] An end-tidal CO_2 detector was attached to the proximal end of the feeding tube, left in place for one minute, and the color change observed. If the color of the qualitative end-tidal CO_2 detector remained purple, the feeding tube was correctly placed in the gastrointestinal tract. If the color of the E_TCO_2 detector was yellow or tan, the feeding tube was incorrectly placed in the airway.

Mechanisms of End-tidal CO_2 Detectors

To understand the advantages, disadvantages, and limitations of end-tidal CO_2 monitoring, a discussion of how detectors work is warranted.

Colorimetric Devices: Mechanism. The colorimetric end-tidal CO_2 detectors are qualitative or semiqualitative devices that change color in the presence of exhaled CO_2 (*Table 1*). A chemically treated pH sensitive foam indicator is placed in the device under a transparent cover that is embedded in a casing that serves as an endotracheal tube adapter. The device is placed between the endotracheal tube and the bag and changes from a purple color (CO_2 absent) to a yellow color in the presence of CO_2, confirming endotracheal tube placement. Various pneumonics have been devised for these colorimetric E_TCO_2 detectors:

Purple = *P*roblem (no or little CO_2 detected),
Tan = *T*hink about a problem,
Yellow = *Y*es (CO_2 detected)[37] or
Yellow = Good as gold (CO_2 detected).[94]

With the colorimetric devices, when the pH sensitive paper is exposed to CO_2, hydrogen ions are formed, resulting in a color change in the paper according to the CO_2 concentration. The color change is reversible and varies from breath to breath. A color scale is associated with the E_TCO_2 concentration:

"A" purple < 4 torr (< 0.5% CO_2),
"B" tan 4-15 torr (0.5 – 2% CO_2),
"C" yellow > 15 torr (> 2% CO_2).

Capnometers and Capnographs: Mechanism. Quantitative measurement of CO_2 concentration is performed by either mass spectrometry or infrared absorption spectrophotometry (*Table*

Table 1. Colorimetric End-tidal CO_2 Detectors

- pH sensitive colorimetric detector
- Turns from purple to yellow if in trachea
- False-negative result (remains purple when in trachea) = extremely low pulmonary blood flow (during CPR), severely hypocarbic patients
- False-positive (turns yellow when in esophagus) after ingestion of carbonated beverages or bag valve mask ventilation (Key: read after 6 breaths → CO_2 wash out → actual reading, eliminates false-positive)
- Avoid using *continuously* in small infants; may rebreathe expired air (secondary to dead space in the E_TCO_2 detector)
- Contamination with acidic gastric contents, respiratory secretions, drugs (e.g., epinephrine) or humidity = tan color or fixed yellow discoloration = unreliable, don't use
- Can not detect hypercarbia/hypocarbia, right main stem bronchus, or oropharyngeal intubation in breathing patient

2).[95,96] The advantage of mass spectrophotometry is that it can measure many gases from carbon dioxide to oxygen or nitrogen, and even anesthetic gases. The disadvantage is its high cost, therefore, its use usually is restricted to the operating suite and for research.

For clinical use, CO_2 analysis generally is measured by infrared absorption spectrophotometry. With this method, a beam of infrared light is passed through the gas being sampled. Carbon dioxide molecules present in the path of light absorb some of the infrared light. The CO_2 concentration of the sample is calculated by comparing the amount of infrared energy absorbed as the light is beamed through the sample with the amount of light absorbed by a CO_2 reference cell.

The sampling techniques employed in infrared absorption spectrophotometry are either mainsteam or sidestream (*Table 3 and Figure 4*).[78,95,96] With mainstream sampling, the sample measurement chamber is located in line with the patient's airway. The advantage of mainstream sampling is an almost instantaneous response time for readings. Unfortunately, mainstream sample chambers can add mechanical dead space to the airway adapter and tend to be fragile, easily damaged, bulky/clumsy, and add weight on the airway, which may cause a pull on the airway circuit. However, recent technological improvements have made mainstream sensors lighter, with less dead space, and more durable.

With sidestream sensors, a gas sample is withdrawn from the patient's airway and diverted by a sampling adapter and narrow-bore tubing to the capnograph (*Figure 4B*). Technical problems related to transport of the sample gas to a distant site for analysis creates the potential for partial obstruction or even occlusion of the tubing by secretions or water vapor as well as creating a delay in response time. Response time is primarily a function of the flow rate by which the sample gas is diverted to the capnograph. Very slow gas-sampling flow rates also may cause artifacts in the capnogram waveform.

Limitations

End-tidal CO_2 detectors are reliable in patients who have enough circulation to pump CO_2-containing blood to the lungs for excretion. Patients in cardiopulmonary arrest have negligible systemic and pulmonary blood flow. Without sufficient blood flow, CO_2 is not delivered to the lungs; therefore, CO_2 in exhaled air is nonexistent. Thus, during CPR, there is the danger of a false-negative reading or a type I error.[47] The endotracheal tube is in the correct position in the trachea, but no CO_2 is exhaled (i.e., the colorimetric detectors remain a purple color) because no CO_2 is transported to the alveoli to be excreted.

Conversely, if E_TCO_2 is detected (e.g., colorimetric device turns yellow), it is very likely that the endotracheal tube is in the airway. Detection of CO_2 indicates that the endotracheal tube is in the airway but does not indicate the specific location or depth in the airway.

