End-tidal Carbon Dioxide Monitoring in Pediatric Emergencies

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Abstract: End-tidal carbon dioxide (CO_2) monitoring is useful in the prehospital setting, emergency department, intensive care unit, and operating room. Capnography provides valuable, timely information about the function of both the cardiovascular and respiratory systems. End-tidal CO_2 monitoring is the single most useful method in confirming endotracheal tube position. It also provides information about dead space, cardiac output, and airway resistance. A thorough understanding of cardiopulmonary physiology and the technical nuances of capnometry is required for its optimal use in children.

This review examines the basic physiology pertinent to end-tidal CO_2 monitoring, its clinical applications, and evidence supporting its use in infants and children.

Key Words: emergencies, cardiac arrest, intubation, end-tidal CO_2 monitoring, cardiac

TARGET AUDIENCE

This CME activity is intended for pediatric emergency and pediatric critical care physicians, and pediatric anesthesiologists.

LEARNING OBJECTIVES

After participating in this CME activity, the reader should be able to:

1. List the indications for tidal CO_2 monitoring.
2. Describe the physiological principles that underlie capnometry and capnography.
3. Recall the limitations of end-tidal CO_2 monitoring.

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Capnometry refers to the quantification of carbon dioxide (CO_2) in exhaled breath, whereas capnography refers to the graphic representation of the CO_2 as a function of either breath volume or time. Analysis and monitoring of exhaled CO_2 have been a basic monitoring standard for the care of anesthetized patients for decades, most recently emphasized by the American Society of Anesthesiologists Task Force on Difficult Airway Management.[1] Capnometry is also highly recommended for confirmation of endotracheal intubation in the prehospital environment, emergency department, and intensive care unit.[2] Although the most prominent role for capnometry in acute care medicine is in the prevention of esophageal intubation, this noninvasive monitor also provides real-time physiological data about cardiac output, airway resistance, and minute ventilation. Correct interpretation of its data requires a thorough understanding of cardiopulmonary physiology, as well as an appreciation of the technical nuances and vulnerabilities of capnometry.

Basic Physiology

Carbon dioxide is produced as a result of aerobic metabolism in human tissue. Conditions associated with increased production of carbon dioxide include exercise, fever, sepsis, hyperthyroidism, fractures, trauma, burns, and high carbohydrate intake. Conditions associated with decreased production of CO_2 include sedation, paralysis, hypothyroidism, and hypothermia (without shivering). Carbon dioxide produced in the tissues diffuses into the circulation and is transported to the lungs for elimination.

Carbon dioxide is transported in the circulation in 3 basic forms. Because it is much more soluble in plasma than is oxygen, 5% to 10% is transported as dissolved CO_2. In addition, 5% to 10% of CO_2 binds to the amino groups of hemoglobin producing carbamino compounds. Finally, 80% to 90% of CO_2 is transported as bicarbonate ion after CO_2 and water react in the presence of carbonic anhydrase. The bicarbonate ion is converted to CO_2 at the alveolar level. Oxygenation of hemoglobin in the pulmonary circulation diminishes the affinity of hemoglobin for CO_2, thus increasing CO_2 delivery to the alveolus.

Carbon dioxide is eliminated through ventilation of the lungs. The lungs can be conceptually divided into a segment

that participates in gas exchange with the bloodstream (alveolar ventilation) and a segment that does not (dead space ventilation). Minute ventilation is the sum of alveolar and dead space ventilation. All patients possess some dead space, referred to as the anatomic dead space. The anatomic dead space represents the portion of the airways dedicated to conducting gas movement to the terminal bronchioles and alveoli.

Dead space can also exist in lung segments distal to the anatomic dead space. This dead space is referred to as physiologic dead space. Physiologic dead space results from heterogeneity in the ratio of ventilation to blood flow in different lung units. Alveolar regions that possess little blood flow relative to ventilation are said to have increased physiologic dead space and hence low Pco_2. Alveolar regions that possess little ventilation relative to blood flow are said to possess shunt and high Pco_2. Shunt and dead space are 2 physiological extremes of V/Q matching, and each alveolus in the lung falls somewhere between these extremes.

Physiologic dead space varies with lung pathology, positive end-expiratory pressure, and fluctuations in pulmonary blood flow. Appreciation of the concept of varying quantities of alveolar dead space during pathological states is essential to understand why end-tidal CO_2 sometimes closely mirrors arterial CO_2 concentrations and at other times does not. Any physiological perturbation that increases physiologic dead space (decreased pulmonary blood flow, alveolar distention) causes the arterial to end-tidal CO_2 gradient to increase. In normal subjects, end-tidal CO_2 levels tend to be slightly lower than arterial levels because of the admixture of anatomic dead space gas that is devoid of CO_2.

