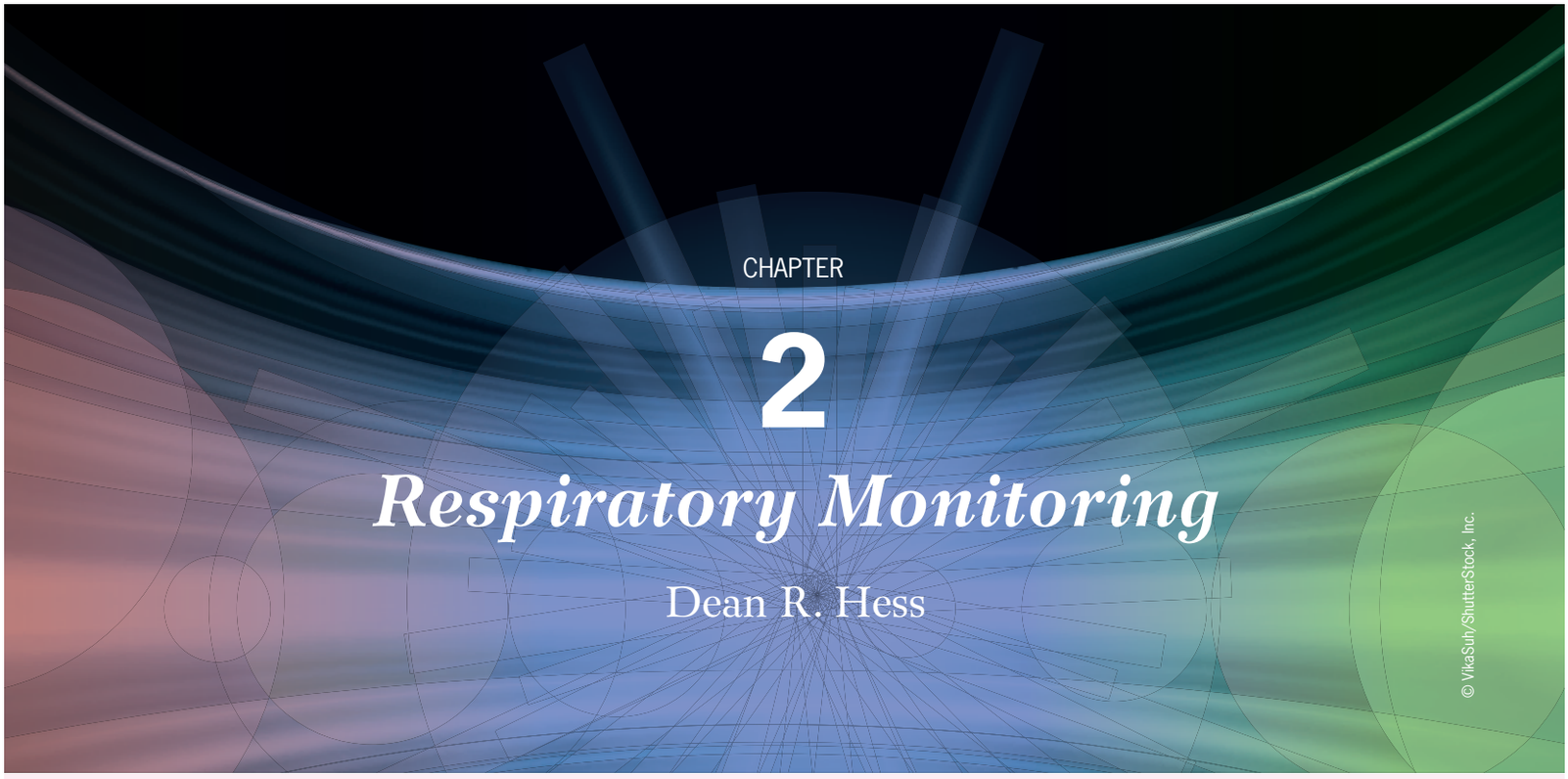


CHAPTER

2

Respiratory Monitoring

Dean R. Hess

OUTLINE

OBJECTIVES

1. Explain how pulse oximetry estimates arterial oxygen saturation.
2. Discuss the limitations of pulse oximetry.
3. Describe techniques to address errors caused by motion and low perfusion.
4. Explain how the pulse oximeter plethysmographic waveform can be used to assess peripheral perfusion.
5. Describe methods used to measure carbon dioxide in the exhaled gas.
6. Compare sidestream and mainstream capnography.
7. Compare time-based and volume-based capnography.
8. Discuss the physiologic issues related to end-tidal Pco_2 and how they affect the relationship between end-tidal and arterial Pco_2.
9. Explain how volume-based capnography can be used to measure carbon dioxide production and cardiac output.
10. Discuss the principle of operation of transcutaneous blood gas monitors.
11. Discuss the limitations of transcutaneous blood gas monitoring.
12. Describe techniques that can be used to measure respiratory rate.
13. Discuss the use of brain Po_2 monitoring.
14. Describe near-infrared spectroscopy.