A dangerous false-positive result or type II error (e.g., colorimetric device turns yellow when the endotracheal tube is actually in the esophagus) may occur if the patient has recently ingested a carbonated beverage, resulting in the presence of CO_2 in the esophagus.[97-99] To avoid this possibility, ventilate six or more times following intubation, then check for E_TCO_2.[100-101] Ventilating six or more times will permit the "cleansing" ventilations to eliminate CO_2 by washing out any extraneous CO_2 in the esophagus secondary to the ingestion of carbonated beverages.[100-101]

With the colorimetric devices, whenever an *indeterminate* reading occurs (e.g., a tan color) or if there is a fixed yellow discoloration, don't use the device. The pH sensitive paper in the colorimetric device may have been contaminated with acidic gastric contents, respiratory secretions, drugs (e.g., epinephrine), or humidity,[102-106] Do not use any colorimetric device that produces a tan or yellow reading throughout the respiratory cycle, and replace it with another colorimetric device.[102,106]

Colorimetric devices have a limited life span. They are accurate for two hours of continuous use, for 24 hours of intermittent use, and only 15 minutes if humidified oxygen or nebulized aerosols are used; the colorimetric devices are affected by humidity.[1,106,107]

Another limitation is the failure of the colorimetric devices to detect hypercarbia or hypocarbia. A false-negative result (e.g., remains purple when in the trachea) could occur when severe hypocarbia exists. Colorimetric devices detect a minimum level of E_TCO_2. Clinical states that result in extremely low exhaled CO_2 levels below the threshold detected by the colorimetric devices may yield a false-negative result. In addition to cardiac arrest, other conditions that may result in a false-negative result include severe airway obstruction, pulmonary edema, and severe hypocarbia.[99,108] False-negative results occur in approximately 25% of all intubated cardiac arrest patients.[109]

The device should not be used continuously in small infants since the dead space from the end-tidal CO_2 detector may result in the rebreathing of expired air.[110] The recommendation has been to avoid using the adult size end-tidal CO_2 detectors in chil-

Table 2. Types of Carbon Dioxide Monitoring Devices

	CHEMICAL DETECTORS	CAPNOMETER	CAPNOGRAPH
DISPLAY	Color change	Number given in mmHg or percentage	Number and waveform or graph
METHOD	Qualitative or semiqualitative	Quantitative	Quantitative
TECHNIQUE	Chemically treated material displays a color change	Gives the CO_2 level at the end of the expiration	Continuous CO_2 representation for entire respiratory cycle
METHODOLOGY	Chemical colormetric change	Mass spectrometry or infrared light absorption spectrometry	Mass spectrometry or infrared light absorption spectrometry
	No color change (purple) = ET tube in esophagus Tan = indeterminate Yellow = ET tube in trachea	Normal: E_TCO_2 = alveolar PCO_2* $PE_TCO_2 = PACO_2$* ** Under normal conditions*	Normal waveform and normal measurements for PE_TCO_2
NORMAL VALUE	Purple color	$PE_TCO_2 < PACO_2$ by 3 mmHg (normal < 6 mmHg)	Waveform has 4 phases and numerical values

dren weighing less than 15 kg or younger than 2 years because the detector's large dead space (38 mL) may cause dilution of the infant's small tidal volume with the inability to detect CO_2 (yielding a false-negative reading). However, now there are colorimetric end-tidal CO_2 devices with a dead space of 3 mL for use in infants weighing less than 1 kg.[111] A recent study indicated that pediatric devices can be used successfully in neonates/infants weighing less than 15 kg or younger than 2 years.[93,95]

Numeric capnometry is less popular then either the colorimetric or the waveform capnography devices for several reasons.[90,112] It costs more than the disposable colorimetric devices, can be contaminated by secretions/fluids, which may affect the accuracy, and most people find it easier to remember a color (e.g., "gold is good") rather than the normal range of E_TCO_2 numbers.[93,109] Furthermore, the capnography waveform may yield more clinically relevant information than the colorimetric or numeric capnometer.[78,87,114]

There is also a Capno-Flo™ resuscitation bag in which the colorimetric device is built into the resuscitation bag. The disadvantage of the Capno-Flo resuscitation bag is that it does not provide a true breath-to-breath color change. However, there is a new INdGO™ resuscitation bag that has built-in replaceable CO_2 detectors and gives breath-to-breath color changes.[94]

When nasal cannulas are used, supplemental oxygen, inhaled gases, and/or "mouth breathing" may dilute the E_TCO_2 concentration and yield falsely low CO_2 readings.[2,113,114] When nasal cannulas are used with sidestream analyzers, ambient air may be entrained causing dilution of the E_TCO_2 concentration with falsely low estimates of the CO_2 level. Similarly, with sidestream analyzers, the locations of the sampling tube in the patient's nasopharyngeal airway or nares may affect the accuracy of the E_TCO_2 reading. Sidestream analyzers with a slow sampling flow rate in a tachynpeic pediatric patient with a low tidal volume will give a falsely low E_TCO_2 reading.[1,2,77] Water vapor and secretions also can obstruct the nasal cannula.[113,115]

Cost has been cited as a limitation to the use of end-tidal CO_2 monitoring.[103,116] The initial purchase price of a capnography unit is greater than for a capnometer device, with the disposable qualitative devices having the least initial cost. However, even the more expensive units have been justified on a cost-benefit ratio based upon several factors. These benefits include reduced ordering of V/Q or spiral computerized tomography scanning of the chest to rule out pulmonary emboli, decreased frequency of arterial blood gases measurements, limiting or discontinuing futile CPR, and avoiding missed intubations with their potential for malpractice litigation.[116,117]

As with pulse oximetry, there are no absolute contraindications to capnography. Most of the limitations of capnography are related to its design and technical aspects and the interpretation of the results, therefore, a review of pathophysiology is warranted.

Pathophysiology

Carbon Dioxide Metabolism. CO_2 is produced as a byproduct of aerobic metabolism in the cells of the body and transported to the lungs.[118] It is transported in the blood from the cells via the systemic veins to the superior and inferior vena cava to the

Table 3. Mainstream and Sidestream Capnography

- Can measure CO_2 level and respiratory rate
- Use infrared (most common) or mass spectrometry to measure CO_2 level
- Sample exhaled air as close to patient as possible

MAINSTREAM

- Inserts a sampling window into ventilator circuit to measure CO_2 level
- Better real-time measurement
- Fewer problems with obstruction 2° to moisture
- Heavier
- Can not be used in nonintubated patients
- Weight of sensor may pull on ventilator tubing (increase possible disconnection)
- Increased mechanical deadspace
- Falsely low CO_2 levels with small TV, high flow rate
- Too slow flow gives artifacts

SIDESTREAM

- Aspirates gas to an off-patient analyzer
- Can be used in nonintubated patients
- Lightweight
- Adds minimal dead space to ventilation system
- Less contamination risk with secretions/ moisture not directly in line with the airway
- Moisture in sampling circuit can occur causing obstruction or inaccurate reading
- Patient may feel uncomfortable with the extra tubing
- Slight delay in measurement