The Capnogram Waveform

Capnography is a powerful monitoring tool that provides valuable information beyond whether the endotracheal tube (ETT) is in the trachea. Visual examination of the capnogram can allow the clinician to detect certain pathological conditions, while verifying the validity of capnometry results. Capnography can be presented as CO_2 concentration versus time or exhaled volume. The time-based capnogram is most commonly used in anesthesia and critical care practice. Valuable information can be gained from each of these curves. However, the information pertaining to various stages of inspiration and expiration including alveolar and anatomic dead space, airway resistance, and gas trapping may be more relevant in the anesthesia and critical care units rather than in the emergency department.

For instance, low-amplitude CO_2 oscillations might reflect slight airway compression by the beating heart, and small clefts or small spontaneous breaths can also be detected in the capnogram of patients who are emerging from neuromuscular blockade as the diaphragm and larynx begin to recover from neuromuscular blockade before the peripheral skeletal muscles. The capnogram also serves as a useful monitor for several ventilator system malfunctions such as an accidental disconnection of the ventilator circuit from the ETT. In anesthesia breathing circuits (which partially rebreathe expiratory gas after it is scrubbed of CO_2 in soda lime canisters), the presence of inspiratory CO_2 indicates either damaged unidirectional breathing circuit valves or expired soda lime.

The volume-based capnogram is used less commonly in the care of critically ill patients but is of interest because of the amount of information that can be gained from this simple test. This examination is known as the single breath test for CO_2 and can be used to quantify dead space in the lung.[3] If the arterial Pco_2 is obtained from arterial blood gas analysis, and the exhaled tidal volume is measured, it is possible to estimate alveolar and anatomic dead space.

Types of Devices

Most bedside capnometers use infrared absorption to quantify CO_2. Infrared capnometers send a beam of infrared radiation from a light source to a detector. The CO_2 in the sample chamber absorbs some of the radiation allowing for the quantity of CO_2 in the sample to be calculated. Typical double-beam capnometers send out infrared light through a reference cell and sample cell. These capnometers must be calibrated at regular intervals, both with a 5% CO_2 gas mixture, as well as frequent zero calibrations with room air. Infrared capnometers may function as a single monitor or may be incorporated into a bedside monitoring system that incorporates other monitoring modalities. Other methods for measurement of CO_2 include Raman spectroscopy and mass spectrometry. Because of their cost and complexity, mass spectrometers and Raman spectroscopy are used more commonly for operating room applications.

Irrespective of the technology used for measurement, bedside capnometers can be classified into 1 of 2 functional design models. These are mainstream and sidestream capnometers. Flow-through or mainstream analyzers measure the CO_2 passing through an adapter placed directly into the breathing circuit. Infrared light transmission through the gas is measured, and CO_2 concentration is determined. Beneficial aspects of mainstream analyzers include fast response providing real-time data and no sample flow to detract from tidal volume (more important with small tidal volumes used in infants). Disadvantages of mainstream analyzers include the bulkiness and weight of the sensor, which tends to exert traction on the smaller ETTs used in infants. In addition, mainstream analyzers are not amenable to monitoring gas flow in nonintubated patients.

Sidestream capnometers continuously aspirate a small quantity of gas from the breathing circuit into a sample cuvette within the monitor. Because the gas sample is aspirated from the circuit into the monitor, there is a delay of

several seconds in analyzing sample. This technique represents a small but continuous leak from the breathing circuit. High aspiration rates and low–dead space sampling tubing decrease the lag time in detecting changes in end-tidal CO_2. In infants, small tidal volumes and very high aspiration rates may entrain both exhaled gas from the patient and fresh gas from the inspiratory limb, resulting in dilution of the sample and underestimation of the end-tidal CO_2 concentration. Benefits of sidestream analyzers include their lack of bulky sensors on the airway, disposable sample tubing, and adaptability for monitoring of nonintubated patients.

Perhaps the most inexpensive, practical, and convenient devices for prehospital and emergency medicine applications are devices that use colorimetric capnometry. The ability of CO_2 to react with and be quantified by color changes in the presence of compounds such as phenolsulfonphthalein, barium hydroxide, cresol red, or phenolphthalein has been known for many years.[4,5] This has resulted in the commercial availability of disposable capnometers, an example of which is the Easy Cap II (Nellcor Puritan Bennett, Pleasanton, Calif) which is used in our institution. These devices are inexpensive and lightweight and can be readily available in the emergency department, prehospital setting, intensive care unit, and wards.

