Capnography Outside the Operating Rooms

Bhavani Shankar Kodali, M.D.*

HISTORICALLY, anesthesiologists seem to be the forerunners in implementing tools and standards for safety in the medical fraternity. In the United States, since 1985, there has been a dramatic decrease in the malpractice insurance premiums of anesthesiologists. Such a decrease has not been seen in other medical or surgical specialties over this time frame. Thanks to the foresight of the American Society of Anesthesiologists (ASA), Anesthesia Patient Safety Foundation (APSF), Association of Anaesthetists of Great Britain and Ireland (AAGBI), and the Association of Anesthesiologists in Holland, capnography was embraced and incorporated into the standards of monitoring during anesthesia to enhance patient safety. Currently, anesthesiologists in many developing countries follow these recommendations (India, Government of Andhra Pradesh Order, AST/775/F25/dated September 2011. Capnography is mandatory for laparoscopic surgeries for reimbursement). Although capnography has become an integral part of anesthesia care in operating rooms for more than 25 yr, its value has been limited to these situations and is not well appreciated beyond these confinements. It is not uncommon in our practice to observe an intubated and ventilated patient, originally monitored with capnography in the operating room, but then transported to the intensive care unit (ICU) without capnography. It is even more surprising that many ICUs do not have capnography either to confirm endotracheal intubation or to continually monitor ventilation. As anesthesiologists, we use capnography to monitor sedation in the operating room because we appreciate that the line between consciousness and unconsciousness is very thin, and the patient can drift from one state to another. However, in many institutions, capnography is not used to monitor ventilation during sedation for procedures performed particularly by nonanesthesiologists outside of the operating rooms. One of the obvious reasons seems to be a lack of a single society overseeing the safety of outside-the-operating-room procedures the way ASA and AAGBI do in the operating room. Nonetheless, in the last 2 yr there has been a surge in understanding and recognizing the value of capnography outside of the operating rooms.[1,2] This "Clinical Concepts and Commentary" will summarize physiology and clinical interpretation of capnography and update the current status of capnography outside of the operating rooms, including public and media awareness, and suggest probable future directions.

Measurement and Physiology

Infrared technology is by far the most common and cost-effective method of carbon dioxide measurement and monitoring. Efforts have been made to decrease the response time and increase the accuracy of infrared technology to produce superior capnography waveforms even in premature babies with small tidal volumes and rapid respiratory rates.[3] The carbon dioxide values are usually displayed as partial pressure (P_{CO_2}). Depending on the location of the carbon dioxide measuring device, there are two sensor types: mainstream and sidestream. In mainstream sensors, the adaptor housing the sensor is interposed between the tracheal tube and breathing circuit, and the measurement of carbon dioxide is made across the airway. In sidestream technology, the respiratory gases are aspirated *via* an adaptor and a 6-foot sampling tube to the monitor housing the infrared sensor. The transport of gases to the infrared measuring device results in a delay of 1–4 s in carbon dioxide measurement and display of capnograms in sidestream capnography.

A conventional capnogram in adults results in a more or less identical shape in all healthy individuals. Any variation from this requires an analysis to determine a physiologic or pathologic cause of the variation. Carbon dioxide waveforms can be plotted against time (time capnogram, fig. 1A) or expired volume (volumetric capnogram, fig. 1B). Time capnography is used more commonly in clinical practice.

* Associate Professor, Department of Anesthesiology, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts.