KEY TERMS

absorption
acoustic technology
Beer-Lambert law
bradypnea
brain tissue Po_2 ($Pbto_2$)
capnogram
capnography
capnometry
end-tidal Pco_2
fiberoptic plethysmography
impedance pneumography
mass spectrometer
near-infrared spectroscopy (NIRS)
penumbra effect
perfusion index (PI)
piezoelectric plethysmography
plethysmographic variability index (PVI)
pulse oximetry
Raman spectroscopy
respiratory inductance plethysmography (RIP)
spectrophotometry
thermistor
thermocouple
transcutaneous monitoring

Introduction

Monitoring is a continuous, or nearly continuous, evaluation of the physiologic function of a patient in real time to guide management decisions, including when to make therapeutic interventions and assessment of those interventions. Monitoring often is used to ensure patient safety. Monitoring also is used to assess patient response to clinical interventions. In this chapter, respiratory monitoring of oxygenation, ventilation, and respiratory rate is discussed. Also discussed are the newer technologies for monitoring brain Po_2 and tissue oxygenation by near-infrared spectroscopy.

Pulse Oximetry

Pulse oximetry noninvasively estimates the hemoglobin oxygen saturation of arterial blood.[1,2] It is based on **spectrophotometry**, the process by which substances are identified by their **absorption** (also called *extinction*) of specific wavelengths in the electromagnetic spectrum. The various hemoglobin molecules absorb wavelengths between 500 and 1000 nm in the infrared and visible light regions. The **Beer-Lambert law** defines the relationship between the concentration of a substance and the amount of light absorbed:

$$A = L \times C \times \varepsilon$$

where L is the optical path length, C is the concentration of the substance, and ε is the absorption of the particular wavelength used. A separate wavelength is required for each substance to be identified. Most pulse oximeters use two wavelengths, red (660 nm) and infrared (940 nm), at which oxyhemoglobin (HbO_2) and deoxyhemoglobin (Hb) have different absorption characteristics.

Red and infrared light-emitting diodes (LEDs) in the oximeter probe serve as light sources (**Figure 2-1**). Because HbO_2 and Hb differ in light absorption at each wavelength, the amount of red and infrared light transmitted is related to oxygen saturation (**Figure 2-2**). A photodiode positioned on the opposite side of the probe serves as the photodetector. To identify the oxygen saturation of arterial blood only, the device relies on the pulsatile nature of arterial flow. During systole, a new volume of blood enters the arteriolar bed, and light absorption increases. During diastole, absorption decreases to a minimal level (**Figure 2-3**). Measuring pulsatile absorption eliminates the effects of nonpulsatile components such as tissue, bone, and venous blood.

Oxygen saturation (Spo_2) is related to the ratio of minimum and maximum absorption at each wavelength (**Figure 2-4**). A calibration curve is plotted for the pulse-added absorption at the two wavelengths and stored in a software algorithm. Devices vary by manufacturer in the type of LED, photodiode, and

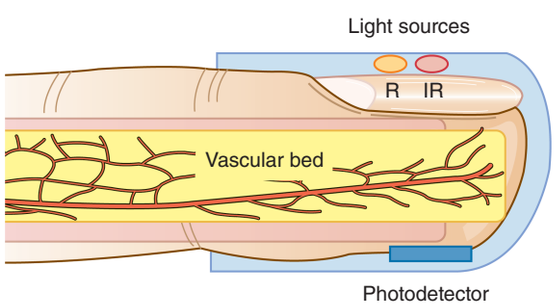


FIGURE 2-1 Pulse oximeter probe fitted over finger, showing position of light sources and detector.

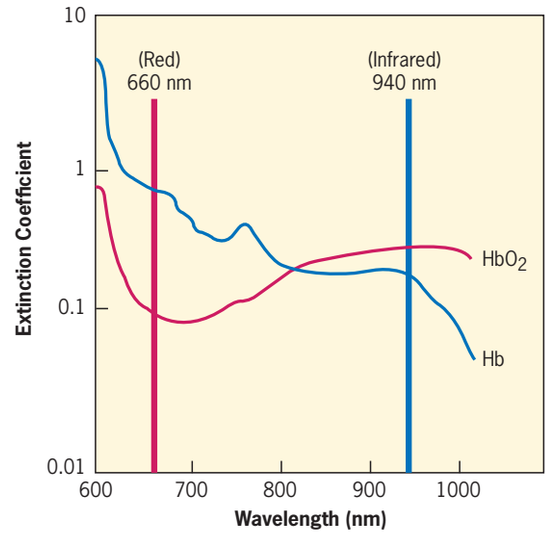


FIGURE 2-2 Absorption spectra for oxyhemoglobin and deoxyhemoglobin for the range of wavelengths relevant to pulse oximetry.

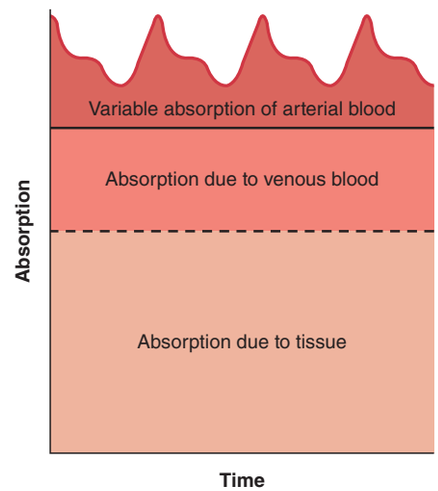


FIGURE 2-3 Dynamic and static light absorption during pulse oximetry.
Used with permission of Philips Respironics.