The Easy Cap II consists of a plastic chamber containing an indicator disc coated with hygroscopic material that reacts with CO_2 to produce hydrogen ions and bring about a color change in the indicator disc. The magnitude of color change is proportional to the CO_2 concentration of the gas. The plastic container chamber attaches to the ETT and the resuscitation bag or ventilator circuit via standard 15- and 22-millimeter connections. The device grades the color change in the chamber with a gold yellow color when the CO_2 concentration is between 2% and 5%, a purple color for a CO_2 concentration of less than 0.5%, and a tan-gray intermediate color for CO_2 concentrations between 0.5% and 2%. These CO_2 detectors have a shelf life of approximately 36 months in the package and can still be used for several hours after being exposed to air. The devices come in adult (>15 kg) and pediatric sizes with chamber dead spaces of 25 to 38 mL for adult devices and less than 10 mL for the pediatric device.

Clinical Applications

The primary role for end-tidal CO_2 monitoring in the emergency department is in the detection and prevention of inadvertent esophageal intubation. Use of end-tidal CO_2 detection devices prevents unrecognized esophageal intubation and allows the treating physician to rapidly and systematically troubleshoot respiratory deterioration in a critically ill infant. Put simply, watchful waiting has no place in the airway management of critically ill children because of their propensity to suffer profound arterial oxygen desaturation.

The end-tidal CO_2 detection device is indispensable in the adult or pediatric patient with the difficult airway. Although in all other patients, it is easy to remove and replace the ETT when doubt exists about location or patency, this may be a dangerous step in patients with known or suspected difficulty with mask ventilation or laryngoscopy. Use of capnometry allows the clinician to avoid removal of a lifesaving airway while tube patency is assessed, endobronchial intubation is ruled out, and intrathoracic pathology and hemodynamic instability are evaluated. Capnography can also be used to monitor cardiac output and minute ventilation and to ensure airway patency during deep sedation.

Confirmation of Endotracheal Intubation

By far, the most valuable use of capnography, or capnometry, is to confirm endotracheal intubation and to detect inadvertent esophageal intubation. ETTs may be placed into the esophagus at the time of attempted endotracheal intubation or may be dislodged during head movement, suctioning, or repositioning of an ETT. The use of CO_2 detection devices to confirm tracheal placement of ETTs has been a basic minimum monitoring standard of the American Society of Anesthesiologists for more than 20 years and was most recently reinforced in the practice guidelines for the management of the difficult airway[1] as well as the emergency airway.[6] The use of CO_2 detection devices has also recently been strongly recommended in the recent edition of the Advanced Cardiac Life Support guidelines of the American Heart Association.[2]

Continuous infrared capnography and disposable colorimetric CO_2 detection devices are both useful for the prevention of esophageal intubation. Disposable colorimetric devices are nonelectronic, light, cheap, and accurate and require no calibration. They are therefore well suited for use in the emergency department, the wards, and the prehospital setting on a moment's notice. They have been repeatedly demonstrated to be highly accurate in differentiating endotracheal from esophageal intubation,[7,8] but they are not infallible and are vulnerable to shortcomings in specific clinical situations.

In the presence of a normal cardiac output, tracheal placement of the ETT will reliably result in colorimetric changes on the colorimetric capnometer that will be yellow to gold indicating a CO_2 concentration of between 2% and 5%. Alternatively, a strong normal-appearing infrared capnogram waveform is highly suggestive of tracheal placement of the ETT. It is prudent to observe the color changes or waveform for 5 to 6 breaths to confirm that the signal does not progressively weaken and disappear. It is possible to initially detect CO_2 after esophageal tube placement if the stomach has been insufflated with expired gas during bag mask ventilation or after the ingestion of carbonated

beverages. This signal, however, will disappear after 5 to 6 breaths as the CO_2 is eliminated from the stomach. ETTs placed in the pharynx or incompletely crossing the vocal cords will also yield a strong signal if there is sufficient gas exchange with the lower airways. Indeed, capnography can appear normal when gas exchange is monitored through a laryngeal mask airway, face mask, or nasal cannula in a spontaneously breathing patient.