A time capnogram has two important segments: inspiratory (phase 0) and expiratory.[4–6] The expiratory segment is further divided into three phases (I, II, III), and an occasional phase IV (fig. 1C), based on the physiology of carbon dioxide evolution from the lungs and airways. Phase I does not contain any expired carbon dioxide (dead space gases, zero P_{CO_2}). In phase II, the P_{CO_2} rises rapidly as carbon dioxide–laden alveolar gas replaces zero-carbon dioxide dead space gas. Phase III is the alveolar plateau that represents the evolution of carbon dioxide from alveoli. If all the alveoli had the same P_{CO_2}, the alveolar plateau would be perfectly flat. In reality, there is a considerable spatial and temporal mismatch in the lungs resulting in variable V/Q ratios and thus, variable P_{CO_2}. Usually the alveoli with lower V/Q ratios and with longer time constants (containing relatively more carbon dioxide) contribute to the later part of phase III. This results in a slight upward slope of the alveolar partial pressure "plateau." Therefore, the slope indirectly represents the V/Q status of the lungs. Hence, the height and slope of the alveolar plateau provide valuable information about ventilation, perfusion, and, more importantly, the V/Q relationship. When there is substantial variation in the V/Q ratio as a result of airway caliber changes, the slope of phase III is exaggerated and can also be associated with a prolonged phase II (fig. 2A). Under these circumstances, the angle between phase II and phase III (the α angle), which is generally 100°, is increased. The therapeutic effect of bronchodilators can be judged by the changes in phase II, phase III, and the α angle. The height of the alveolar plateau is related to the ratio of cardiac output to alveolar ventilation. For a given ventilation, the alveolar plateau height increases or decreases with abrupt changes in cardiac output.[7,8] The maximum P_{CO_2} at the end expiration is displayed as a numerical value, called the end-tidal P_{CO_2} (P_{ETCO_2}). The values vary between 35 and 40 mmHg. At the end of phase III, the P_{CO_2} decreases rapidly to zero when carbon dioxide–free gas is inhaled during inspiration. The angle between phase III and the inspiratory downstroke is generally 90° (the β angle) (fig. 1 A). However, this angle increases in the presence of rebreathing (fig. 2, B and C). Occasionally, at the end of phase III, there may be a terminal upward blip (fig. 1C), which is generally seen in the capnograms of children, pregnant, or obese patients (phase IV).[5,9,10] The rapid initial emptying of alveolar gas compartments containing rather constant carbon dioxide concentrations is responsible for the near-horizontal initial part of phase III in the carbon dioxide trace. However, as the expiratory flow decreases toward the end of expiration, the carbon dioxide content of the expired air increases markedly and thus produces a terminal steep rise or upward blip in the carbon dioxide tracing. This is because, in the latter part of expiration, the delayed alveolar emptying results in higher carbon dioxide concentrations due to the continuous release of carbon dioxide into the alveoli. Normally, the alveolar gases with high carbon dioxide remain within the airways and are not analyzed by the carbon dioxide sensor near the mouth. However, the use of a large tidal volume and low-frequency ventilation enables these gases to reach the carbon dioxide sensor that registers a high carbon dioxide concentration.
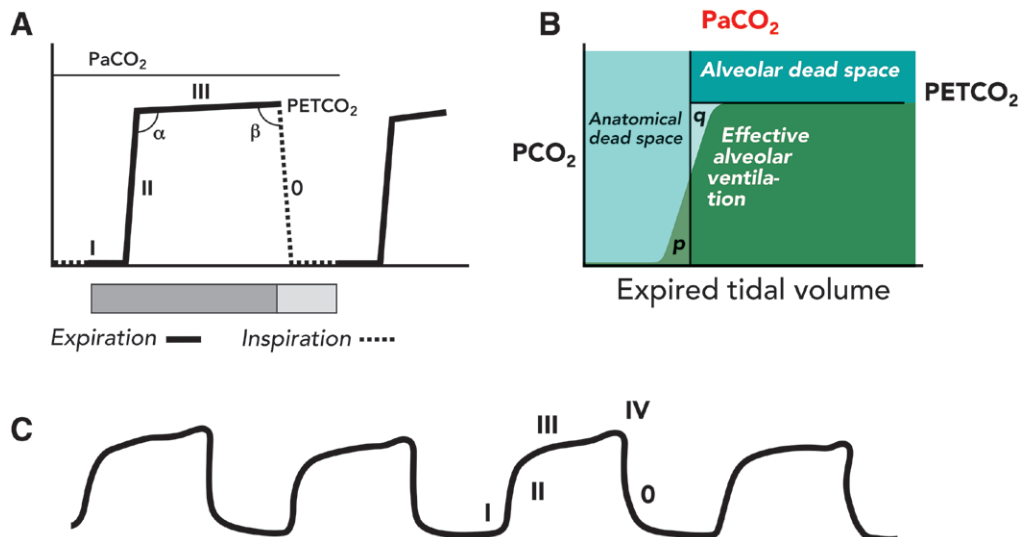
Fig. 1. *A*, Time capnogram showing segments, phases and angles. Inspiratory segment is phase 0, and expiratory segment is divided into three phases: I, II, and III. Maximum value of carbon dioxide at the end of the breath is designated as P_{ETCO_2}. It is lower than P_{aCO_2} by about 5 mmHg because of alveolar dead space. The angle between phase II and phase III is α angle, and between phase III and inspiratory downstroke is β angle. *B*, Volume capnogram (P_{CO_2} *vs.* expired volume): Volume capnogram showing subdivisions of tidal volume. Area under the carbon dioxide curve is effective alveolar ventilation. Area above the carbon dioxide curve and below the arterial P_{aCO_2} line indicates physiological dead space. A *vertical line* is drawn across phase II such that the two *triangles* p and q are equal in area. This divides physiologic dead space into anatomic and alveolar dead space. *C*, A time capnogram recorded during cesarean delivery general anesthesia showing phase IV (For details of phase IV, refer to reference 4). P_{ETCO_2} = end-tidal P_{CO_2}.
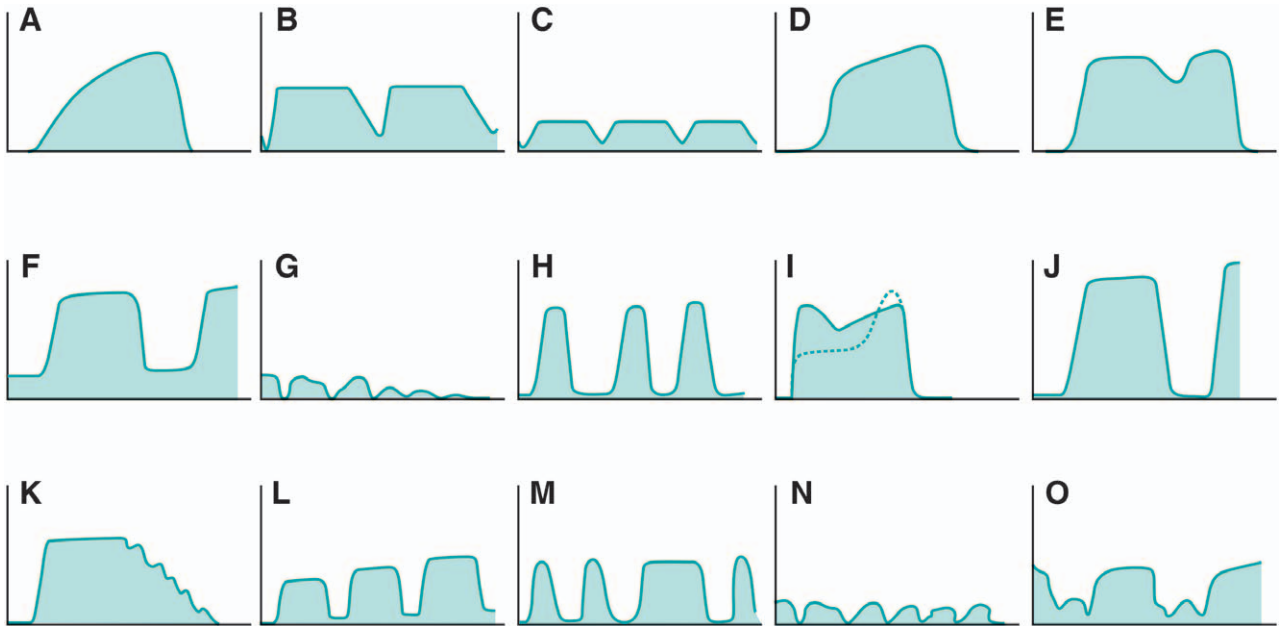
Fig. 2. *A,* Prolonged phase II, increased α angle, and steeper phase III suggest bronchospasm or airway obstruction. *B,* Expiratory valve malfunction resulting in elevation of the baseline, and the angle between the alveolar plateau and the downstroke of inspiration is increased from 90°. This is due to rebreathing of expiratory gases from the expiratory limb during inspiration. *C,* Inspiratory valve malfunction resulting in rebreathing of expired gases from inspiratory limb during inspiration (reference 5 for details). *D,* Capnogram with normal phase II but with increased slope of phase III. This capnogram is observed in pregnant subjects under general anesthesia (normal physiologic variant and details in reference 9). *E,* Curare cleft: Patient is attempting to breathe during partial muscle paralysis. Surgical movements on the chest and abdomen can also result in the curare cleft. *F,* Baseline is elevated as a result of carbon dioxide rebreathing. *G,* Esophageal intubation resulting in the gastric washout of residual carbon dioxide and subsequent carbon dioxide will be zero. *H,* Spontaneously breathing carbon dioxide waveforms where phase III is not well delineated. *I,* Dual capnogram in one lung transplantation patient. The first peak in phase III is from the transplanted normal lung, whereas the second peak is from the native disease lung. A variation of dual capnogram (steeple sign capnogram – dotted line) is seen if there is a leak around the sidestream sensor port at the monitor. This is because of the dilution of expired P_{CO_2} with atmospheric air. *J,* Malignant hyperpyrexia where carbon dioxide is raising gradually with zero baseline suggesting increased carbon dioxide production with carbon dioxide absorption by the soda lime. *K,* Classic ripple effect during the expiratory pause showing cardiogenic oscillations. These occur as a result of to-and-for movement of expired gases at the sensor due to motion of the heartbeat during expiratory pause when respiratory frequency of mechanical ventilation is low. Ripple effect like wave forms also occur when forward flow of fresh gases from a source during expiratory pause intermingles with expiratory gases at the sensor. *L,* Sudden raise of baseline and the end-tidal P_{CO_2} ($PETCO_2$) due to contamination of the sensor with secretions or water vapor. Gradual rise of baseline and $PETCO_2$ occurs when soda lime is exhausted. *M,* Intermittent mechanical ventilation (IMV) breaths in the midst of spontaneously breathing patient. A comparison of the height of spontaneous breaths compared to the mechanical breaths is useful to assess spontaneous ventilation during weaning process. *N,* Cardiopulmonary resuscitation: capnogram showing positive waveforms during each compression suggesting effective cardiac compression generating pulmonary blood. *O,* Capnogram showing rebreathing during inspiration. This is normal in rebreathing circuits such as Mapleson D or Bain circuit.