Figure 4. Types of Analyzers for Capnography

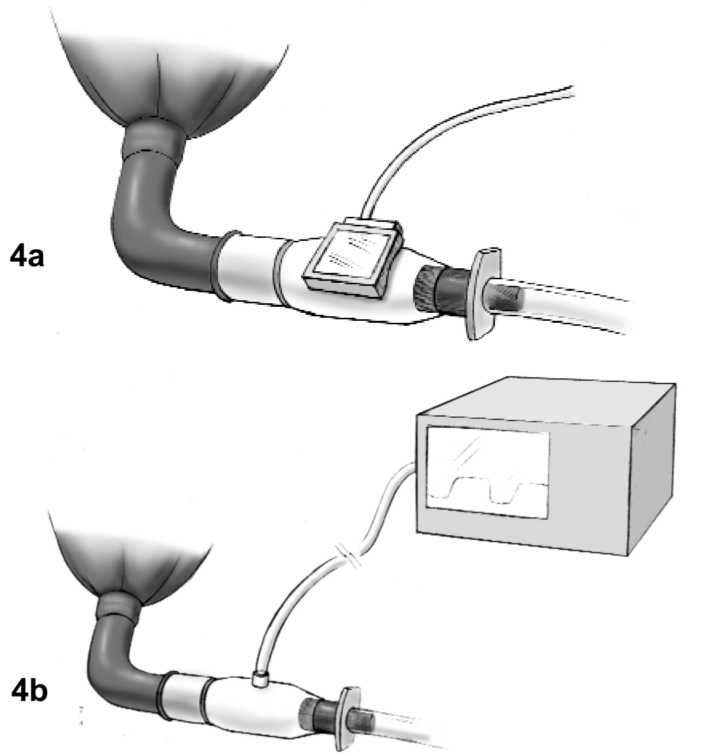

Figure 4a: Mainstream analyzer. **Figure 4B** Sidestream analyzer.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

right side of the heart to the pulmonary artery, and then to the pulmonary capillary bed. There, CO_2 diffuses from the pulmonary capillaries across the pulmonary capillary–alveolar membrane into the alveoli. With ventilation, CO_2 is exhaled to the outside air and eliminated. The now-oxygenated blood in the pulmonary capillary bed then returns to the heart (e.g. left atrium) via the pulmonary veins. Summarizing, CO_2 metabolism/excretion involves three processes: 1) metabolism or production by the cells, 2) circulation that transports CO_2 to the lungs, and 3) ventilation whereby CO_2 is eliminated via expiration.[119] Any factor or disease that affects any one or combination of these three processes will, in turn, affect the exhaled CO_2 level (*Table 4*). This exhaled CO_2 is then detected with the result displayed by the various devices.

Respiration. Ventilation is the delivery of fresh air (and thus, oxygen) to the lung and removal of CO_2 from the blood. Perfusion is the circulation of blood through the vasculature. Gas exchange (i.e., carbon dioxide removal and oxygen delivery) occurs in the pulmonary capillaries. Diffusion is the movement of air between the alveoli and the pulmonary capillaries. Ventilation-perfusion matching is the contact between the alveolar gas and the pulmonary capillary bed. Thus, for normal respiration to occur, all components (i.e., ventilation [V], perfusion [Q], with matching of ventilation-perfusion [V-Q] and diffusion) need to be functioning appropriately.[118]

Ventilation-Perfusion (V/Q). In the ideal situation where all alveolar capillary units have equal matching of ventilation and perfusion, the V/Q ratio = 1. The V/Q ratio, the net PO_2 and net PCO_2 levels of the blood coming from all areas of the lung (e.g., in the pulmonary veins returning to the left atrium) is an average of what is occurring in all the individual alveolar capillary units.

Because of gravity, in the normal upright individual, there is an increasing gradient of blood flow from the apices of the lungs to the lung bases. A similar gradient (but less marked) in the opposite direction occurs for ventilation. In the healthy individual, ventilation is greatest in the apices and perfusion is greatest in the bases. Thus, under normal conditions, the V/Q ratio = 0.8.

Theoretically, the V/Q ratio could range from 0, where ventilation is totally absent (V = O, V/Q ratio = 0), to infinity (∞), when perfusion is completely absent (Q = 0, V/Q ratio = V/0 = ∞). When ventilation is totally absent, the alveolar capillary unit acts like a "shunt" (V = 0, V/Q = 0, shunt). When perfusion is totally absent, the alveolar capillary unit functions as "dead space" (Q = 0, V/Q = ∞, dead space).

Dead Space. The anatomic dead space is the part of each breath that does not reach the alveoli and does not participate in gas exchange. With each breath, part of the fresh air inspired

Table 4. Clinical Conditions that Affect E_TCO_2

INCREASED E_TCO2

- Increased CO_2 production – Increased metabolic rate
  - Sepsis
  - Trauma, burns
  - Fever
  - Malignant hyperthermia
  - Seizures
  - Thyrotoxicosis, hyperthyroidism
  - High cardiac output status
  - Physical activity (e.g., exercise, shivering)
- Transient increased CO_2
  - High carbohydrate intake
  - Iatrogenic causes (e.g., bicarbonate administration, release of a tourniquet, addition of CO_2 during laparoscopy)
- Decreased ventilation
  - Hypoventilation: apnea, bradypnea
  - Respiratory center depression: drugs, CNS depression of respiration: stroke, tumor, infections
  - Respiratory insufficiency: muscle disorders, peripheral neurologic diseases, spinal cord injury diseases

DECREASED E_TCO_2

- Decreased CO_2 production (with decreased delivery to the lung)
  - Decreased metabolic rate (e.g., hypothyroidism)
  - Hypothermia
  - Sedation
  - Paralysis
- Increased Ventilation
  - Hyperventilation
  - Respiratory center stimulation
- Decreased delivery of CO_2 to lungs
  - Decreased systemic blood flow: cardiac arrest, hypoperfusion, hemorrhage, hypotension
  - Decreased pulmonary blood flow: pulmonary emboli
- Ventilation perfusion mismatch (V/Q Inequality)
  - Respiratory diseases (e.g., asthma, COPD, pneumonia, pulmonary emboli)