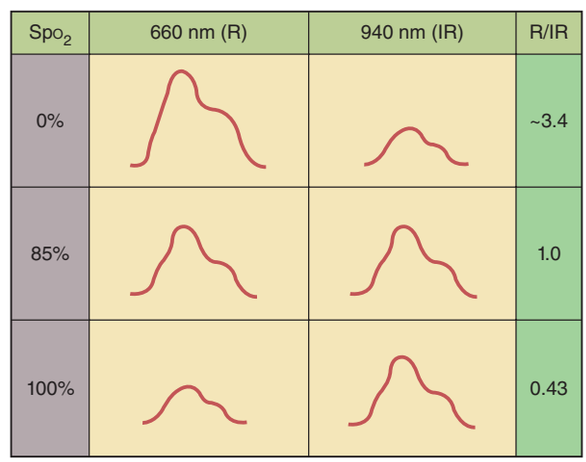


FIGURE 2-4 Relationship between red and infrared light absorption for different oxygen saturations.

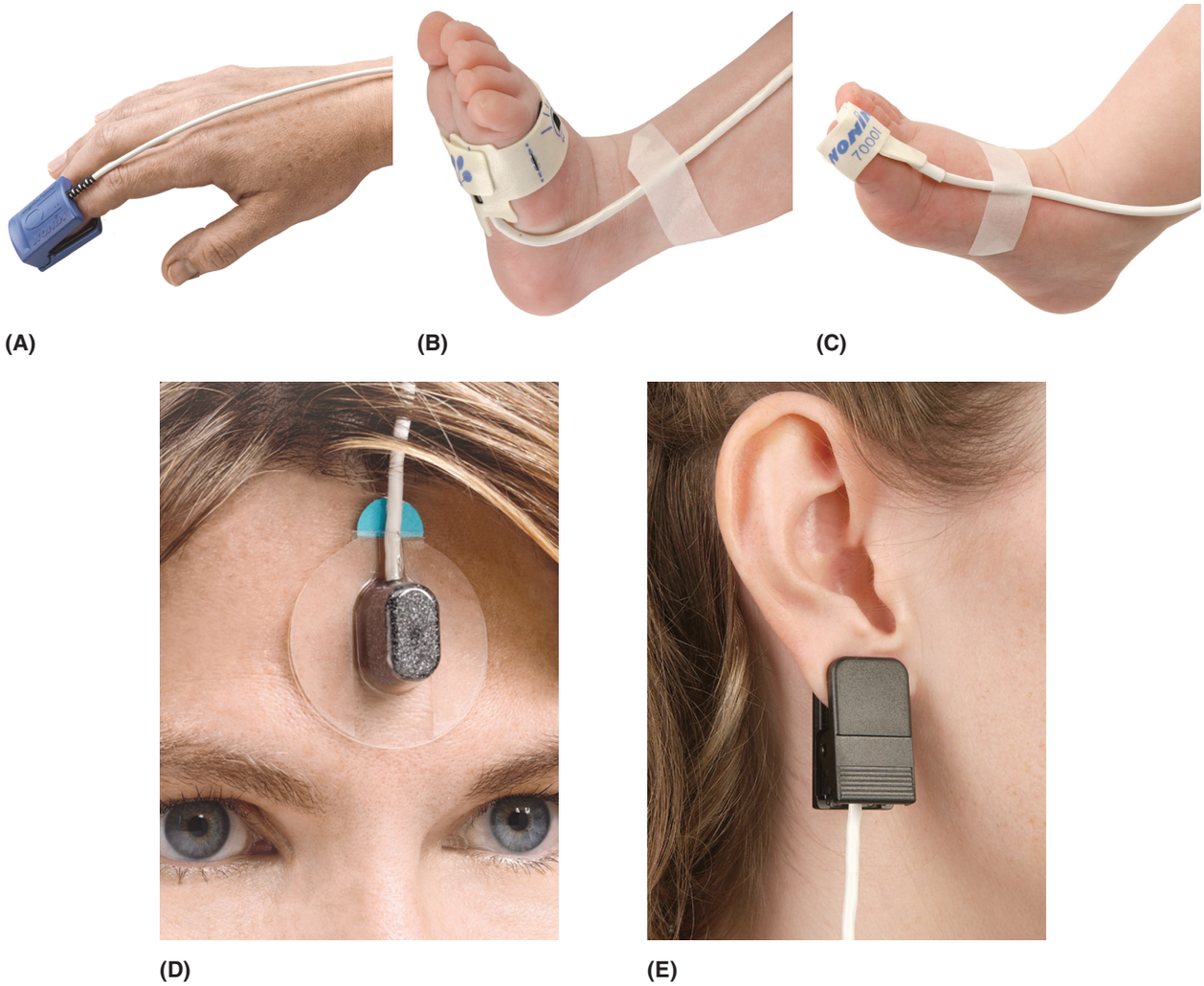


FIGURE 2-5 Examples of pulse oximetry probes. (**A**) Finger probe. (**B**) Foot probe. (**C**) Toe probe. (**D**) Forehead probe. (**E**) Ear probe.
Courtesy of Nonin Medical, Inc.

microprocessor used. Because the Spo_2 calculation is based on a constantly updated signal ratio, no calibration is required.