Pregnant subjects who normally have a reduced functional residual capacity, a low total thoracic compliance, and an increased carbon dioxide production are likely to exhibit phase IV in the capnograms during general anesthesia and intermittent positive pressure ventilation using large tidal volumes.[5]

Because the P_{CO_2} is plotted against expired volume in a volume capnogram, the waveform can be related to various components of tidal volume (fig. 1B). However, there is no inspiratory component in this curve. In both the time capnogram and the volume capnogram, $Paco_2$ to $PETCO_2$ difference can be used as a surrogate of physiologic dead space (fig. 1B). The normal $Paco_2$-$PETCO_2$ gradient is about 5 mmHg. This is due to the mixing of alveolar gases containing carbon dioxide with dead space gases containing no carbon dioxide. The understanding of the above physiology is vital to the interpretation of capnography.

Clinical Interpretation of Capnography

Clinical information can be obtained from three sources in capnography: numerical value of $PETCO_2$, shape of the capnograms, and the difference between $PETCO_2$ and $Paco_2$.

Numerical values should be used as a tool in the differential diagnosis (table 1). On the other hand, the shapes of the capnograms offer more specific diagnostic clues (fig. 2A–O). It is difficult to use capnography as a diagnostic tool by itself. However, if the changes in P_{ETCO_2} values or variations in the carbon dioxide waveforms are used in conjunction with accompanying data, such as heart rate, blood pressure, respiratory flow, pulmonary inflation pressures, and minute volumes, the diagnostic accuracy of capnography can be enhanced. Tautz *et al.*[11] described a case report where there was a gradual increase in P_{ETCO_2} values during anesthesia in a 55-yr-old man. This was later associated with increasing heart rate and body temperature. A systematic and methodical check of the patient's hemodynamic and respiratory variables and the anesthesia machine did not reveal any defect in the anesthetic system or airway obstruction. The P_{ETCO_2} values continued to increase to 65 mmHg, despite minute ventilation of 18 l/min. A diagnosis of malignant hyperpyrexia was made. Treatment for malignant hyperpyrexia was initiated, and rapid resolution of hypercarbia and hyperthermia was achieved.

Table 1. Various Conditions that Should Be Considered in the Differential Diagnosis of Either Increasing or Decreasing P_{ETCO_2} Values

Causes of Abnormal P_{ETCO_2}	Increase in P_{ETCO_2}	Decrease in P_{ETCO_2}
Metabolic	Recovery from anesthesia (shivering)	Hypothermia
	Malignant hyperthermia	
	Neuroleptic malignant syndrome	Metabolic acidosis
	Thyroid storm	
	Severe sepsis	
Circulatory	Tourniquet release	Induction of anesthesia
		Pulmonary embolism
	Carbon dioxide insufflation - Laparoscopy	Profound hypovolemia
	Treatment of acidosis	Cardiogenic shock
		Hemorrhagic shock
		Intracardiac shunt
Respiratory	Hypoventilation	Pulmonary edema
	COPD	Intrapulmonary shunt
	Asthma	Hyperventilation
Technical	Exhausted carbon dioxide absorber	Disconnection
	Contamination of the monitor	Blockage in tubing

COPD = chronic obstructive pulmonary disease; P_{ETCO_2} = partial pressure of end-tidal carbon dioxide.

The P_{ACO_2}-P_{ETCO_2} gradient, a surrogate of physiologic dead space, is valuable in assessing the V/Q relationship. A changing gradient denotes unstable circulatory hemodynamics or variable alveolar ventilation as a result of dynamic changes in compliance or resistance in the lungs. If the gradient stabilizes over the course of clinical management, it can be surmised that stability of alveolar ventilation and perfusion has been achieved. This valuable utility of capnography is underused in ICU settings.

Current Status of Capnography Outside of the Operating Rooms

In the last 2 yr, the ASA (New standards of Basic Anesthesia Monitoring, effective July 2011), AAGBI (Updated statement from AAGBI, May 2011), and American Heart Association (2010) have revised and updated their recommendations on the use of capnography outside of the operating room locations. Recent studies have also highlighted the morbidity and mortality related to the underuse of capnography in ICUs.[1,12] In addition, public interest has been generated with FOX News and National Public Radio publicizing the role of capnography in cardiopulmonary resuscitation (CPR).