Intermediate tan color on a colorimetric detection device indicates a CO_2 concentration between 0.5% and 2% and may indicate either esophageal placement with detection of gastric CO_2 or tracheal placement in the setting of low cardiac output. The clinician confronted with indeterminate findings in the setting of low cardiac output must choose between confirmation of ETT placement using alternative techniques or immediate replacement of the ETT. As a general rule, and especially if the patient is deteriorating, we favor immediate replacement of the ETT if there is a question about tube location.

A purple color on the colorimetric capnometer or an absent infrared capnogram after placement of an ETT indicates an exhaled CO_2 concentration of less than 0.5%. In the setting of a normal cardiac output, this finding indicates esophageal intubation. However, in the absence of pulmonary blood flow such as during a cardiac arrest, there will be no CO_2 delivered to the lungs, and hence, capnometry may produce a false-negative or indeterminate result for tracheal placement until effective cardiopulmonary resuscitation is underway or spontaneous circulation is restored. In this setting, tracheal placement must be verified by alternative clinical methods.

In infants with severely diminished lung compliance, it may not be possible to effectively ventilate the lower airways with an inappropriately small ETT. In this circumstance, the fresh gas from the ventilator or resuscitation bag will be heard to leak audibly from the airway, chest excursions will be small, and a weakly positive CO_2 signal will be noted. Such patients may deteriorate rapidly, and although the ETT is in the trachea, it needs to be replaced with a cuffed or larger uncuffed ETT to provide effective respiratory support. Alternatively, CO_2 may be absent or weakly positive in children with nearly complete tracheal obstruction because of secretions, blood, or a foreign body. In these circumstances, there will be difficulty in ventilation, minimal chest rise, and an audible leak as the inspired gas leaks out through the upper airway. Finally, indeterminate or negative capnographic findings can be noted in infants in whom a disposable adult-sized capnometer is used to confirm endotracheal intubation. The adult-sized Easy Cap II has a detection chamber dead spaces of 25 to 38 mL. Neonates and small infants who are ventilated with tidal volumes of 8 to 10 mL/kg will fail to completely fill the detection chamber. This can result in failure to saturate the indicator paper with expiratory gas and may produce an indeterminate colorimetric change on the indicator.

Alternatives to Capnography for Confirmation of Endotracheal Intubation

Capnometry is the single most useful method in confirming endotracheal intubation. Other alternatives such as direct visualization of the larynx, fiber-optic bronchoscopy, and esophageal detection devices should be considered as secondary methods.

The clinician can perform direct laryngoscopy after endotracheal intubation to demonstrate that the ETT is passing through the vocal cords. However, this confirmatory modality possesses grave pitfalls when airway trauma, swelling, secretions, and obesity can make it difficult or impossible to visualize the airway structures. Flexible fiber-optic bronchoscopy for confirmation of correct ETT location is quick and easy to perform but requires the operator to be familiar with the operation of the instrument and carries the burdens of expense and maintenance. Simpler, commercially available fiber-optic bronchoscopes that are relatively inexpensive, hand-held, and battery-powered and possess disposable fiber-optic catheters (Rapiscope, Cook Critical Care, Bloomington, Ind) are a possible alternative to more costly fiber-optic bronchoscopes for this purpose.[9]

Commercially available esophageal detector devices are in essence bulb syringes that are used to aspirate air from the trachea. If the ETT is in the esophagus, air will not fill freely from the esophagus. This device is vulnerable to the presence of tracheal secretions, which can obstruct bulb filling. These devices are inexpensive, not affected by cardiac output, and portable and do not require calibration or electricity. In addition, they have been shown to be accurate in small children and larger children and are not affected by the insufflation of gastric air or the presence of a nasogastric tube.[10,11]

Chest radiographs and arterial blood gas analyses are not suitable as first-line methods for verification of ETT location. In addition, because of the close proximity of the stomach, esophagus, and chest cavity in children, examinations of breath sounds in the chest and stomach are not foolproof methods for confirmation of ETT location.

End-Tidal CO_2 as a Monitor of Ventilation

Capnography and capnometry as a monitor of ventilation are limited by the fact that it simultaneously monitors the cardiovascular and pulmonary systems and as such is affected by dysfunction in either system. Despite this, capnography can be used as a reliable monitor of ventilation during ongoing resuscitation in the emergency department.