Most pulse oximeter probes (**Figure 2-5**) use *transmittance spectrophotometry*, sending light through the arterial bed to a photodetector on the opposite side. With *reflectance spectrophotometry*, pulse oximeter sensors place the light source and detector on the same side of the arterial bed.

Pulse oximeter measurements have an accuracy of ±4% at Spo_2 greater than 80%. They are less accurate at Spo_2 less than 80%, but the clinical importance of this is questionable. The calibration curves are developed from studies on healthy volunteers and vary by manufacturer depending on the range of concentrations achieved by the volunteers and the accuracy of the gold standard, usually a co-oximeter. Not only do manufacturer-derived calibration curves vary from manufacturer to manufacturer but also the output of the LEDs can vary from probe to probe. Ideally, the same pulse oximeter and probe should be used for repeated measurements in the same patient.

To appreciate the implications of the accuracy of pulse oximetry, one must consider the oxyhemoglobin equilibration (or dissociation) curve. If the pulse oximeter displays a Spo_2 of 95%, the true saturation

Respiratory Recap

Pulse Oximetry

- Pulse oximetry measures oxygen saturation with a variation of the Beer-Lambert law.
- Accuracy is ±4% and can be affected by abnormal hemoglobin, motion, and low perfusion.
- Some pulse oximeters measure hemoglobin, carboxyhemoglobin, and methemoglobin.
- Some pulse oximeters display the perfusion index and plethysmogram variability index.

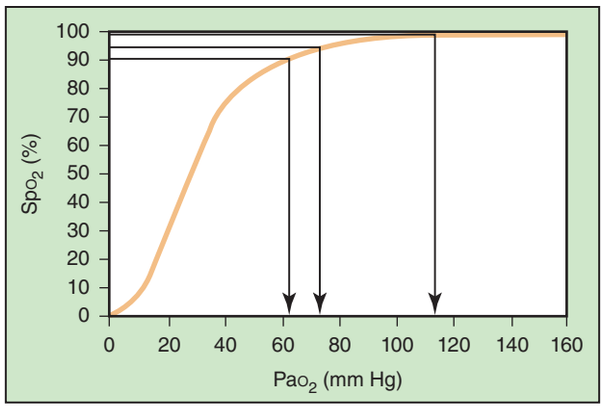


FIGURE 2-6 If the pulse oximeter displays Spo_2 95%, the arterial oxygen saturation could be as low as 91% or as high as 99%. Note that this translates to a wide range of Pao_2.

could be as low as 91% or as high as 99% (**Figure 2-6**). If the true saturation is 91%, the Pao_2 will be about 60 to 70 mm Hg. If the true saturation is 99%, however, the Pao_2 might be very high. A shift of the oxyhemoglobin equilibration curve can change the Spo_2, although no change in Pao_2 has occurred (**Figure 2-7**). For example, a respiratory acidosis will cause the curve to shift to the right, resulting in a decrease in Spo_2 even with no change in Pao_2.

In the intensive care unit (ICU), pulse oximetry is monitored on a continuous basis. Outside the ICU, the availability of portable, battery-powered units has resulted in the common practice of spot-checking hospitalized patients during clinical care or oxygen therapy. Although this practice may enhance appropriate oxygen therapy, allowing weaning or discontinuation of unnecessary prescriptions, it has some potential problems. It provides no direct information about the $Paco_2$ and may not accurately reflect the Pao_2 because of changes in the shape and position of the oxyhemoglobin dissociation curve.

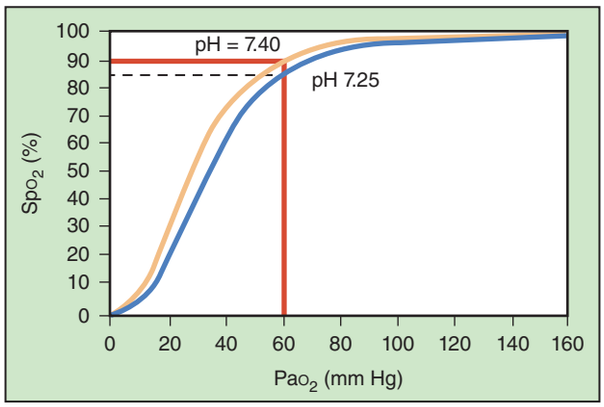


FIGURE 2-7 Note that a shift in the oxyhemoglobin equilibration curve results in a change in Spo_2 without a change in Pao_2.

Limitations

Most pulse oximeters measure only the percentage of HbO_2 relative to the sum of HbO_2 and Hb (functional saturation):

$$Spo_2\ (\%) = HbO_2/(HbO_2 + Hb) \times 100$$

Because of the light absorption characteristics of carboxyhemoglobin (HbCO) relative to HbO_2 (**Figure 2-8A**), the oximeter overestimates HbO_2 saturation by an amount roughly equal to the HbCO level.[3] For methemoglobin (Hbmet), the light absorption for red and infrared light is nearly identical, resulting in a Spo_2 estimate of 85% (**Figure 2-8B**).[3] Thus, Hbmet causes the Spo_2 to be inaccurately low for an arterial oxygen saturation greater than 85% and it causes the Spo_2 to be inaccurately high for an oxygen saturation less than 85%. Fetal hemoglobin and sickle cell anemia[4] do not affect the accuracy of pulse oximetry.