TECHNICAL (MECHANICAL/EQUIPMENT) PROBLEMS

- Equipment problems
  - Disconnected from ventilator
  - Leak around cuff of endotracheal tube
  - Inadequate sampling
  - Complete airway obstruction
- Near zero E_TCO_2
  - Airway disconnection
  - Ventilator malfunction
  - Total obstruction of the endotracheal tube
- Low (but not zero) E_TCO_2
  - Endotracheal tube in hypopharynx
  - Partial airway obstruction
  - Partial ventilator circuit disconnection
  - Leak in airway system
- Increased E_TCO_2
  - Rebreathing expired air
  - Defective exhalation valve
  - Excessive mechanical dead space
  - Leak in ventilator circuit

Figure 5. Normal Capnogram: 4 Phases

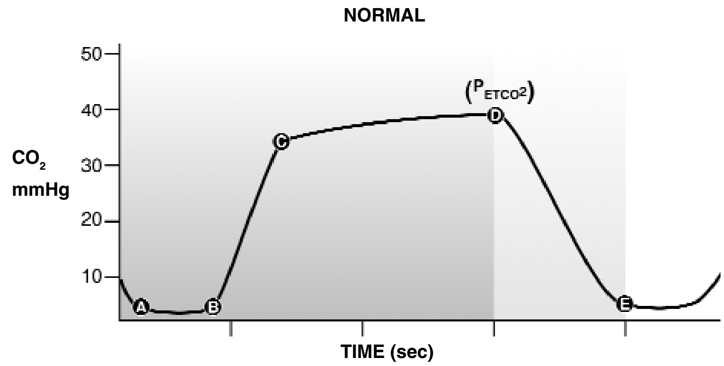

Figure 5.
Phase 1: A to B = baseline = E_TCO_2 = O = Inspiration and early expiration of anatomic dead space
Phase 2: B to C = rapid upstroke = Initial exhalation of alveolar gas
Phase 3: C to D = Plateau = Continued exhalation of alveolar gas
Phase 4: D to E = Inspiration = Rapid decrease in E_TCO_2
Point D = Maximum E_TCO_2 or PE_TCO_2

Image courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

(about 30%) does not reach the alveoli but stays in the conducting airways (i.e., nasopharynx, oropharynx, larynx, trachea, mainstem bronchus, right/left bronchi, and terminal bronchioles).[120]

The other 70% of the air inspired with each breath does reach the alveoli and does participate in gas exchange.[120] This is the alveolar ventilation. In a normal adult at rest with a respiratory rate (RR) of 12-16 breaths per minute and a tidal volume (TV) of 500 mL, the total ventilation (V_T) per minute is seven liters (V_T = RR X TV = 14/min x 500 mL/min = 7000 mL/min = 7 l/min). The dead space ventilation (V_D) is about 2 liters and the alveolar ventilation (V_A) (the ventilation available for gas exchange) is approximately 5 liters, where $V_T = V_D + V_A$ or 7 liters = 5 liters + 2 liters. In certain diseases, some alveoli will be ventilated but not perfused. Thus, the ventilation in these nonperfused alveoli is wasted, resulting in an increase in dead space. When dead space increases with total minute ventilation staying the same, alveolar ventilation decreases and $PACO_2$ increases. An example of increased dead space occurs with pulmonary emboli.

Capnogram

The capnogram is a graph of the CO_2 concentration (in mm) on the X-axis versus time on the Y-axis (*Figure 5*).[4,61] The capnogram is a waveform or graphic representation of the CO_2 levels during a breath or ventilatory cycle. The capnogram yields more data than a single E_TCO_2 reading.

There are four distinct components of a single-breath capnogram (*Figure 5*).[4] The baseline with a "zero" E_TCO_2 (Phase 1) represents inspiration with air taken into the alveoli and early expiration. The E_TCO_2 level is zero because inspired air is essentially free of CO_2. Phase 1 or the baseline of zero (*A to B on Figure 5*) also includes initial expiration because the initial gases expelled are from the anatomic dead space (e.g., the conducting airways that do not participate in gas exchange).

There is a sudden increase in E_TCO_2 level from baseline (Phase 2) as exhalation of alveolar gas occurs (*from B to C on Figure 5*). During the alveolar or expiratory plateau phase, expiration continues with alveolar air being exhaled (*from C to D on Figure 5*). There is a mild upward slope to the plateau phase as air is first exhaled from parts of the lung with lower resistance, higher V/Q ratio, and lower CO_2 levels than from areas of the lung with higher resistance, lower V/Q ratio, and higher CO_2 levels. The end of expiration is at point D. This is the highest point on the graph, and represents E_TCO_2 levels, the number displayed by the capnometer. The inspiratory phase (phase 4) (*point D to E on Figure 5*) is a sharp downslope to return to baseline caused by the influx of essentially CO_2-free inspired air into the alveoli.

Diseases/Conditions Affecting the Capnograms. The appearance of the capnogram can be diagnostic of various disorders (*Figures 1-3*).[1,4,121] For example, a capnogram with an increased baseline (phase 1), but normal overall waveform appearance indicates rebreathing of CO_2. This can occur with a malfunctioning ventilator circuit in intubated patients, with insufficient inspiratory flow, or an inadequate expiratory time (*Figure 1*).

A prolonged upstroke of phase 2 is caused by conditions that lengthen or impede expiration: reactive airway diseases (e.g., acute bronchospasm as with asthma, chronic obstructive pulmonary disease, or bronchiolitis) or in ventilated patients with a kinked endotracheal tube (*Figures 1-3*).[4]

The slope of the expiratory plateau phase (phase 3) is affected by both the expiratory resistance and pulmonary dead space. Evaluating changes in the expiratory phase (phase 3) and phase 2 has been suggested as a way to monitor the response of asthmatic patients to therapy (*Figure 3*). In ventilated patients, a spontaneous inspiratory effort is denoted by a dip or cleft in phase 3. This *curare cleft* is a result of some CO_2-free inspired air (from the patient's spontaneous inspiration) passing over the capnograph's sampling port (*Figure 1*).