Capnography for Procedural Sedation

With advances in interventional radiology, electrophysiology, and cardiac catheterization, there has been a substantial growth in the number of sedation-requiring procedures being performed outside of the operating rooms. For many of these procedures, sedation is provided by nurses under the supervision of the physician performing the surgical, radiologic, or endoscopic procedure. It is well known that hypoxia occurs in these procedural sedation cases. When midazolam and ketamine were used for 77 emergency room procedures, 6% had apnea that required positive pressure ventilation and 75% had hypoxia (oxygen saturation <90%) at some point during the procedure.[13] Analysis of Procedural Sedation in the Community Emergency Department (ProSCED) data results of procedures performed in emergency rooms in community hospitals (1,000 patients in 14 hospitals) revealed an overall complication rate of 4.1%, with 1.1% of patients requiring assisted ventilation.[14] In a study of endoscopic retrograde pancreaticocholangiography procedures where 96% of patients (3,058/3,179) received sedation supervised by gastroenterologists, the overall mortality was 0.06%. Midazolam, promethazine, and meperidine were used for sedation in these cases. One hundred twenty-four patients required reversal agents for respiratory depression and somnolence.[15] This subgroup was associated with morbidity and mortality (6% and 1.6% respectively). Replacing some of the drugs used in the above study with propofol has not eliminated the risk of hypoxia.[16] It is ironic that more stringent standards of monitoring are not enforced when sedation is administered by nonanesthesiologists, some of whom may not be as adept

as anesthesiologists in securing and maintaining ventilation. Furthermore, many procedure sites are located far from main operating room personnel who often provide rescue help. Therefore, it is necessary that monitoring standards for procedural cases performed outside of the operating rooms be reevaluated. The ASA and AAGBI have issued revised standards in 2011 to monitor ventilation by capnography to enhance safety of patients undergoing sedation, irrespective of the location of procedural sedation. The recommendation of continual monitoring of ventilation by capnography during moderate-to-deep sedation is based on the fact that it is difficult to predict how an individual patient will respond to an administered sedative. In a randomized controlled trial in patients undergoing propofol sedation in the emergency room, one group of treating physicians had access to capnography and the other group did not. Hypoxia was defined as an oxygen saturation less than 93% for 15 s or greater, and respiratory depression was defined as a P_{ETCO_2} of 50 mmHg or greater, an absolute increase or decrease from baseline of 10% or greater in P_{ETCO_2} values, or a loss of carbon dioxide waveform for 15 s or greater. Hypoxia was observed in 25% of subjects with capnography and 42% with blinded capnography ($P = 0.035$). Another interesting observation of significance in this study was that changes in capnography forewarned of respiratory depression in all cases of hypoxia (sensitivity 100%, specificity 64%). The median time from capnographic evidence of respiratory depression to hypoxia was about 60 s (range 5–240 s).[17] A recent meta-analysis reviewed studies involving adverse respiratory events during procedural sedation, and whether or not capnography was used in these cases. In the cases where capnography was not used, pulse oximetry and visual inspection of chest rise was the standard for monitoring patients receiving sedation. The results showed that respiratory depression was approximately 17 times more likely to be detected in procedural sedation cases when capnography was used in combination with pulse oximetry and visual inspection of chest rise compared to the group without capnography.[18] Furthermore, a recently published study demonstrated that hypoxia occurs even in the most routine gastrointestinal endoscopy procedures.

Capnography triggers early intervention and decreases the incidence of oxygen desaturation during colonoscopy performed under propofol sedation (capnography-open arm) compared to a group where capnography was blinded (capnography-blinded arm).[19] Furthermore, the positive effect of capnography was even more pronounced when comparing the incidence rates of severe hypoxemia (oxygen saturation <85%). The incidence of these events was decreased by more than half in the capnography group when compared with the group using standard monitoring only. These studies demonstrate the importance and utility of capnography during procedural sedation. It must be emphasized, however, that there may be dilution of expiratory gases with oxygen or air resulting in lower than normal end-tidal carbon dioxide values. What is important under these circumstances is the detection of changes from the baseline P_{ETCO_2} value, changes in waveform shape, or changes in respiratory rate. Each change should alert the sedation provider to closely monitor the patient for airway obstruction or respiratory depression (fig. 3). If respiratory efforts are present on visual inspection, simple maneuvers, such as jaw thrust, can overcome the partial airway obstruction as a result of excessive sedation and increase the P_{ETCO_2} values.

The recommendations of ASA and AAGBI predominantly apply to ASA and AAGBI members only and are not yet universally accepted (American Society of Gastroenterologists Document 2012). This discrepancy is often the key topic of discussion during internal institutional meetings contemplating introducing capnography for sedation procedures outside the operating room. The responsibility is on anesthesiologists to convince the group members of the institution that capnography is a vital tool for ensuring patient safety. American Society of Gastroenterologists are not in agreement with ASA or AAGBI standards that capnography should be used in all cases of moderate sedation. In a statement issued this year, they state that sedation-related mortality in gastrointestinal endoscopy is approximately 8/100,000, which they consider to be extraordinarily safe. Presently the anesthesia-related mortality is 8.2 per million hospital surgical discharges.[20] This
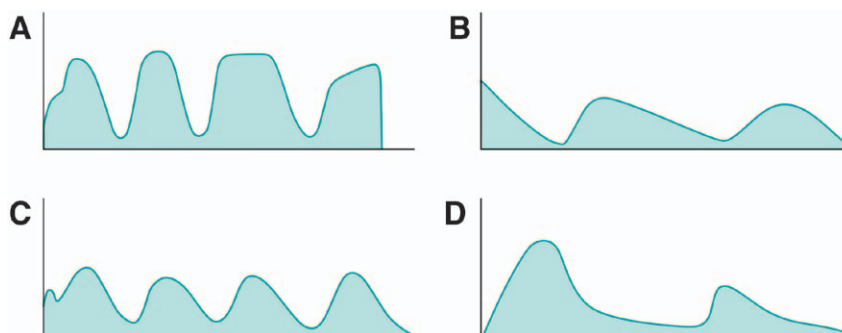
Fig. 3. Capnograms after sedation: The height is decreased in (*B*) compared to (*A*), and respiratory rate is decreased in (*D*) compared to (*C*). It is important to recognize changes in capnograms during sedation compared to presedation capnograms. The shape of presedation capnograms depends on the dilution of expired P_{CO_2} by oxygen or air.

implies that a patient is 10 times more likely to die during a gastroenterology procedure performed with sedation than as a result of general anesthesia. Capnography use combined with pulse oximetry was introduced by ASA not based on a randomized trial showing that these novel devices of mid-80s decreased mortality, but on a logical conclusion that capnography together with pulse oximetry could have prevented 93% of anesthesia mishaps that contributed to anesthetic morbidity and mortality. Despite the absence of prospective randomized controlled studies showing the direct benefit of pulse oximetry and capnography on mortality, we have seen the potential benefits of those decisions in decreasing anesthetic mortality from 1 in 10,000 to 1 in 100,000 anesthetics. Gastroenterology procedures are not as benign as portrayed. ASA Closed Claims Database Analysis reveals that 24% of claims were endoscopy related, and capnography could have prevented some of them.[21] The American Society of Gastroenterologists document agreed with the utility of capnography in endoscopic retrograde pancreaticocholangiography and endoscopic ultrasound procedures requiring sedation, but vehemently disagreed in the use of capnography for routine endoscopy procedures. However, a recent study demonstrated and emphasized that capnography decreased the incidence of hypoxia by more than 50% during a routine colonoscopy.[19] Studies of these kinds will change the perception of gastroenterologists and other physicians in recognizing the value of capnography in the near future.