Care must be taken to ensure that the pulse oximeter probe is fitted correctly. If the pulse oximeter probe does not fit correctly, light can be shunted from the LEDs directly to the photodetector. This will cause a falsely low Spo_2 if Sao_2 is greater than 85% and a falsely elevated Spo_2 if Sao_2 is less than 85%. This is called the **penumbra effect**.

The accuracy and performance of pulse oximeters are affected by deeply pigmented skin.[5] Although one study suggests that nail polish may have less effect on the accuracy of pulse oximetry than previously thought, it is prudent to remove nail polish before pulse oximetry is initiated.[6] Intravascular dyes (methylene blue and indocyanine green) also cause an underestimation of Spo_2. Hyperbilirubinemia has no effect on accuracy because the absorption peak for bilirubin (460 nm) is below that used in pulse oximetry. Xenon and fluorescent lighting affect some probes, a problem that can be prevented by shielding.

Pulse oximeters require a pulsating vascular bed. Under conditions of low flow, pulse oximetry becomes unreliable. Under these conditions, an ear probe may be more reliable than a finger probe. Although pulse oximeters are generally reliable over a wide range of hemoglobin levels, they become less accurate and reliable with conditions of severe anemia (hematocrit <24 g/dL at low saturations, and hematocrit $<10\%$ at all saturations). Venous pulses and a large dicrotic notch may affect the accuracy of pulse oximetry.

Pulse oximetry is usually a safe procedure. Tissue injury may result from incorrect probe application or electrical shock and burns from substitution of incompatible probes between instruments.

Approaches to Deal with Errors Caused by Motion and Low Perfusion

Pulse oximetry is accurate when all hemoglobin is either oxyhemoglobin or deoxyhemoglobin, when there are no other absorbers between the LEDs and the

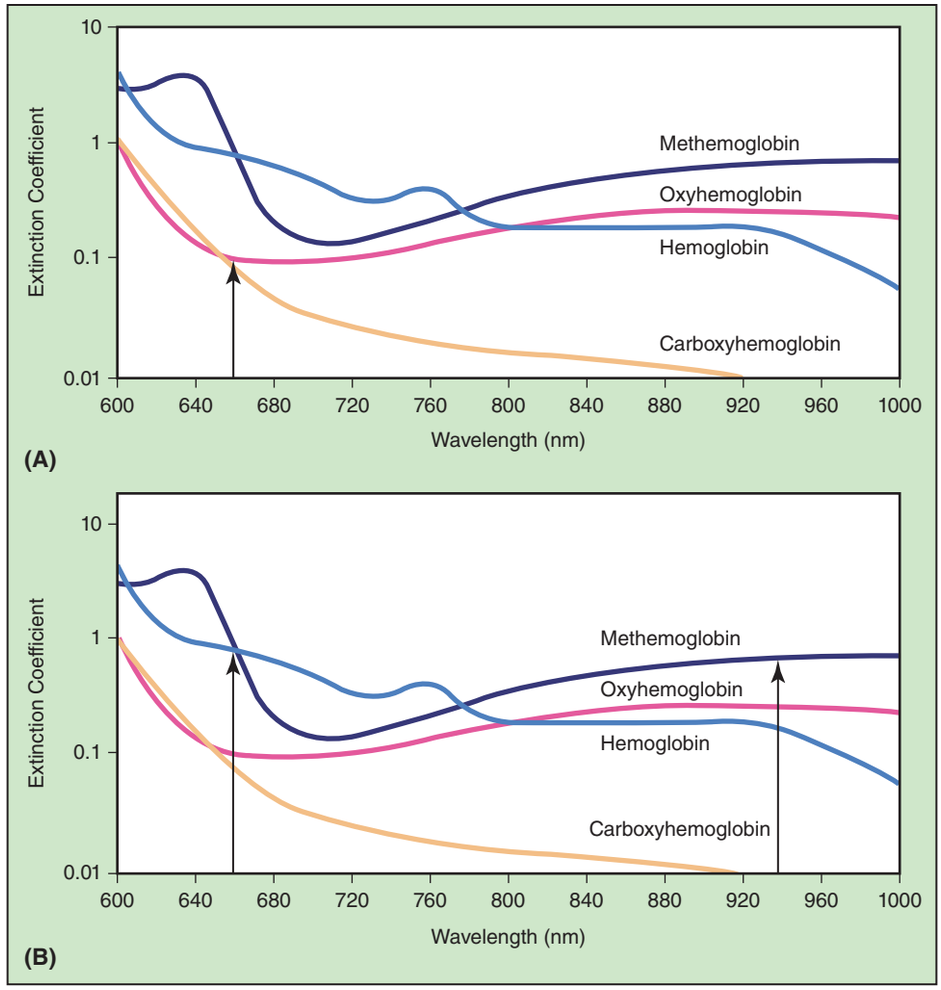


FIGURE 2-8 (**A**) At 660 nm, note that the absorptions for oxyhemoglobin and for carboxyhemoglobin are nearly identical. (**B**) Note that the absorption for methemoglobin is nearly identical at 660 nm and 940 nm.

detector other than those present during the empirical calibration, and when all the blood that pulsates is arterial blood. Motion and low perfusion can induce considerable errors in pulse oximetry accuracy.[7] With low perfusion, there is an increase in the ratio of venous blood to arterial blood at the measuring site. Moreover, lower perfusion is associated with lower pulse amplitude, so the noise of motion has a greater effect when combined with a low signal. Strategies to address issues related to motion and low perfusion include averaging the saturation data over a longer period of time and suspending the reporting of data until clean data are available.

