To monitor means to measure or observe a physiologic parameter either continuously or intermittently. Monitoring devices provide a “snapshot in time” and a window into the clinical status of the patient, detecting deterioration, tracking improvement, or measuring the effects of interventions. Monitoring parameters such as clinical observation, routine vital sign measurement, and electrocardiographic monitoring are basic tools in the practice of emergency medicine.

This chapter focuses on the following monitoring modalities: oxygenation monitoring with pulse oximetry, ventilation monitoring with end-tidal carbon dioxide (ET\textsubscript{co2}) measurement and waveform analysis, and hemodynamic monitoring with noninvasive blood pressure (BP) measurement. Fetal monitoring immediately after maternal trauma is also briefly discussed.

## NONINVASIVE BLOOD PRESSURE MEASUREMENT

Automatic noninvasive BP measurement has become a popular and, if applied appropriately, an accurate method of determining BP. Advantages include more time for staff to attend to other tasks, timed repetition of BP measurements, continuous display of the systolic pressure, and a multiparameter display (e.g., systolic, diastolic, and mean BP; pulse rate).

Two types of noninvasive BP measurement devices are currently available:

1. Cuff-type
2. Radial arterial noninvasive waveform analysis

The noninvasive cuff-type devices use a detection system based on auscultatory, oscillometric, or Doppler principles.\textsuperscript{1,2} Automatic oscillometric devices determine BP by electronically determining the pulse amplitude. This method and Doppler are the most accurate of the indirect methods. The cuff is automatically inflated at predetermined intervals to a preset level. As the machine gradually deflates the cuff, it senses the amplitude of the oscillations (pulsations) transmitted to the cuff by movement of the arterial wall under the cuff. An abrupt increase in the magnitude of the oscillation signals an opening of the artery and an increase in volume under the cuff; this is the systolic pressure. The magnitude of the oscillation increases to a peak and then falls rapidly. The point where there is no longer an alteration in the magnitude of the oscillation is the diastolic pressure. Some devices calculate the mean arterial pressure (MAP); others identify it as the cuff pressure at the point of largest oscillation.\textsuperscript{1}

Noninvasive cuff-type oscillometric devices can be cycled every 15 to 20 seconds in the “STAT” mode when necessary to provide rapid but intermittent BP readings.\textsuperscript{3} Accuracy during rapid cycling is the same as during less frequent sampling, but to prevent pressure injury from the high frequency of cycling, most cuff-type automatic BP devices revert to the intermittent mode after a brief period of rapid cycling.

The shortcomings of cuff-based noninvasive BP monitoring are those of any cuff measurement technique; patients with obese arms, uncooperative moving patients, and patients with very high or very low BP. Even with these limitations, automatic devices are more accurate and reliable than manual auscultation in patients with very low or high BP because the sensing devices are more sensitive than the human ear.\textsuperscript{2} The cycle length of the inflation-deflation sequence of the older devices was exceedingly long and led to frequent failure. The newer devices have rectified this problem.

A newer method of continuous, noninvasive BP monitoring measures radial artery BP and pulse rate every 12 to 15 beats. The Vasotrac (Medwave Inc., Arden Hills, St. Paul, MN) device measures BP and pulse rate and displays a radial arterial pressure waveform.\textsuperscript{4} It consists of a reusable circular sensor (diameter 1.20\textquoteright; width 0.35\textquoteright) which is strapped over the radial artery at the wrist. The wrist sensor module is designed to measure only the pulsatile energy perpendicular to the artery, using cyclical compression and decompression. The processor requires 12 to 15 consecutive beats without interference (movement artifacts) to obtain adequate energy information to generate the pulsatile calibrated beat.\textsuperscript{4}

Although the device is expensive and requires the patient to remain relatively still, a limited number of studies have demonstrated that this noninvasive method of continuous BP measurement is comparable to that provided by an invasive arterial catheter.\textsuperscript{4,6}

The most accurate method of measuring BP is with an intraarterial catheter transduced to an electronic display. The ability to identify beat-to-beat variability, respiratory variation, and longer trends is unsurpassed. In addition, arterial catheter placement enables frequent sampling of arterial blood without additional arterial punctures. Arterial pressure monitoring is
used increasingly in EDs, particularly as lack of available beds in the intensive care unit mandates longer stays in the emergency department (ED) for critically ill patients. The risk of arterial injury or thrombosis related to arterial line insertion is low, but real, and can result in vascular compromise.