In the meantime, how do we approach the discussion about introducing capnography for sedation outside of operating rooms? The seven pronged argument shall be: (1) the most common damaging events in the Closed Claims overall database (22%) are respiratory events; (2) hypoxic episodes are more likely to occur without capnography than with capnography, and capnography facilitates the detection of events that are likely to lead to hypoxia without intervention; (3) occurrence of hypoxia is not limited to endoscopic retrograde pancreaticocholangiography and endoscopic ultrasound procedures but also occurs during routine procedures such as colonoscopy; (4) the physician performing the procedure should be prudent enough not to have his or her patient in the hypoxic zones while performing the procedure; (5) using capnography routinely and gaining experience with the use and interpretation of capnograms will enable sedation providers to interpret capnograms more precisely during difficult cases; (6) anecdotal case reports of death as a result of procedural sedation have been publicized in tragic dental cases and also during gastroenterology procedures; and (7) last, because the current guidelines by the Center for Medicare and Medicaid Services require the anesthesiology department to oversee procedural sedation in an institution, it is prudent to follow ASA standards and monitor ventilation with capnography.

Keeping in view of the current recommendations of the ASA, guidelines issued by the Center of Medicare and Medicaid, and to have consistency in sedation practice all across the institution, our establishment has decided to monitor ventilation with capnography in all patients requiring moderate sedation irrespective of the location, beginning October 2012. Necessary education and training of personnel are currently in progress.

Capnography in Cardiopulmonary Resuscitation

The revised guidelines of Advanced Cardiac Life Support (ACLS) 2010 recommend the use of quantitative waveform capnography not only for confirmation of tracheal tube placement but also to monitor the effectiveness of chest compressions. For given ventilation in acute settings, P_{ETCO_2} serves an indirect monitor of cardiac output generated by chest compressions. The return of spontaneous circulation is sometimes difficult to assess with other methods, but it is clearly demonstrated on the capnography measurements by an abrupt increase in the P_{ETCO_2} value. Continuous waveform capnography also provides immediate detection of tube displacement, much earlier than pulse oximetry. The role of capnography in directing effective CPR has been known for many years.[7,22] However, the recognition and implementation of this concept into ACLS guidelines have taken about 20 yr. Input from several organizations, data collection and analysis, and equipment availability might be a few factors that may have contributed to this delay. Nonetheless, capnography has now been adapted into ACLS guidelines and will take a few more years to implement into routine use, given the constraints of training and the availability of equipment. Based on the findings of the National Audit Project in United Kingdom, AAGBI also endorsed the use of capnography in all patients undergoing advanced life support.[1] It was duly recognized by AAGBI that capnography is not yet a standard on resuscitation carts, but they advised that efforts should be made to make one available promptly for advance life support.

During CPR, the capnography tracing should not be flat but should have positive waveform trace (fig. 2N). A flat capnography trace during CPR should alert the life support group leader of a misplaced tracheal tube. Although a recent retrospective observational study demonstrated that patients who gained return of spontaneous circulation (ROSC) had significantly higher P_{ETCO_2} values compared to those who did not have ROSC, it is difficult to ascertain the prognostic value of attained P_{ETCO_2} values during CPR.[23,24] This is because the values of P_{ETCO_2} during CPR are dependent not only on the effectiveness of CPR but also on the primary cause of cardiac arrest, such as cardiac, respiratory, or pulmonary embolism. Despite these uncertainties, there is evidence that P_{ETCO_2} during CPR can be used as a predictor for survival. Levine *et al.* performed a prospective observational study in 150 consecutive victims of cardiac arrest outside of the hospital. Patients were intubated, and P_{ETCO_2} values were obtained during resuscitation. They

found that a PETCO$_2$ value of less than 10 mmHg or less measured 20 min after the initiation of ACLS accurately predicted death in patients with cardiac arrest.[25] Recently, mathematical models are also being created to determine the prognostic value of "time *versus* PETCO$_2$ values" after the initiation of CPR.[26] Peak PETCO$_2$ values in patients with and without ROSC differed significantly at 8 and 10 min after intubation, but not at 4 or 5 min. Patients without ROSC had significantly smaller (4 and 10 min) areas under the PETCO$_2$ curve than those with ROSC. The cumulative max end-tidal carbon dioxide greater than 20 mmHg at all time points between 5 and 10 min was the variable most likely to predict ROSC (sensitivity = 88%, specificity = 77%, <0.001). The authors of this study claim that using those models, the successful outcome of resuscitation can be predicted in less than 10 min in 70% of the cases after the initiation of CPR. There is a considerable interest presently to use PETCO$_2$ values during CPR to determine the initiation of extra corporeal life support. The French guidelines for the initiation of extra corporeal life support in patients with refractory cardiac arrest include PETCO$_2$ values equal to or greater than 10 mmHg during CPR as one of the preconditions.[27] With the current recommendation of using capnography for ACLS, substantial robust data will be generated in the future to determine the value of PETCO$_2$ attained during CPR to predict neurologic outcome. Until such outcome studies are published, capnography should be used to assess effectiveness of CPR. A declining PETCO$_2$ value during CPR may suggest rescuer fatigue or ineffective chest compressions by the rescuer. It should also alert the team leader to seek other factors contributing to declining cardiac output generated during CPR, such as hemorrhage, tamponade, pneumothorax, *etc*.