Manufacturers of pulse oximeters have developed motion-resistant technologies and sophisticated algorithms to eliminate motion artifacts from the pulse signal.[8] The discrete saturation transform (DST) uses a reference signal generator, an adaptive filter, and a peak picker, which work in concert to determine the most likely Spo_2 value based on the incoming signals. Signal Extraction Technology (SET) uses DST and parallel signal processing engines to separate the arterial signal from sources of noise to measure Spo_2 and pulse rate accurately. The Fourier artifact-suppression technology (FAST) algorithm identifies the frequency components of the pulse rate and compares those to the frequency components of the incoming signal to select the component that is at the pulse rate for both the red and infrared wavelengths. The variable cardiac gated averaging algorithm attenuates incoming signals that do not occur synchronously with the average rhythm of the pulse rate and allows the parts of the waveform that are synchronous with the heart rate to remain not attenuated and thus contribute more to the calculated Spo_2. Because these algorithms are proprietary, the details on how each manufacturer's technology identifies

STOP AND THINK

A patient has a measured Pao_2 of 55 mm Hg, but the Spo_2 is 97%. How do you explain this apparent discrepancy?

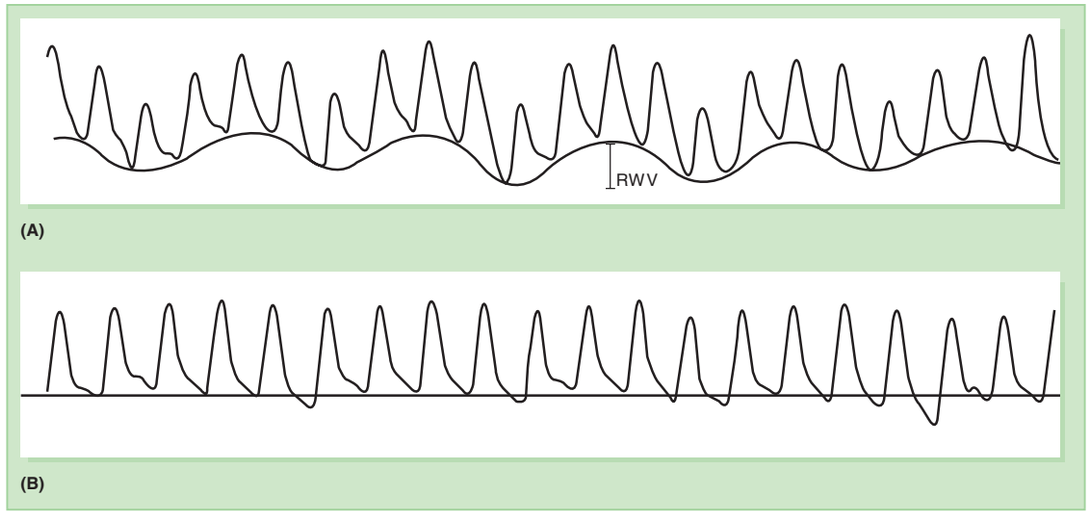


FIGURE 2-9 Pulse oximeter tracings from a 60-year-old woman with an exacerbation of chronic obstructive pulmonary disease who was admitted to the ICU in ventilatory failure. (**A**) The patient's pulse oximetry tracing at the time of admission, revealing the respiratory variability in the pulse oximeter plethysmography tracing. Her measured pulsus paradoxus at this time was 16 mm Hg. (**B**) The patient's pulse oximetry tracing after 12 hours of aggressive therapy. Her pulsus paradoxus at this time was 8 mm Hg. Note the absence of respiratory waveform variation (RWV) in the baseline of the oximeter tracing after the clinical improvement in airflow and the resolution of elevated pulsus paradoxus.

Reproduced from Hartert TV, Wheeler AP, Sheller JR. Use of pulse oximetry to recognize severity of airflow obstruction in obstructive airway disease: correlation with pulsus paradoxus. *Chest.* 1999;115:475–481. Used with permission from the American College of Chest Physicians.

and processes the incoming signals are not available. The clinical performance of new-generation pulse oximeters is better than that of earlier devices, although there is no strong and convincing evidence that the performance of any single new-generation device is superior to that of any of the others.

Pulse Oximetry to Measure Hemoglobin, Carboxyhemoglobin, and Methemoglobin

New pulse oximetry technology uses more than seven wavelengths of light to measure Spo_2 as well as Spco (pulse oximeter estimate of HbCO), SpMet (pulse oximeter estimate of HbMet), and SpHb (pulse oximeter estimate of hemoglobin concentration).[3] There are several limitations of this technology. Because it uses the conventional two-wavelength red and infrared algorithm to determine Spo_2, when there are significant levels of either HbCO or HbMet, the displayed Spo_2 will be subject to the same errors described earlier. However, the presence of a high Spco or SpMet display would alert the user to this error. Another limitation is the crosstalk between the HbMet and HbCO measurement channels. In the presence of significant Hbmet levels, the device will display a falsely elevated Spco but a correct SpMet. In this setting, the device will display an error message indicating that the Spco may not be accurate.