Situations when noninvasive BP measurement may prove inadequate and invasive monitoring via an arterial catheter should be considered include:

1. Exceedingly high (>250 mm Hg systolic) or low (<80 mm Hg systolic) pressures. Although the invasive methods are also less accurate at these extremes, the error is significantly less than with noninvasive methods.
2. Patients requiring continuous BP monitoring (e.g., rapid antihypertensive therapy with sodium nitroprusside) due to the potential for rapid fluctuations in BP.
3. In impending shock states, the best chance to insert an arterial line may be in the ED while the arterial pulse is still readily palpable, although this should not delay transferring the patient to a more appropriate location for definitive care.
4. Patients with anatomic abnormalities (e.g., no suitable limb to undertake noninvasive measurement, morbidly obese patient).
5. Conditions where frequent arterial sampling is required. The requirement in such cases is for vascular access rather than the monitoring per se. Patients who are ill enough to require frequent arterial sampling usually benefit from continuous arterial BP monitoring.

**BLOOD GAS MONITORING**

Although the ability to monitor oxygen utilization at the cellular level might be considered ideal, current technology permits less precise measures of performance. Transcutaneous oxygen and CO2 monitoring, conjunctival oxygen pressure, pulse oximetry, and ETCO2 monitoring (capnography, capnometry) are all used to indicate the adequacy of pulmonary gas exchange and arterial blood gas [ABG] tensions and to assess ventilatory efficacy.

**Pulse Oximetry**

The pulse oximeter provides a rapid, noninvasive, and continuous measurement of arterial oxygen saturation that has become a uniform standard for patient monitoring throughout medicine. Oximeters are easy to use and interpret, pose no risk to the patient, and are relatively inexpensive, although reliable interpretation of the information given by these devices requires an appreciation of the limitations of the technology.

Transmission oximetry is the most common type of oximetry used in clinical practice. Transmission oximetry is based on differences in the optical transmission spectrum of oxygenated and deoxygenated hemoglobin. In addition to arterial hemoglobin, other absorbers in the light path include skin, soft tissue, and venous and capillary blood. Pulse oximeters measure the pulse variations in red and infrared (IR) light transmitted through a tissue bed. Data averaged over several arterial pulse cycles are then presented as oxygen saturation as measured using pulse oximetry (SpO2). Studies have shown an excellent correlation between arterial hemoglobin oxygen saturation and SpO2 in patients with normal perfusion.

The limitations of oximetry technology are related to alterations in local or systemic perfusion and severe vasoconstriction (e.g., shock, hypothermia), excessive movement, interference with transfer through the nail bed (e.g., from synthetic fingernails or nail polish), and alterations in hemoglobin (e.g., severe anemia, abnormal hemoglobins). Carboxyhemoglobin (COHb) and methemoglobin (MetHb) contribute to light absorption and cause errors in oximetry readings. The pulse oximeter senses COHb as though it were mostly oxyhemoglobin and provides a falsely high reading. MetHb produces a large pulsatile absorbance signal at both the red and IR wavelengths, which forces the absorbance ratio toward unity, corresponding to an SpO2 of 85%. Thus, with high levels of MetHb, the SpO2 is erroneously low when the arterial saturation is above 85% and erroneously high when the arterial saturation is below 85%. Erroneously high readings (about 3–5%) and a higher incidence of failure to detect signals have been reported in dark-skinned races.

Signals tend to be weaker from ears than from fingers, except in hypotension or peripheral vasoconstriction, but ear responses are faster.

Pulse oximetry is particularly useful in the ED evaluation of patients with acute cardiopulmonary disorders such as bronchiolitis, asthma, heart failure, and chronic obstructive pulmonary disease (COPD) and in patients with drug-induced or traumatic alterations in consciousness. It is mandatory in patients undergoing procedural or deep sedation and in those requiring definitive airway management. However, it is valuable in any patient for whom continuous knowledge of oxygen levels is helpful in their treatment. Pulse oximetry decreases the frequency with which ABG sampling is required. Continuous monitoring may indicate the insidious development of shock as vasoconstriction and deterioration of signal detection develop. Improvements in pulse oximeter technology have resulted in improved accuracy and reliability during patient motion. In short, this valuable device has become an established component of the monitoring armamentarium of emergency medicine.