Exhaled CO_2 tension is normally within 2 to 5 mm Hg of arterial samples under normal conditions. A rising end-tidal CO_2 may be caused by increased CO_2 production

(fever, sepsis, seizure, hyperthyroidism, bicarbonate administration, and malignant hyperthermia), increased cardiac output, inadequate alveolar ventilation (inadequate ventilator rate and inadequate tidal volume), or equipment malfunction (kinked or obstructed ETT, rebreathing CO_2 because of unidirectional valve malfunction, and exhausted CO_2 absorber). A low or decreasing end-tidal CO_2 level can reflect decreased CO_2 production (hypothermia, sedation, and paralysis), decreased blood flow to the lungs (cardiac arrest, pulmonary embolism, exsanguination, hypovolemia, and myocardial failure), excessive alveolar ventilation (excessive rate or tidal volume and improving lung function), or equipment malfunction (ventilator disconnection, esophageal tube displacement, complete airway obstruction by secretions, partial or complete obstruction of sidestream sampling tubing, and very large leak around the ETT).

Assessment of the gradient between arterial and end-tidal CO_2 provides important physiological information in critically ill children. The clinician should remember that elevated end-tidal CO_2 values almost always indicate the presence of elevated arterial CO_2 levels. Conversely, decreased end-tidal CO_2 levels may be present when arterial levels are high, low, or normal. A widening gradient between arterial and end-tidal levels is physiologically indicative of increased pulmonary dead space or decreased cardiac output. The clinical decision to rely upon capnography as a monitor of adequacy of ventilation can only be made after assessment of the degree of cardiovascular and respiratory dysfunction in a given patient.

End-Tidal CO_2 as a Monitor of Cardiac Output

Capnography and capnometry can be a very useful monitor of cardiac output in appropriate patients at risk for hemodynamic instability. In patients with fixed minute ventilation and stable ventilation/perfusion relationships within the lung, end-tidal CO_2 levels will be proportional to cardiac output. In its extreme form, when cardiac output drops to zero, end-tidal CO_2 will be zero. Monitoring end-tidal CO_2 provides rapid real-time information because it is affected as soon as hemodynamic perturbation is present, and the magnitude of the decrease in end-tidal CO_2 is proportional to the magnitude of the hemodynamic derangement. Unfortunately, as previously discussed, its value as a pure monitor of cardiac output is diminished when lung pathology coexists.

The ability of the capnograph to rapidly mirror changes in hemodynamics when respiratory mechanics are stable has caused clinicians to follow capnometric trends during resuscitation. Numerous animal studies have demonstrated correlation between the level of end-tidal CO_2 and the coronary perfusion pressure and cardiac output, and they demonstrated a marked increase in end-tidal CO_2 with return of spontaneous circulation.[12,13] Human studies have confirmed in nontraumatic cardiac arrest that end-tidal CO_2 increases markedly with return of spontaneous circulation,[14] and have attempted to correlate resuscitation end-tidal CO_2 values with the probability of return of spontaneous circulation.[15,16]

End-Tidal CO_2 Monitoring in Conscious Sedation

In pediatrics, capnography also has a very practical application in the promotion of safe and effective sedation. Sedation for diagnostic and therapeutic procedures can result in a continuum from mild (conscious) sedation to general anesthesia. It is not at all uncommon to develop upper airway obstruction (ranging from partial to complete) during sedative administration. After inserting an intravenous catheter through 1 of the nasal prongs of a nasal cannula, the catheter is trimmed to the length of the nasal prong (Fig. 1). A sidestream analyzer is then attached to the catheter after it is securely taped into the cannula. A patent airway can be