The results of studies evaluating the clinical accuracy of pulse oximetry to detect HbCO suggest caution. The accuracy of Spco is ±6% and, therefore, it should not be used for triage or patient management. An elevated Spco could broaden the diagnosis of CO poisoning in patients without symptoms. But a low Spco in patients suspected of CO poisoning should never rule out CO poisoning and should always be confirmed by blood HbCO.[9–11] Studies evaluating the accuracy of SpHb have reported mixed results.[12,13] Due to this uncertainty, use of SpHb has not been widely adopted.

Use of the Plethysmographic Waveform

Pulse oximetry has non–oxygenation-monitoring applications. The pulse oximetry plethysmographic (POP) waveform may display the effect of pulsus paradoxus, and therefore the severity of air trapping in obstructive airway disease (**Figure 2-9**).[14–18] In patients with obstructive lung disease and elevated pulsus paradoxus, there is an altered pulse oximetry baseline tracing manifested as the respiratory waveform variation. Pulsus paradoxus is significantly correlated with the degree of respiratory waveform variation of the pulse oximetry tracing and the amount of auto-PEEP (positive end-expiratory pressure).

Respiratory variations in POP waveform amplitude during positive pressure ventilation has also been shown to be useful in prediction of fluid responsiveness. POP waveform amplitude during positive pressure ventilation is measured on a beat-to-beat basis as the vertical distance between peak and preceding valley trough in the waveform (**Figure 2-10**). Maximal POP (POP_{max}) and minimal POP (POP_{min}) are determined over the same respiratory cycle. ΔPOP is calculated using the following formula:

$$\Delta POP\ (\%) = 100 \times \frac{POP_{max} - POP_{min}}{(POP_{max} + POP_{min})/2}$$

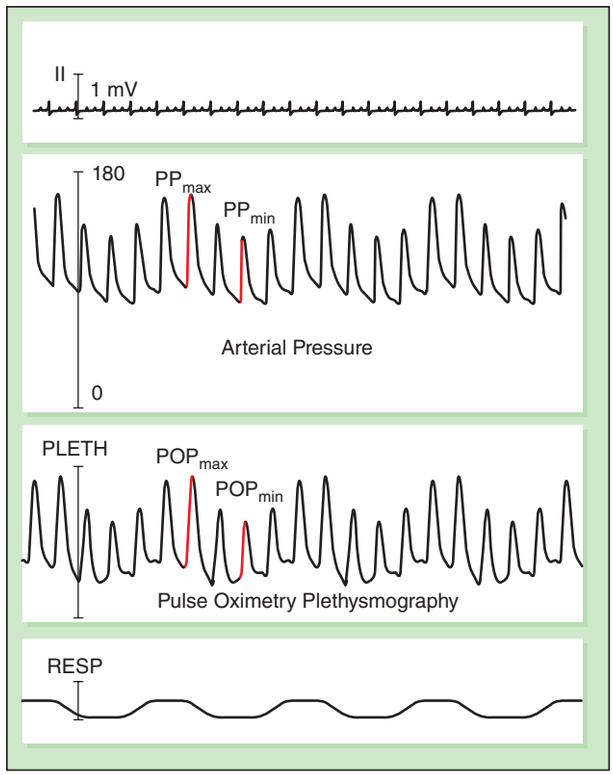


FIGURE 2-10 Comparison of invasive arterial pressure and pulse oximeter plethysmography recordings. Simultaneous recording of electrocardiographic lead (II), systemic arterial pressure (PA), pulse oximetry plethysmography (PLETH), and respiratory signal (RESP) in one illustrative patient. POP, pulse oximetry plethysmographic; PP, pulse pressure.

Reproduced from Cannesson M, Besnard C, Durand PG, et al. Relation between respiratory variations in pulse oximetry plethysmographic waveform amplitude and arterial pulse pressure in ventilated patients. *Crit Care.* 2005;9:R562–R568.

A ΔPOP greater than 15% is predictive of fluid responsiveness in mechanically ventilated patients with circulatory failure.[15,16]

Some pulse oximeters display the **perfusion index (PI)** and **plethysmographic variability index (PVI)** as a reflection of POP. PI is the ratio of the pulsatile blood flow to the nonpulsatile blood in peripheral tissue. It is a noninvasive measure of peripheral perfusion that can be continuously and noninvasively obtained from a pulse oximeter. PI is calculated by pulse oximetry as the pulsatile signal (during arterial inflow) as a percentage of the nonpulsatile signal, both of which are derived from the amount of infrared (940 nm) light absorbed. Whereas the pulse oximeter plethysmogram represents a volume change and the arterial blood pressure represents a pressure change, cyclical shifts in the plethysmogram reflect similar cyclic changes in blood pressure. These changes reflect an intrathoracic pressure relative to the intravascular volume. PVI is a measure of the dynamic changes in the PI that occur during the respiratory cycle:

$$PVI\ (\%) = 100 \times (PI_{max} - PI_{min})/PI_{max}$$

Similar to ΔPOP, the greater the PVI, the greater variability there is in the waveform variability over a respiratory cycle.