However, adequate oxygen saturation does not ensure adequate ventilation, particularly in patients with decreased levels of consciousness. ETCO2 monitoring is required for accurate assessment of ventilation.

**End-Tidal Carbon Dioxide Monitoring**

The concentration of CO2 in an exhaled breath is intrinsically linked to tissue metabolism, systemic circulation, and ventilation. Capnography is the graphic record, represented as a waveform, or capnogram, of the instantaneous CO2 concentrations in respired gases during a respiratory cycle. Capnography provides continuous, real-time, breath-to-breath feedback on the clinical status of the patient, allows the clinician to determine the baseline ventilatory status and to track changes over time. Capnography is also a diagnostic monitoring modality because certain disease conditions are associated with characteristic waveforms. Although the concentrations of CO2 can be displayed continuously through the respiratory cycle, by convention only the maximum CO2 concentration at the end of each tidal breath, the ETCO2, is ordinarily displayed. Capnometry is the quantitative measurement of ETCO2 displayed as a number without a waveform. Colorimetric detectors use color scales to estimate ranges of ETCO2, but are not sufficiently accurate to give quantitative measurements. Their use is therefore limited to confirmation of correct endotracheal tube (ETT) placement and its continuous location in the trachea.

Although originally used during general anesthesia in the operating room, ETCO2 monitoring has become a standard monitoring modality in the ED and nonhospital medical setting.

Carbon dioxide monitors are configured as either sidestream or mainstream, depending on the location of the photoelectric
detector or sensor. Mainstream devices measure CO₂ directly from the airway, with the sensor attached directly to the ETT. Sidestream devices, more commonly used by emergency medical service (EMS) personnel and in the ED, aspirate a sample of gas through tubing into a sensor located inside the monitor, and are used for both intubated and nonintubated patients. They are lightweight and may be integrated into special nasal-oral cannulae that simultaneously sample CO₂ and deliver low-flow oxygen, allowing for continuous oxygen delivery during procedural sedation and analgesia.

Colorimetric CO₂ detectors use pH-sensitive filter paper impregnated with metacresol purple, which changes color from purple (<4 mm Hg CO₂) to tan (4–15 mm Hg CO₂) to yellow (>20 mm Hg CO₂) depending on the concentration of CO₂. 15,22,23 (See Chapter 1, Figs. 1-3 and 1-4.) The indicator, housed in a plastic casing, is inserted between the ET and the ventilator bag and detects changes on a breath-by-breath basis. 16 They are also inexpensive and easy to use, and should be available in every ED and on every EMS unit that performs intubation for confirmation of ET placement if capnography or capnometry is not available.

In patients with normal cardiopulmonary function, there is a close correlation between alveolar CO₂ (Paco₂) and arterial CO₂ (Paco₂). The ETCo₂ is usually 2 to 5 mm Hg less than the Paco₂ because of the contribution of physiologic dead space gas to the end-tidal gases. 24 Conditions that affect ventilation-perfusion ratios (including pulmonary embolism), cardiac arrest, hypovolemia, obstructive lung disease, and the lateral decubitus position, can widen the Pa-ETCo₂ gradient. 25,26,48 Several recent studies, however, have shown high concordance between ETCo₂ and Paco₂ in adult asthmatics and in children with moderate and severe respiratory distress from bronchiolitis, asthma, and pneumonia. 27 Although ETCo₂ may not always accurately reflect the absolute Paco₂ in critically ill patients, it is still valuable in detecting ventilatory trends and identifying sudden airway events.

Analysis of the shape of the capnogram can yield valuable diagnostic information. 19 A normal capnogram has four phases (Fig. 3-1A). Phase 1-2 represents a CO₂-free portion of the respiratory cycle. Most often this is the inspiratory phase, although it may represent apnea or a disconnection of the device from the patient. An elevation of this baseline above zero implies rebreathing of CO₂, as in increased dead space in the circuit or contamination of the sensor. 18

Phase 2-3, the rapid upstroke of the curve, represents the transition from inspiration to expiration and the mixing of dead space and alveolar gas. Prolongation of phase 2-3 (Fig. 3-1B) occurs with obstruction to expiratory gas flow (e.g., obstructive lung disease, bronchospasm, kinked ETT) or leaks in the breathing system.