Lengthening of inspiration results in a prolonged phase 4 downstroke. For example, this condition could occur with airway obstruction. In a ventilated patient, there may be a leak, either in the endotracheal tube cuff or in the ventilation circuit (*Figure 1*).

A loss of the waveform with a decrease in E_TCO_2 level to near zero in a ventilated patient indicates extubation or an acute equipment malfunction, while a decrease in E_TCO_2 levels to low (but not zero) values with an abnormal waveform may occur with partial airway obstruction or a kinked endotracheal tube (*Figure 1*).

Use of E_TCO_2 During Mechanical Ventilation. The E_TCO_2 measurement can be used to estimate the $PaCO_2$ level only in patients with stable hemodynamics without underlying lung disease (e.g., chronic obstructive pulmonary disease) and at a constant temperature.[4,74,77,121,122]

Relationship of End-Tidal CO_2 to Alveolar CO_2 and Arterial CO_2. Under normal conditions, the alveolar CO_2 measurement correlates with the mixed venous CO_2 ($PVCO_2$) measurement, which in turn equilibrates with the arterial blood carbon dioxide ($PaCO_2$) measurement. Assuming normal circumstances, there is a small gradient of 2-5 mmHg between the $PaCO_2$ measurement and the E_TCO_2 (or PE_TCO_2) measurement. Thus, the P (a-E_T)CO_2 gradient should be less than 6 mmHg.

There are many conditions that can affect the P (a-E_T) CO_2 gradient. This gradient is increased with age, under anesthesia as well as in disease states such as with pulmonary emboli and low cardiac output. The pitfalls in using E_TCO_2 to estimate $PaCO_2$ levels in all patients is obvious when the variables that affect E_TCO_2 levels are reviewed. Variables that affect the E_TCO_2 level can be categorized into several groups:

1) CO_2 production,
2) pulmonary perfusion, and
3) alveolar ventilation.

A fourth category may be technical factors.

Assuming perfusion and ventilation are constant, then variables that increase CO_2 production will lead to an increased delivery of CO_2 to the alveoli causing an increase in E_TCO_2 levels. Factors that result in an increased metabolic rate causing an increased CO_2 production include sepsis, the administration of sodium bicarbonate, seizures, fever, thyrotoxicosis, hypertension, the addition of CO_2 (e.g., during laparoscopy), physical activity (e.g., exercise and shivering), high cardiac output states, and malignant hyperthermia.

Conversely, factors with decreased E_TCO_2 levels from decreased CO_2 production (with decreased delivery of CO_2 to the lungs) are conditions with a decreased metabolic rate including hypothyroidism, hypothermia, sedation, and paralysis.

The E_TCO_2 level is decreased in conditions where the pulmonary perfusion is decreased including cardiopulmonary arrest, hypovolemia, low cardiac output states, and hypotension.

The E_TCO_2 level is increased in states where the cardiac output—and thus pulmonary blood flow—is increased due to increased delivery of CO_2 to the alveoli.

Under conditions of hypoventilation such as apnea, respiratory insufficiency or central nervous system depression of respiration, or during rebreathing of expired air, the E_TCO_2 level is increased (*Figures 2, 3*). Conversely, when hyperventilation occurs, the E_TCO_2 level is decreased (*Figure 3*).

Any situation that causes V/Q mismatch can affect the P (a-E_T) CO_2 gradient. When dead space is increased, the P (a-E_T)CO_2 gradient is increased because more lung units are ventilated than perfused with less blood flow containing CO_2 going to the lung. Therefore, less CO_2 is presented to the alveoli for excretion, therefore, the E_TCO_2 level is decreased.

The capnogram will demonstrate a rounded, more slowly rising expiratory upstroke when there is V/Q mismatch from increased dead space. The normal capnogram has a flat alveolar plateau (*C to D on Figure 5*) because the expired gas from the lung units have comparable V/Q relationships. With significant V/Q abnormalities, the E_TCO_2 level differs because some lung units have low E_TCO_2 concentrations; they are underventilated (due to dead space), while other lung units that are normal will have a high E_TCO_2 concentration.

Pulmonary emboli is a condition associated with increased dead space and a low E_TCO_2 concentration with an increased $PaCO_2 – E_TCO_2$ gradient.

Summary

There are numerous uses of end-tidal CO_2 monitoring that should be beneficial to clinicians (*Table 5*). The first and most important application is as an aid for intubation where typically an absence of CO_2 indicates esophageal intubation and the presence of CO_2 indicates placement in the airway. It can be an additional—but not exclusive—monitoring tool in ED patients yielding a clue to inadvertent dislodgement of an endotracheal tube or a sudden change in clinical condition. It has a negative predictive value for diagnosing pulmonary emboli. It can be used during CPR to predict the efficacy of CPR and the outcome of resuscitation. In patients with stable cardiopulmonary hemodynamics, the E_TCO_2 concentration correlates with the $PaCO_2$ level, and the trend can be used to follow a given patient (e.g., a head injured patient), which may decrease the number of arterial blood gases measurements needed. End-tidal CO_2 monitoring can be a valuable tool for the emergency physician in many clinical situations (*Table 6*).