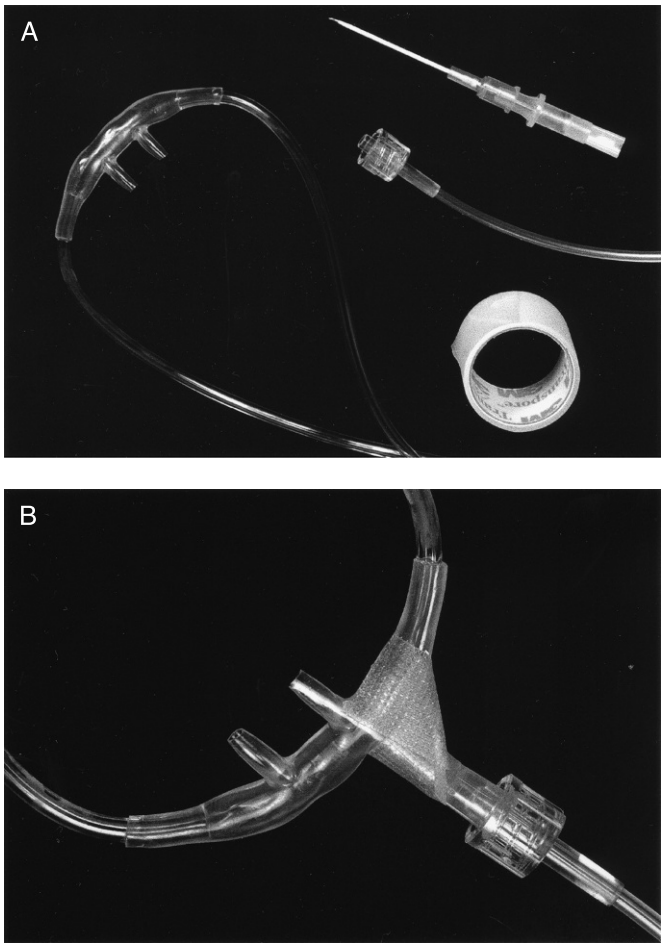

FIGURE 1. Capnography can be easily performed after adaptation of a standard nasal cannula with an intravenous catheter. A, This figure shows the attachment of the intravenous catheter to 1 of the nasal prongs. B, The catheter hub is then connected to tubing of a sidestream analyzer.

monitored continuously and allows for intervention before severe hypercarbia or hypoxemia can develop. The efficacy of this monitor can be decreased with high oxygen flow rates, which tend to flush the exhaled gas away from the sampling orifice.

CONCLUSIONS

Capnography is a noninvasive and accurate means to avoid unrecognized esophageal intubation and can be used in appropriate clinical circumstances to monitor cardiac output and minute ventilation and to facilitate deep sedation. Because it is a simultaneous monitor of pulmonary and cardiovascular systems, it is prone to the effect of confounding influences from both systems. With an understanding of physiological principles and the inherent limitations of this monitor, capnography can be a very effective adjunct in the care of children with acute cardiorespiratory disease.

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CME EXAM

Instructions for the *Pediatric Emergency Care* CME Program Examination

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CME EXAMINATION
May 2005

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End-tidal Carbon Dioxide Monitoring in Pediatric Emergencies, *Sullivan et al*

1. The differential diagnoses of absent end-tidal CO_2 at the time of intubation include all of the following EXCEPT:
   a) Esophageal tube placement.
   b) Inadequate pulmonary blood flow.
   c) Inadequate or absent cardiac output.
   d) Pulmonary contusion.
2. A widening gradient between arterial and end-tidal CO_2 is indicative of all of the following EXCEPT:
   a) Exsanguination.
   b) Increased physiological or alveolar dead space.
   c) Decreased cardiac output.
   d) Carbon monoxide poisoning.
3. Benefits of end-tidal CO_2 monitoring in critically ill patients include all of the following EXCEPT:
   a) Early detection of mucous plugging of endotracheal tube.
   b) Early detection of alveolar hypoventilation in the pressure control mode of ventilation.
   c) Visual detection of air trapping due to reactive airway disease.
   d) Detection of inappropriate size of the endotracheal tube.
4. Reasons for false-positive capnographic confirmation (tube in esophagus, capnography indicates tracheal placement) of endotracheal tube placement include all of the following EXCEPT:
   a) Carbonated beverages in the stomach.
   b) Endotracheal tube in pharynx but exchanging gas.
   c) Esophageal intubation after prolonged and difficult bag mask ventilation.
   d) Decreased intrapulmonary shunt with intact cardiac output.
5. Reasons for false-negative capnographic confirmation (tube in trachea, capnography indicates esophageal placement) of endotracheal tube placement include all of the following EXCEPT:
   a) Absent cardiac output.
   b) Massive pulmonary embolism.
   c) Markedly decreased dead space within the lung.
   d) Increased intrapulmonary shunt with intact cardiac output.

ANSWER SHEET FOR THE *PEDIATRIC EMERGENCY CARE* CME PROGRAM EXAM

May 2005

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4. Ⓐ Ⓑ Ⓒ Ⓓ Ⓔ
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   [ ] Yes [ ] No

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CME EXAM ANSWERS

Answers for the Pediatric Emergency Care CME Program Exam

Below you will find the answers to the examination covering the review article in the February 2005 issue. All participants whose examinations were received by April 15, 2005 and who achieved a score of 80% or greater will receive a certificate from Wolters Kluwer Health.

EXAM ANSWERS

February 2005

1. D
2. B
3. D
4. C
5. C