Phase 3-4, the alveolar plateau, represents the predominance of CO₂-rich alveolar gas in the breath stream and tends to slope gently upward with the uneven emptying of alveoli. Point 4 (the ETCo₂) represents the maximum CO₂ concentration in each breath and is the number that appears on the monitor. The slope of this phase can be increased by the same obstructive factors that increase the slope of phase 2-3 and is also a normal physiologic variation in pregnancy. 16 A dip in the plateau indicates a spontaneous respiratory effort during mechanical ventilation, as in hypoxia, hypercarbia, or inadequate anesthesia (Fig. 3-1C). 19,21

Phase 4-5, the inspiratory downstroke, is a nearly vertical drop to baseline. This slope can be prolonged and blend in with the expiratory phase in endotracheal cuff leaks (Fig. 3-1D). Abnormal respiratory patterns that are fast or chaotic limit the usefulness of ETCo₂ monitoring because characteristic waveform patterns are difficult to discern.

Capnography is used in the ED in many intubated and nonintubated clinical scenarios. It can confirm ET placement in the trachea, continuously monitor tube position in the trachea during transport, provide qualitative and quantitative methods of assessing cardiac output, gauge effectiveness of cardiopulmonary resuscitation (CPR) during cardiac arrest, determine prognosis in CPR and in trauma, maintain appropriate ETCo₂ levels in patients with elevated intracranial pressure, estimate Paco₂ in patients with normal lung function, aid in the detection and diagnosis of pulmonary embolism, assess response to treatment in patients with acute respiratory distress, determine adequacy of ventilation in patients with altered mental status (including drug-induced alterations in consciousness during procedural sedation and analgesia), assess ventilatory status of actively seizing patients, and help detect metabolic acidosis.

Along with visualizing tracheal rings on bronchoscopy, capnography is the other “gold standard” used to confirm intubation of the trachea (see Chapter 1). Misleading ETCo₂ readings can occur with esophageal intubation after bag or mask ventilation and ingestion of carbonated beverages or antacids.
However, detection of ET\textsubscript{CO\textsubscript{2}} usually ceases after six breaths and, if capnography is used, the tracings look abnormal.\textsuperscript{28} ET\textsubscript{CO\textsubscript{2}} is also falsely elevated for 5 to 10 minutes after injection of sodium bicarbonate.\textsuperscript{29} In nonarrest settings the ET\textsubscript{CO\textsubscript{2}} approaches 100% sensitivity and specificity in confirming correct tube placement and is also useful for monitoring for accidental extubation.

Airway, breathing, and circulatory assessment of critically ill or injured patients can be rapidly determined using ET\textsubscript{CO\textsubscript{2}} values and the capnogram.\textsuperscript{30} The presence of a normal capnogram denotes a patent airway and spontaneous breathing, and normal ET\textsubscript{CO\textsubscript{2}} levels indicate adequate ventilation and perfusion. Capnography can therefore be used to assess critically ill patients (including victims of chemical terrorism with nerve gas exposure) and patients who are actively seizing.\textsuperscript{30,31} Unlike pulse oximetry and electrocardiography, capnographic measurement is airway-based and therefore is not subject to motion artifact. It also provides reliable readings in low perfusion states.\textsuperscript{32}

Animal and human studies have shown that ET\textsubscript{CO\textsubscript{2}} is a useful noninvasive measurement that is highly correlated with cardiac output and is the earliest indicator of return of spontaneous circulation (ROSC) in CPR.\textsuperscript{33-35,40} ROSC is heralded by an almost immediate increase in ET\textsubscript{CO\textsubscript{2}} from baseline. Multiple studies showed that ET\textsubscript{CO\textsubscript{2}} has prognostic value in terms of mortality during CPR.\textsuperscript{35-39} No patient with a mean ET\textsubscript{CO\textsubscript{2}} less than 10 mm Hg after 20 minutes of CPR survived, giving ET\textsubscript{CO\textsubscript{2}} measurement a high negative predictive value for failure of resuscitation. Despite these promising findings, capnography requires further prospective validation to confirm its utility as a prognostic tool in cardiac arrest.