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Table 5. Clinical Uses of End-tidal CO_2 Monitoring

- Confirmation of endotracheal tube (ET) placement (avoid esophageal placement of ET tube)
- Maintainance of a desired CO_2 level in a given patient (e.g., when hyperventilating a head injured patient or allowing permissive hypercapnia in ventilated patients)
- Evaluation of dead space, calculate V_D/V_T (rule out pulmonary emboli)
- Use in monitoring for procedural sedation and analgesia, and for anesthesia
- Evaluation of the adequacy of cardiopulmonary resuscitation (CPR) and to predict ROSC/survival.
- Monitoring of the integrity of the ventilatory circuit including the artificial airway
- Determination of underlying disease process based upon waveform (capnography)
- Monitoring of the response to treatment (e.g., an asthmatic patient's response to an aerosol) by a change in waveform (capnography)
- Confirmation of nasogastric tube (NG) placement (avoid tracheal placement of NG tube)

Table 6. Pearls and Pitfalls

- Clinical tests (primary confirmation techniques) for ET tube placement are not 100% reliable.
- Remember false-positive and false-negative results can occur with the verification of ET tube placement by the colorimetric E_TCO_2 devices.
- The detection of CO_2 indicates that the ET tube is in the airway and not in the esophagus. However, it does not indicate *where* the ET tube is in the airway.
- A positive result for CO_2 (e.g., yellow on the colorimetric devices) does not rule out a malpositioned ET tube. For example, the ET tube could be in the larynx above the vocal cords or in the right main-stem bronchus.
- A V_D/V_T ratio < 0.4 in a patient with previously normal lungs essentially rules out (96.7% negative predictive value) a pulmonary emboli.
- The capnogram can be useful for evaluating CPR, diagnosing various pulmonary diseases, and monitoring response to treatment.
- The E_TCO_2 level can be correlated with and used to estimate the $PaCO_2$ only under certain conditions; when the patient is hemodynamically stable at a constant temperature.

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Physicians participate in this continuing medical education program by reading the article, using the provided references for further research, and studying the questions at the end of the article. Participants should select what they believe to be the correct answers, then refer to the list of correct answers to test their knowledge.

To clarify confusion surrounding any questions answered incorrectly, please consult the source material. After completing this activity, you must complete the evaluation form that will be provided at the end of the semester and return it in the reply envelope provided to receive a certificate of completion. When your evaluation is received, a certificate will be mailed to you.

CME Objectives

The CME objectives for *Pediatric Emergency Medicine Reports* are to help physicians:

a.) Quickly recognize or increase index of suspicion for specific conditions;

b.) Understand the epidemiology, etiology, pathophysiology, historical and physical examination findings associated with the entity discussed;

c.) Correctly formulate a differential diagnosis and perform necessary diagnostic tests;

d.) Apply state-of-the-art therapeutic techniques (including the implications of pharmacologic therapy discussed) to patients with the particular medical problems discussed;

e.) Provide patients with any necessary discharge instructions.

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CME QUESTIONS

11. Which one of the following statements regarding capnography is *incorrect?*
    - A. It gives a numeric display of the end-tidal CO_2 level.
    - B. It gives a waveform of the expired CO_2 level.
    - C. It does not give a waveform of the expired CO_2 level.
    - D. It is a noninvasive measurement of the exhaled CO_2.
    - E. It gives the expired CO_2 level over time (e.g. in a given ventilatory cycle).

12. Which one of the following statements does *not* apply to a colorimetric end-tidal CO_2 device?
    - A. It changes color in the presence of CO_2.
    - B. A tan color is an indeterminate reading.
    - C. It is a qualitative or semiqualitative device.
    - D. A yellow color indicates the absence of CO_2.
    - E. A purple color signifies the absence of CO_2.

13. Which one of the following statements regarding endotracheal (ET) tube placement has *not* been reported ?
    - A. There is a greater likelihood of a misplaced ET tube in pediatric patients.
    - B. There is a greater likelihood of a misplaced ET tube in adults than in children.
    - C. An incidence of misplaced ET tubes as high as 40-50% has been reported in neonates.
    - D. A complication rate as high as 26% has been reported in an anesthesia setting.
    - E. Fifteen percent of anesthesia-related accidents resulting in brain injury or death were attributed to unrecognized esophageal intubation.

14. Which one of the following statements regarding primary and secondary confirmation of endotracheal tube placement is correct ?
    - A. Primary confirmation techniques are 100% reliable.
    - B. False-negative results do not occur with the secondary confirmation techniques.
    - C. False-positive results can occur with the secondary confirmation techniques.
    - D. The esophageal detector device is considered a primary confirmation technique.
    - E. A positive result of any one of the clinical tests to confirm endotracheal intubation eliminates the need for secondary confirmation.

15. Capnography has been used in which of the following settings?
    - A, Operating room
    - B. In procedural sedation and analgesia
    - C, In the intensive care unit
    - D. None of the above
    - E. All of the above

16. Which one of the following statements regarding end-tidal CO_2 monitoring and cardiopulmonary resuscitation (CPR) is *incorrect*?
    - A. End-tidal CO_2 monitoring does not predict the likelihood of return of spontaneous circulation.
    - B. The adequacy of chest compressions during CPR can be assessed by capnography.
    - C. In one study, no patients with an end-tidal CO_2 measurement less than 10 mm Hg during CPR survived.
    - D. End-tidal CO_2 monitoring during CPR has been correlated with coronary perfusion pressure and cardiac output.
    - E. End-tidal CO_2 monitoring during CPR has been used to predict the likelihood of successful CPR.

17. Uses of end-tidal CO_2 monitoring include all of the following, *except:*
    - A. Monitoring of ventilated patients
    - B. Monitoring of head injured patients who need hyperventilation
    - C. Evaluation of sleep apnea patients
    - D. Monitoring of heart rate
    - E. Monitoring during transport

18. All of the following statements regarding capnogram waveforms are correct, *except*:
    - A. It may give a clue to the underlying pulmonary disease.
    - B. It may indicate the severity of the disease.
    - C. It can monitor the response to treatment.
    - D. It is used to detect hypercarbia in pediatric patients with seizures.