A 2011 publicized case report illustrated the hypothetical value of capnography during CPR in a 54-yr-old man who sustained cardiac arrest and collapsed in a grocery store.[28] Capnography assured that effective CPR was being performed and the resuscitation team continued with resuscitation efforts for 96 min when sustained spontaneous heartbeat and circulation were finally restored. Throughout the resuscitation, end-tidal carbon dioxide was consistently in the 28–36 mmHg range during ventricular fibrillation/CPR. These levels of carbon dioxide were consistent with effective chest compression generating reasonable pulmonary blood flow justifying continuation of resuscitation. When the twelfth shock restored ventricular fibrillation to an organized rhythm, there was no palpable pulse, but a PETCO$_2$ of 37 mmHg suggested that spontaneous circulation had resumed and CPR was terminated. The patient underwent coronary stent placement and was discharged on the tenth day with no neurologic or cognitive deficit. FOX News and National Public Radio reported this story explaining in lay terms to the public about capnography and its value during CPR.

Based on the current guidelines of ACLS and AAGBI, we have mounted a capnography unit on our movable code stand. The unit is turned on at the first notification of the code so that it undergoes calibration process by the time the code team arrives at the code location. In addition, the stand has a video laryngoscope for an unanticipated difficult intubation.

Capnography in ICUs

Despite many intensivists recognizing the value of capnography, there has not been a consolidated organizational effort to implement capnography to monitor ventilation routinely in ICUs. Regular use of capnography in ICUs varies from 22 to 64%.[29–31] It is more often used routinely in some European countries because of the Helsinki declaration.[32] The Helsinki document (June 2010) was prepared jointly by the European Board of Anaesthesiology and the European Society of Anaesthesiology to improve the safety of patients being cared for by anesthesiologists working in the medical fields of perioperative care, intensive care medicine, emergency medicine, and pain medicine. The results of the study, "Fourth National Audit Project" undertaken jointly by the Royal College of Anaesthetists and the Difficult Airway Society of United Kingdom, should encourage physicians to use capnography more often in ICUs.[1] Although this is not a randomized study, it is a prospective study in which the data of serious airway complications occurring during anesthesia, in the ICU, and in the emergency department were collected and analyzed. Reports of major complications of airway management (death, brain damage, emergency surgical airway, unanticipated ICU admissions, prolonged ICU stay) were obtained from all National Health Service Hospitals over a period of 1 yr. The data from the study show that in 2008–2009, there were 16 airway deaths from the 3 million patients undergoing general anesthesia monitored with continuous capnography, resulting in a death rate of 1 in 180,000. Similarly, there were 18 deaths from 48,000 ICU patients receiving ventilation, resulting in a death rate of 1 in 2,700. These data imply that it is 66 times more likely to have an airway catastrophe in an ICU where capnography is not used compared with an operating room where continual capnography is the standard of care.[1,32] What is more alarming is the conclusion of the study group that 74% of ICU airway deaths or persistent neurologic injury could have likely been prevented if continuous capnography had been used. An additional observation from ICU and emergency department data was the unrecognized esophageal intubation. This contributed to five deaths among six where esophageal intubation was not recognized. Capnography was not used in five of the six instances. In the sixth, a flat capnography trace was misinterpreted as being due to cardiac arrest. The authors of the Fourth National Audit Project put forward three recommendations pertaining to capnography in ICUs. First, capnography should be used for intubations of all critically ill patients, irrespective of location. Second,

continuous capnography should be used in all ICU patients with tracheal tubes (including tracheostomy) who are intubated and ventilator dependent. Cost and technical difficulties may be practical impediments to the rapid introduction of routine capnography; however, these need not prevent its implementation. Where capnography is not used, the clinical reason for not using it should be documented and reviewed regularly. Finally, training all clinical staff who work in ICU should include interpretation of capnography. Teaching should focus on identification of airway obstruction or displacement.

One can argue that expert anesthesiologists could have prevented all esophageal intubations in the above study, but we all do so under the cover of capnography at least in the operating rooms. Besides, there are several other reasons why capnography should be considered a routine monitor in ICU patients: (1) there is often variable expertise among different ICUs; (2) ICU patients have substantial cardiac or respiratory comorbidity compared to many routine anesthesia cases in the operating room, and therefore the margin of error and consequent hypoxia are more likely to be detrimental in ICU patients compared to healthy ASA 1 or 2 category patients; (3) the data from ICUs also suggested that undiagnosed inadvertent endotracheal tube displacement in ICU patients accounted for a substantial number of deaths or brain damage; (4) the 2010 International Consensus guidelines on CPR and American Heart Association recommendations advocate the use capnography not only for confirming the tracheal placement of the endotracheal tube but also for gauging the effectiveness of CPR. (According to the U.S. National Registry of Cardiopulmonary Resuscitation, 46% of cardiac arrests [40,050 of 86,748] occur in ICUs, and these cardiac arrests have the worst outcomes [15.5% survival to discharge].)[33] The logical conclusion is to use capnography as an essential adjunct to monitor the integrity of airway, cardiac output, and ventilation; (5) use of capnogram wave shape helps in diagnosing bronchospasm, airway obstruction, or kinked tracheal tube; (6) use of arterial to end-tidal P_{CO_2} difference as a surrogate of alveolar dead space; (7) diagnosis of inadvertent placement of the nasogastric tube in the tracheobronchial tree; (8) assisting in percutaneous tracheostomies; (9) use of capnography during the apnea test to confirm brainstem death; (10) use of capnography as a guide to metabolic rate; (11) estimation of spontaneous breaths during weaning process; (12) decreasing the high cost associated with repeated blood gases; and (13) substantial interest is being shown in using volumetric capnography to assess progressive changes in dead space during the course of the ICU management using either the Bohr or Enghoff approach.[34]

---

† http://www.ics.ac.uk/professional/standards_and_guidelines/capnography_guidelines. Accessed July 23, 2012.

‡ EMS Information Bulletin - #048, Pennsylvania Department of Health, August 2007, The Commonwealth of Massachusetts, Advisory to all Ambulance Services, October 2003. Accessed July 23, 2012.

In the monitoring advisory bulletin (May 2011), the AAGBI alerted their members about the fourth National Audit Project.[1] The Intensive Care Society of United Kingdom also published a booklet (2011) titled "Standards for Capnography in Critical Care (Standards and Guidelines)."† They made a strong recommendation to use capnography in all critically ill patients during the procedures of tracheostomy or endotracheal intubation when performed in the ICU and in all critically ill patients who require mechanical ventilation during interhospital or intrahospital transfer. For continual use of capnography during mechanical ventilation in ICU, the society was unable to make a strong recommendation citing lack of direct evidence that continuous capnography reduced the chances of catastrophic harm due to an airway misadventure during routine mechanical ventilation, and suggested further research into this area.