Capnography is the only ventilation monitoring modality that is accurate and reliable in actively seizing patients.\textsuperscript{30,31} Capnographic data (capnogram, ET\textsubscript{CO\textsubscript{2}}, respiratory rate) can be used to distinguish among actively seizing patients with apnea (flatline waveform, no ET\textsubscript{CO\textsubscript{2}} readings, and no chest wall movement), ineffective ventilation with low tidal volume breathing (small capnograms, low ET\textsubscript{CO\textsubscript{2}}), and effective ventilation (normal capnogram, normal ET\textsubscript{CO\textsubscript{2}}).

Capnography can also rapidly detect the common airway, respiratory, and central nervous system complications associated with the nerve agents in chemical terrorism, including apnea, upper airway obstruction, laryngospasm, bronchospasm, and respiratory failure.\textsuperscript{17,30}

Capnography provides dynamic monitoring of ventilatory status in patients with acute respiratory distress, such as from asthma, bronchiolitis, COPD, congestive heart failure, croup, and cystic fibrosis. By measuring ET\textsubscript{CO\textsubscript{2}} and respiratory rate with each breath, capnography provides instantaneous feedback on the clinical status of the patient. Respiratory rate is measured directly from the airway by nasal-or oral cannulae, providing a more reliable reading than impedance respiratory monitoring. In upper airway obstruction and laryngospasm, for example, impedance monitoring detects chest wall movement, interprets this as a valid breath, and displays a respiratory rate, even though the patient is not ventilating. In contrast, capnography detects no ventilation and shows a flatline capnogram.

Bronchospasm in obstructive lung disease leads to upward slanting of the expiratory plateau of the capnogram (Fig. 3-2, middle panel). Changes in ET\textsubscript{CO\textsubscript{2}} over time and the slope of this phase of the capnogram have been shown to correlate well with spirometric measurements (forced expiratory volume in 1 second [FEV\textsubscript{1}] and peak expiratory flow rate [PEFR]).\textsuperscript{41-43} Capnography has the advantage of being independent of effort, gender, age, and height and is a useful objective measure in asthmatic patients who are unwilling or unable to cooperate with spirometry (e.g., young children, ventilated patients, and patients in acute respiratory distress). Capnography can also be used to distinguish obstructive from restrictive lung disease.\textsuperscript{44} Characteristic capnographic patterns associated with restrictive and obstructive lung disease are shown in Figure 3-2 (bottom panel).

Capnography can also detect the common adverse airway and respiratory events associated with procedural sedation and analgesia.\textsuperscript{17} Capnography is the earliest indicator of airway or respiratory compromise and displays an abnormally high or low ET\textsubscript{CO\textsubscript{2}} before pulse oximetry detects a falling oxyhemoglobin saturation, especially in patients receiving supplemental oxygen. Both central and obstructive apnea can be almost instantaneously detected by capnography. Capnography may be more sensitive than clinical assessment of ventilation in the detection of apnea. In a recent study, 10/39 (26%) of patients experienced 20-second periods of apnea during procedural sedation and analgesia. All ten episodes of apnea were detected by capnography but not by the anesthesia providers.\textsuperscript{44}

Obtunded or unconscious patients, including those with alcohol intoxication, intentional or unintentional drug overdose, and postictal patients (especially those treated with benzodiazepines), may have impaired ventilation. Capnography can differentiate between postictal patients with effective ventilation and those with ineffective ventilation as well as provide continuous monitoring of ventilatory trends over time to identify those patients at risk for respiratory depression and respiratory failure.