E. It does not correlate with spirometry measurements in asthmatic patients.

19. Which one of the following conditions does *not* apply to the use of end-tidal CO_2 monitoring for the diagnosis of or to rule out pulmonary emboli?
    A. The V_D/V_T ratio equals $PaCO_2$ plus E_TCO_2 divided by the $PaCO_2$ or $V_D/V_T = PaCO_2 + E_TCO_2$. $PaCO_2$
    B. A V_D/V_T ratio less than 0.4 in a patient with previously normal lungs has a negative predictive value of 96.7% for pulmonary emboli.
    C. The dead space is computed from the expired CO_2 tension.
    D. $V_D/V_T = (PaCO_2 — E_TCO_2) / PaCO_2$

20. All of the following characteristics apply to end-tidal CO_2 monitoring, *except*:
    A. Noninvasive
    B. Effort dependent
    C. Painless
    D. May decrease the need for arterial blood gases measurement
    E. Does not depend upon patient cooperation

ANSWERS

11. C
12. D
13. B
14. C
15. E
16. A
17. D
18. E
19. A
20. B

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PEDIATRIC Emergency Medicine Reports™

The Practical Journal of Pediatric Emergency Medicine

End-tidal CO_2 monitoring

Clinical Uses of End-tidal CO_2 Monitoring

- Confirmation of endotracheal tube (ET) placement (avoid esophageal placement of ET tube)
- Maintainance of a desired CO_2 level in a given patient (e.g., when hyperventilating a head injured patient or allowing permissive hypercapnia in ventilated patients)
- Evaluation of dead space, calculate V_D/V_T (rule out pulmonary emboli)
- Use in monitoring for procedural sedation and analgesia, and for anesthesia
- Evaluation of the adequacy of cardiopulmonary resuscitation (CPR) and to predict ROSC/survival.
- Monitoring of the integrity of the ventilatory circuit including the artificial airway
- Determination of underlying disease process based upon waveform (capnography)
- Monitoring of the response to treatment (e.g., an asthmatic patient's response to an aerosol) by a change in waveform (capnography)
- Confirmation of nasogastric tube (NG) placement (avoid tracheal placement of NG tube)

Mainstream and Sidestream Capnography

- Can measure CO_2 level and respiratory rate
- Use infrared (most common) or mass spectrometry to measure CO_2 level
- Sample exhaled air as close to patient as possible

MAINSTREAM

- Inserts a sampling window into ventilator circuit to measure CO_2 level
- Better real-time measurement
- Fewer problems with obstruction 2° to moisture
- Heavier
- Can not be used in nonintubated patients
- Weight of sensor may pull on ventilator tubing (increase possible disconnection)
- Increased mechanical deadspace
- Falsely low CO_2 levels with small TV, high flow rate
- Too slow flow gives artifacts

SIDESTREAM

- Aspirates gas to an off-patient analyzer
- Can be used in nonintubated patients
- Lightweight
- Adds minimal dead space to ventilation system
- Less contamination risk with secretions/ moisture not directly in line with the airway
- Moisture in sampling circuit can occur causing obstruction or inaccurate reading
- Patient may feel uncomfortable with the extra tubing
- Slight delay in measurement

Clinical Conditions that Affect E_TCO_2

INCREASED E_TCO2

- Increased CO_2 production – Increased metabolic rate
  - Sepsis
  - Trauma, burns
  - Fever
  - Malignant hyperthermia
  - Seizures
  - Thyrotoxicosis, hyperthyroidism
  - High cardiac output status
  - Physical activity (e.g., exercise, shivering)
- Transient increased CO_2
  - High carbohydrate intake
  - Iatrogenic causes (e.g., bicarbonate administration, release of a tourniquet, addition of CO_2 during laparoscopy)
- Decreased ventilation
  - Hypoventilation: apnea, bradypnea
  - Respiratory center depression: drugs, CNS depression of respiration: stroke, tumor, infections
  - Respiratory insufficiency: muscle disorders, peripheral neurologic diseases, spinal cord injury diseases

DECREASED E_TCO_2

- Decreased CO_2 production (with decreased delivery to the lung)
  - Decreased metabolic rate (e.g., hypothyroidism)
  - Hypothermia
  - Sedation
  - Paralysis
- Increased Ventilation
  - Hyperventilation
  - Respiratory center stimulation
- Decreased delivery of CO_2 to lungs
  - Decreased systemic blood flow: cardiac arrest, hypo-perfusion, hemorrhage, hypotension
  - Decreased pulmonary blood flow: pulmonary emboli
- Ventilation perfusion mismatch (V/Q Inequality)
  - Respiratory diseases (e.g., asthma, COPD, pneumonia, pulmonary emboli)

TECHNICAL (MECHANICAL/EQUIPMENT) PROBLEMS

- Equipment problems
  - Disconnected from ventilator
  - Leak around cuff of endotracheal tube
  - Inadequate sampling
  - Complete airway obstruction
- Near zero E_TCO_2
  - Airway disconnection
  - Ventilator malfunction
  - Total obstruction of the endotracheal tube
- Low (but not zero) E_TCO_2
  - Endotracheal tube in hypopharynx
  - Partial airway obstruction
  - Partial ventilator circuit disconnection
  - Leak in airway system
- Increased E_TCO_2
  - Rebreathing expired air
  - Defective exhalation valve
  - Excessive mechanical dead space
  - Leak in ventilator circuit

Types of Carbon Dioxide Monitoring Devices

	CHEMICAL DETECTORS	CAPNOMETER	CAPNOGRAPH
DISPLAY	Color change	Number given in mmHg or percentage	Number and waveform or graph
METHOD	Qualitative or semiqualitative	Quantitative	Quantitative
TECHNIQUE	Chemically treated material displays a color change	Gives the CO_2 level at the end of the expiration	Continuous CO_2 representation for entire respiratory cycle
METHODOLOGY	Chemical colormetric change	Mass spectrometry or infrared light absorption spectrometry	Mass spectrometry or infrared light absorption spectrometry
	No color change (purple) = ET tube in esophagus	Normal: E_TCO_2 = alveolar PCO_2*	Normal waveform and normal measurements for PE_TCO_2
	Tan = indeterminate	$PE_TCO_2 = PACO_2$*	
	Yellow = ET tube in trachea	** Under normal conditions*	
NORMAL VALUE	Purple color	$PE_TCO_2 < PACO_2$ by 3 mmHg (normal < 6 mmHg)	Waveform has 4 phases and numerical values

Capnograms in Patients with Other Diseases

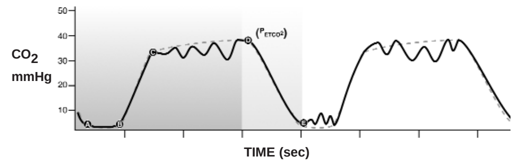

Figure A. Distortions throughout ventilator cycle occur during all phases, both inspiration and expiration. Example: hiccups, diaphragmatic contractions, intermittent chest compressions during CPR.