Despite the lack of direct evidence of the value of capnography during routine ventilation in the ICU, it must be emphasized that unless it is used continually, misplaced endotracheal tubes may not be detected in a timely fashion to call upon rescue methods. A maternal death occurred in the ICU when the tracheostomy tube dislodged in a patient with a difficult airway while the patient was being turned.[35] As is with any monitoring technology, the overall benefit of capnography should be taken into account rather than one individual aspect. Using capnography more often will also allow clinicians to use this device effectively in a crisis environment. If the use of capnography increases with the above recommendations, we are sure to have more data in the near future about its effectiveness in an ICU setting.[31]

Transportation of Patients on Ventilator Within and Outside the Institution

If a case is made that all patients requiring ventilation are to be monitored with capnography, it is imperative then to monitor these patients while being transported to and from ICUs and between institutions. Monitoring carbon dioxide waveforms during transport assures the integrity of airway and ventilation. In one study, six of nine mishaps during interhospital or intrahospital transfers were detected by pulse oximetry and capnography.[36] If ventilation is kept constant, an abrupt decrease in P_{ETCO_2} values must be immediately investigated; it may be due to decreased cardiac output. In the prehospital setting, some states have issued government notification to emergency medical services asking their personnel to obtain necessary training in the interpretation of capnography and to use capnography as first responders.‡

Monitoring of Postoperative Patients Requiring Narcotic Pain Medications

The APSF was concerned about opioid-induced respiratory depression in postoperative patients receiving continuous or patient-controlled infusions, leading to morbidity and

mortality.[37] Depending on the definition, the incidence of respiratory depression varies from 1 to 40%. Akin to capnography monitoring during sedation procedures, there is evidence that capnography can provide an early warning of respiratory depression in these patients. In a study of 178 patients receiving patient-controlled infusions and monitored with pulse oximetry and capnography, the incidence of desaturation (oxygen saturation <90%) and bradypnea (respiratory rate <10/min) lasting more than 3 min ranged from 12 to 41%.[38] One patient required rescue positive pressure ventilation. The APSF put forth several recommendations that included monitoring the ventilation of patients receiving narcotics with capnography because it is the most reliable detector of hypoventilation. However, the implementation of this equipment to postoperative patients requires further refinements in technology to decrease false-positive alarms and making the system more comfortable for the postoperative patient. A better approach is to develop algorithms blending pulse oximetry and capnography to yield greater benefit with less false-positive events. Nonetheless, at-risk patients should benefit from this technology.

Future of Capnography

It is only a question of time, when capnography will be used more often outside of the operating rooms. Physicians from other specialties are becoming more aware of the value of capnography in enhancing patient safety. They are actively exploring other ancillary uses and advantages of capnography monitoring such as determining the prognostic role of P_{ETCO_2} values at rest and during exercise in patients with heart failure to predict major cardiac events.[39] Substantial efforts are needed to train physicians, respiratory therapists, and nursing personnel in the interpretation of capnography waveforms. The manufacturers of capnography equipment should direct their forces to produce reliable, cost-effective portable capnography units that are capable of quick display and calibration of carbon dioxide waveforms. Capnography units should be a default in future intensive care ventilators because the current direction of thought favors their use in ICUs.[40] Training in the ICUs should include methods of avoiding contamination of carbon dioxide–measuring sensors with secretions and interpretation of capnography waveforms. Anesthesiologists are better equipped with capnography knowledge and logically should be the forerunners in helping to deploy capnography outside of the operating rooms in their respective institutions.

References

1. Cook TM, Woodall N, Harper J, Benger J; Fourth National Audit Project: Major complications of airway management in the UK: Results of the Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Part 2: Intensive care and emergency departments. Br J Anaesth 2011; 106:632–42

2. Whitaker DK: Time for capnography - everywhere. Anaesthesia 2011; 66:544–9

3. Hagerty JJ, Kleinman ME, Zurakowski D, Lyons AC, Krauss B: Accuracy of a new low-flow sidestream capnography technology in newborns: A pilot study. J Perinatol 2002; 22:219–25

4. Lumb A: Nunn's Applied Respiratory Physiology, 7th edition. London, Churchill Livingstone, 2010; 174–7

5. Bhavani-Shankar K, Kumar AY, Moseley HS, Ahyee-Hallsworth R: Terminology and the current limitations of time capnography: A brief review. J Clin Monit 1995; 11:175–82

6. Bhavani-Shankar K, Philip JH: Defining segments and phases of a time capnogram. Anesth Analg 2000; 91:973–7

7. Falk JL, Rackow EC, Weil MH: End-tidal carbon dioxide concentration during cardiopulmonary resuscitation. N Engl J Med 1988; 318:607–11

8. Maslow A, Stearns G, Bert A, Feng W, Price D, Schwartz C, MacKinnon S, Rotenberg F, Hopkins R, Cooper G, Singh A, Loring S: Monitoring end-tidal carbon dioxide during weaning from cardiopulmonary bypass in patients without significant lung disease. Anesth Analg 2001; 92:306–13

9. Fletcher R: The single breath test for carbon dioxide (Thesis). Lund, Sweden, Berlings, 1980; 25–32

10. Bhavani-Shankar K, Moseley H, Kumar AY, Delph Y: Capnometry and anaesthesia. Can J Anaesth 1992; 39:617–32

11. Tautz TJ, Urwyler A, Antognini JF, Riou B: Case scenario: Increased end-tidal carbon dioxide: A diagnostic dilemma. Anesthesiology 2010; 112:440–6

12. Cook TM, Woodall N, Frerk C; Fourth National Audit Project: Major complications of airway management in the UK: Results of the Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Part 1: Anaesthesia. Br J Anaesth 2011; 106:617–31

13. Chudnofsky CR, Weber JE, Stoyanoff PJ, Colone PD, Wilkerson MD, Hallinen DL, Jaggi FM, Boczar ME, Perry MA: A combination of midazolam and ketamine for procedural sedation and analgesia in adult emergency department patients. Acad Emerg Med 2000; 7:228–35

14. Sacchetti A, Senula G, Strickland J, Dubin R: Procedural sedation in the community emergency department: Initial results of the ProSCED registry. Acad Emerg Med 2007; 14:41–6

15. Papachristou GI, Gleeson FC, Papachristou DJ, Petersen BT, Baron TH: Endoscopist administered sedation during ERCP: Impact of chronic narcotic/benzodiazepine use and predictive risk of reversal agent utilization. Am J Gastroenterol 2007; 102:738–43