In addition to its established uses for assessment of ventilation and perfusion, capnography is a valuable tool for assessing metabolic status. Recent studies have shown that ET\textsubscript{CO\textsubscript{2}} and serum bicarbonate (HCO\textsubscript{3}) are linearly correlated in diabetes and in pediatric gastroenteritis, and ET\textsubscript{CO\textsubscript{2}} can be used as an indicator of metabolic acidosis in these patients (Figs. 3-3 and 3-4, respectively).\textsuperscript{45,46} As a patient becomes acidotic, HCO\textsubscript{3} decreases and a compensatory respiratory alkalosis develops with an increase in minute ventilation and a resultant decrease in ET\textsubscript{CO\textsubscript{2}}. The more acidotic, the lower the HCO\textsubscript{3}; the higher the respiratory rate, the lower the ET\textsubscript{CO\textsubscript{2}}. Furthermore, ET\textsubscript{CO\textsubscript{2}} can be used to distinguish diabetics in ketoacidosis (metabolic acidosis, compensatory tachypnea, low ET\textsubscript{CO\textsubscript{2}}) from those who are not (nonacidotic, normal respiratory rate, normal ET\textsubscript{CO\textsubscript{2}}). A similar association between ET\textsubscript{CO\textsubscript{2}} and HCO\textsubscript{3} was demonstrated in children with gastroenteritis, in whom an ET\textsubscript{CO\textsubscript{2}} = 31 mm Hg is 76% sensitive and 96% specific for the presence of metabolic acidosis (Fig. 3-4).\textsuperscript{47}

![Figure 3-2](image_url)

**Figure 3-2.** Capnogram shape in normal subjects (top panel), patients with bronchospasm (middle panel), and those with obstructive and restrictive (bottom panel) lung disease. FEV\textsubscript{1}, forced expiratory volume in 1 second; FVC, forced vital capacity.
Trauma occurs in about 7% of pregnant females. Although maternal mortality rates in trauma do not differ from those for non-pregnant females with comparably severe injury, fetal mortality rates increase over those for pregnant women who have not suffered a traumatic injury. The American College of Obstetricians and Gynecologists recommends that the pregnant patient with a viable fetus undergo fetal monitoring for 2 to 6 hours after an injury characterized with any degree of abdominal jarring.

Fetal monitoring is used by emergency physicians to detect occult fetal distress and inform therapy and referral. Persistent fetal tachycardia, bradycardia, loss of baseline variability or decelerations following uterine contractions (e.g., Braxton Hicks contractions), and uterine hyperactivity require urgent obstetric consultation. Although most emergency medicine residents are trained to recognize the cardiotocographic findings indicative of fetal distress, most EDs do not have this monitoring equipment available. Ultrasound machines are used widely to measure and monitor fetal heart rate.

### CEREBRAL FUNCTION MONITORING

The Bispectral index (BIS) monitors analyses and processes a patient’s electroencephalogram during sedation to produce a single number—the Bispectral index. This unitless number, ranging from 0 to 100, is used as an indicator of the depth of sedation, with 0 representing EEG silence and 100 a fully awake adult.

BIS monitoring has been studied in the ED in an attempt to objectify sedation endpoints by titrating to a target BIS score. The evidence of its ability to reliably reflect depth of sedation is conflicting, however. More importantly, the threshold beyond which ventilatory compromise occurs has not been determined, further limiting the usefulness of routine BIS monitoring for sedation in the ED. Gill and colleagues found that BIS monitoring reliably distinguished patients undergoing procedural sedation and analgesia who were sedated to the point of general anesthesia from those with lesser degrees of sedation but did not discriminate mild-to-moderate sedation or moderate-to-deep sedation. The findings of Miner and coauthors supported this contention in that the assignment of a preprocedural BIS target sedation level of moderate or deep procedural sedation did not influence the level of sedation achieved, the rate of respiratory depression, the occurrence of complications, the time to return of baseline mental status, or the success of the procedure. They concluded that the assignment of a preprocedural target sedation level was not an effective means of changing the outcome of procedural sedation in the ED.

In small pediatric ED studies, however, Agrawal and co-workers and Overly and associates found BIS monitoring correlated with clinical sedation scores. Determination of utility and effectiveness on outcome for children undergoing procedural sedation and analgesia awaits larger trials.

### KEY CONCEPTS

1. Monitoring modalities, when used appropriately, help to identify the effectiveness of interventions, predict deterioration, track the patient’s clinical course, and inform clinical decision-making.
2. ET\textsubscript{CO\textsubscript{2}} monitoring, especially capnography, supplements oximetry by providing useful information regarding pathologic conditions and response to therapy.
3. Alarm limits should be adjusted to ensure reasonable warnings are delivered, optimally reducing the number of false alarms. Disabling alarms is dangerous.

The references for this chapter can be found online by accessing the accompanying Expert Consult website.