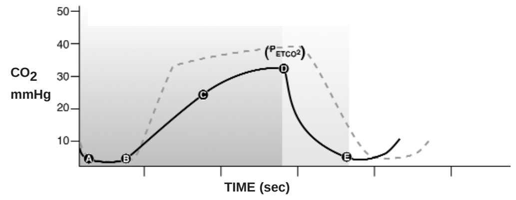

Figure B. Mild Asthma with Hyperventilation. Decreased E_TCO_2, prolonged expiratory phase, gradual rise from B to C, loss of sharp upstroke from B to C.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

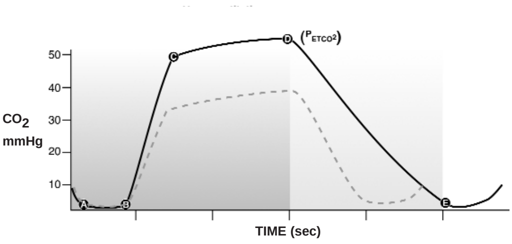

Figure C. Hypoventilation. Increased E_TCO_2, normal waveform. Example: CNS depression.

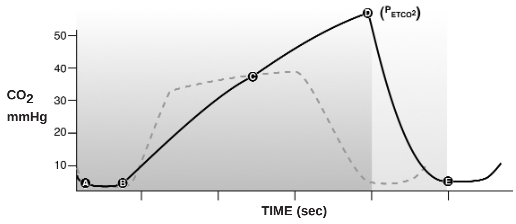

Figure D. Asthma-Severe. Hypoventilation (tiring), increased E_TCO_2 and abnormal waveform, no sharp upstroke from B to C, prolonged expiratory phase, gradual rise from B to C.

Capnograms in Patients with Various Respiratory Diseases

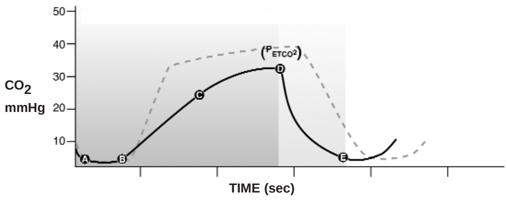

Figure A. Obstructive Airway Disease. A gradual rise from B to D, loss of sharp upstroke (no rapid rise from B to C), a steady gradual increase (from B to D), loss of flat plateau from C to D, (somewhat like a slanted bell-shaped curve)

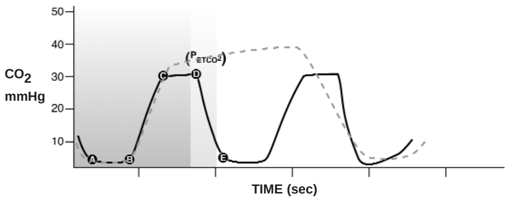

Figure B. Restrictive Airway Disease. Flat plateau (from C to D) is replaced by a gradual increase. A sharp upstroke fro B to C remains but is at a lesser height (from B to C).

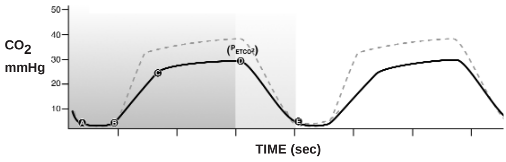

Figure C. Decreased Pulmonary Blood Flow. Decreased height (decreased E_TCO_2) while maintaining the "normal" wave form. Example: pulmonary emboli or cardiac arrest.

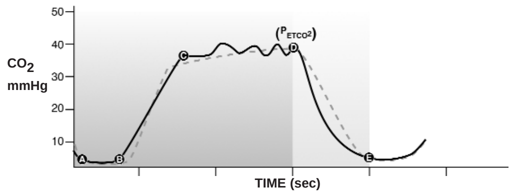

Figure D. Uneven Alveolar Emptying. Oscillations in plateau phase from differences in individual E_TCO_2 from various alveoli.

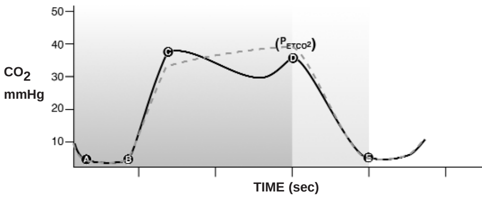

Figure E. Biphasic. Biphasic plateau phase due to markedly different alveoli. Example, single lung transplant.

Figures courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

Normal Capnogram: 4 Phases

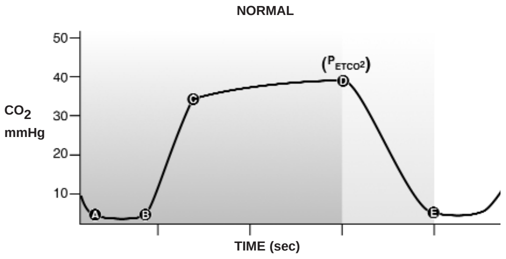

Figure.
Phase 1: A to B = baseline = E_TCO_2 = O = Inspiration and early expiration of anatomic dead space
Phase 2: B to C = rapid upstroke = Initial exhalation of alveolar gas
Phase 3: C to D = Plateau = Continued exhalation of alveolar gas
Phase 4: D to E = Inspiration = Rapid decrease in E_TCO_2
Point D = Maximum E_TCO_2 or PE_TCO_2

Image courtesy of Center for Medical Art & Photography, Cleveland Clinic and Sharon Mace, MD, FACEP, FAAP.

Supplement to *Pediatric Emergency Medicine Reports*, February 2006: "End-tidal CO_2 Monitoring: Noninvasive Respiratory Monitoring for the Child in the ED." *Author:* **Sharon E. Mace, MD, FACEP, FAAP**, Associate Professor, Ohio State University School of Medicine; Faculty, MetroHealth Medical Center/Emergency Medicine Residency; Clinical Director, Observation Unit, Director, Pediatric Education/Quality Improvement, Cleveland Clinic Foundation, Cleveland, Ohio. *Peer Reviewer:* **David Kramer, MD, FACEP, FAAEM,** Program Director, Emergency Medicine Residency, and Vice-Chair, Department of Emergency Medicine, York Hospital, York, Pennsylvania.