16. Pino RM: The nature of anesthesia and procedural sedation outside of the operating room. Curr Opin Anaesthesiol 2007; 20:347–51

17. Deitch K, Miner J, Chudnofsky CR, Dominici P, Latta D: Does end tidal CO2 monitoring during emergency department procedural sedation and analgesia with propofol decrease the incidence of hypoxic events? A randomized, controlled trial. Ann Emerg Med 2010; 55:258–64

18. Waugh JB, Epps CA, Khodneva YA: Capnography enhances surveillance of respiratory events during procedural sedation: A meta-analysis. J Clin Anesth 2011; 23:189–96

19. Beitz A, Riphaus A, Meining A, Kronshage T, Geist C, Wagenpfeil S, Weber A, Jung A, Bajbouj M, Pox C, Schneider G, Schmid RM, Wehrmann T, von Delius S: Capnographic monitoring reduces the incidence of arterial oxygen desaturation and hypoxemia during propofol sedation for colonoscopy: A

randomized, controlled study (ColoCap Study). Am J Gastroenterol 2012; 107:1205–12

20. Li G, Warner M, Lang BH, Huang L, Sun LS: Epidemiology of anesthesia-related mortality in the United States, 1999-2005. Anesthesiology 2009; 110:759–65

21. Bhananker SM, Posner KL, Cheney FW, Caplan RA, Lee LA, Domino KB: Injury and liability associated with monitored anesthesia care: A closed claims analysis. Anesthesiology 2006; 104:228–34

22. Sanders AB, Kern KB, Otto CW, Milander MM, Ewy GA: End-tidal carbon dioxide monitoring during cardiopulmonary resuscitation. A prognostic indicator for survival. JAMA 1989; 262:1347–51

23. Scarth E, Cook T: Capnography during cardiopulmonary resuscitation. Resuscitation 2012; 83:789–90

24. Heradstveit BE, Sunde K, Sunde GA, Wentzel-Larsen T, Heltne JK: Factors complicating interpretation of capnography during advanced life support in cardiac arrest–a clinical retrospective study in 575 patients. Resuscitation 2012; 83: 813–8

25. Levine RL, Wayne MA, Miller CC: End-tidal carbon dioxide and outcome of out-of-hospital cardiac arrest. N Engl J Med 1997; 337:301–6

26. Einav S, Bromiker R, Weiniger CF, Matot I: Mathematical modeling for prediction of survival from resuscitation based on computerized continuous capnography: Proof of concept. Acad Emerg Med 2011; 18:468–75

27. Adnet F, Baud F, Cariou A, Carli P, Combes A, Devictor D, Dubois-Randé JL, Gérard JL, Gueugniaud PY, Ricard-Hebon A, Langeron O, Leprince P, Longrois D, Pavie A, Pouard P, Rozé JC, Trochu JN, Vincentelli A: Guidelines for indications for the use of extracorporeal life support in refractory cardiac arrest. Ann Fr Anesth Reanim 2009; 28: 182–90

28. White RD, Goodman BW, Svoboda MA: Neurologic recovery following prolonged out-of-hospital cardiac arrest with resuscitation guided by continuous capnography. Mayo Clin Proc 2011; 86:544–8

29. Kannan S, Manji M: Survey of use of end-tidal carbon dioxide for confirming tracheal tube placement in intensive care units in the UK. Anaesthesia 2003; 58:476–9

30. Georgiou AP, Gouldson S, Amphlett AM: The use of capnography and the availability of airway equipment on Intensive Care Units in the UK and the Republic of Ireland. Anaesthesia 2010; 65:462–7

31. Husain T, Gatward JJ, Hambidge OR, Asogan M, Southwood TJ: Strategies to prevent airway complications: A survey of adult intensive care units in Australia and New Zealand. Br J Anaesth 2012; 108:800–6

32. Whitaker DK, Brattebø G, Smith AF, Staender SE: The Helsinki Declaration on Patient Safety in Anaesthesiology: Putting words into practice. Best Pract Res Clin Anaesthesiol 2011; 25:277–90

33. Peberdy MA, Ornato JP, Larkin GL, Braithwaite RS, Kashner TM, Carey SM, Meaney PA, Cen L, Nadkarni VM, Praestgaard AH, Berg RA; National Registry of Cardiopulmonary Resuscitation Investigators: Survival from in-hospital cardiac arrest during nights and weekends. JAMA 2008; 299: 785–92

34. Tusman G, Sipmann FS, Bohm SH: Rationale of dead space measurement by volumetric capnography. Anesth Analg 2012; 114:866–74

35. Cantwell R, Clutton-Brock T, Cooper G, Dawson A, Drife J, Garrod D, Harper A, Hulbert D, Lucas S, McClure J, Millward-Sadler H, Neilson J, Nelson-Piercy C, Norman J, O'Herlihy C, Oates M, Shakespeare J, de Swiet M, Williamson C, Beale V, Knight M, Lennox C, Miller A, Parmar D, Rogers J, Springett A: Saving Mothers' Lives: Reviewing maternal deaths to make motherhood safer: 2006–2008. The Eighth Report of the Confidential Enquiries into Maternal Deaths in the United Kingdom. BJOG 2011; 118(Suppl 1): 1–203

36. Rückoldt H, Marx G, Leuwer M, Panning B, Piepenbrock S: [Pulse oximetry and capnography in intensive care transportation: Combined use reduces transportation risks]. Anasthesiol Intensivmed Notfallmed Schmerzther 1998; 33:32–6

37. Weigner MB, Lee LA; for the Anesthesia Patient Safety Foundation: No patient shall be harmed by opioid-induced respiratory depression. APSF Newsletter 2011; 26:21–40

38. Overdyk FJ, Carter R, Maddox RR, Callura J, Herrin AE, Henriquez C: Continuous oximetry/capnometry monitoring reveals frequent desaturation and bradypnea during patient-controlled analgesia. Anesth Analg 2007; 105:412–8

39. Arena R, Guazzi M, Myers J, Chase P, Bensimhon D, Cahalin LP, Peberdy MA, Ashley E, West E, Forman DE: The prognostic utility of cardiopulmonary exercise testing stands the test of time in patients with heart failure. J Cardiopulm Rehabil Prev 2012; 32:198–202

40. Hodges E, Griffiths A, Richardson J, Blunt M, Young P: Emergency capnography monitoring: Comparing ergonomic design of intensive care unit ventilator interfaces and specific training of staff in reducing time to activation. Anaesthesia 2012; 67:850–4