Capnography

Capnometry and capnography are noninvasive techniques that measure the carbon dioxide levels in expired gas (**CPG 2-1**).[19] **Capnometry** refers to the

CLINICAL PRACTICE GUIDELINE 2-1

Capnometry and Capnography During Mechanical Ventilation

Indications

- To evaluate exhaled CO_2, especially P_{ETCO_2}, which is the maximum partial pressure of CO_2 exhaled during a tidal breath (just before the beginning of inspiration).
- To monitor the severity of pulmonary disease and evaluate the response to therapy, especially therapy intended to improve the ratio of dead space to tidal volume (V_D/V_T).
- As an adjunct to determine that tracheal rather than esophageal intubation has taken place (low or absent cardiac output may negate its use for this indication); colorimetric CO_2 detectors are adequate devices for this purpose.
- To continuously monitor the integrity of the ventilatory circuit, including the artificial airway.
- To evaluate the efficiency of mechanical ventilatory support through determination of the difference between the arterial partial pressure of carbon dioxide (P_{aCO_2}) and the P_{ETCO_2}, reflecting CO_2 elimination.
- To monitor the adequacy of pulmonary and coronary blood flow; to estimate effective (nonshunted) pulmonary capillary blood flow by a partial rebreathing method; as an adjunctive tool to screen for pulmonary embolism; to monitor the matching of ventilation to perfusion during independent lung ventilation for unilateral pulmonary contusion.

- To monitor inspired CO_2 when CO_2 gas is administered therapeutically.
- To graphically evaluate the ventilator–patient interface; evaluation of the capnogram may be useful in the detection of rebreathing of CO_2, obstructive pulmonary disease, waning neuromuscular blockade (curare cleft), cardiogenic oscillations, esophageal intubation, cardiac arrest, or contamination of the monitor or sampling line with secretions or mucus.
- Measurement of the volume of CO_2 elimination to assess metabolic rate or alveolar ventilation or both.

Contraindications

- There are no absolute contraindications to capnography in mechanically ventilated adults provided the data obtained are evaluated in light of the patient's clinical condition.

Hazards and Complications

- Capnography with a clinically approved device is a safe, noninvasive test associated with few hazards. With mainstream analyzers, use of too large a sampling window may introduce an excessive amount of dead space into the ventilator circuit. Care must be taken to minimize the amount of additional weight placed on the artificial airway by the sampling window or, in the case of a sidestream analyzer, by the sampling line.

Limitations

- The composition of the respiratory gas mixture may affect the capnogram, depending on the measurement technology used; the infrared spectrum of CO_2 has some similarities to the spectra of oxygen and nitrous oxide; the reporting algorithm of some devices (primarily mass spectrometers) assumes that the only gases present in the sample are those that the device is capable of measuring—when a gas that the mass spectrometer cannot detect (such as helium) is present, the reported values of CO_2 are incorrectly elevated in proportion to the concentration of the undetectable gas present.
- The breathing frequency may affect the capnograph. High breathing frequencies may exceed the response capabilities of the capnograph. In addition, a breathing frequency above 10 breaths/min has been shown to affect devices differently.
- The presence of Freon (used as a propellant in metered dose inhalers) in the respiratory gas has been shown to artificially increase the CO_2 reading of mass spectrometers (that is, to show an apparent increase in the CO_2 concentration). A similar effect has not yet been demonstrated with Raman or infrared spectrometers.
- Contamination of the monitor or sampling system by secretions or condensate, use of a sample tube that is too long, a sampling rate that is too high, or obstruction of the sampling chamber can lead to unreliable results.
- Use of filters between the patient airway and the sampling line of the capnograph may lead to lowered P_{ETCO_2} readings.
- Low cardiac output may cause a false-negative result when attempting to verify endotracheal tube position in the trachea. False-positive results have been reported with endotracheal tube position in the pharynx and when antacids or carbonated beverages, or both, are present in the stomach.
- Decreased tidal volume delivery is possible during volume modes, some dual control modes, and time-cycled pressure limited ventilation with low continuous flow rates if the sampling flow rate of a sidestream analyzer is too high, especially in neonates and pediatrics.
- Inaccurate measurement of expired CO_2 may be caused by leaks of gas from the patient/ventilator system preventing collection of expired gases.

Modified from AARC clinical practice guideline: capnometry and capnography during mechanical ventilation—2003 revision and update. *Respir Care*. 2003;48:534–537. Reprinted with permission.

numeric display of CO_2 measurements taken from the airway. When the CO_2 is plotted against time and displayed graphically as a waveform, it is called **capnography**. Most capnometers measure CO_2 by infrared absorption, although mass spectrometry and Raman spectrometry can also be used.

Two airway sampling systems are used in capnometry: *mainstream* sensors and *sidestream* sensors (**Figure 2-11**). There are advantages and disadvantages of each approach (**Table 2-1**). The mainstream capnometer is placed directly into the breathing circuit, usually directly at the airway. Infrared light is passed across the airstream to a photodetector. Improvements in analyzer technology and miniaturization have resulted in the development of low-dead-space, lightweight, and durable mainstream sensors. Because they are positioned on the airway, they may be adversely affected by the accumulation of moisture, secretions, and debris. Mainstream designs are best suited to patients with artificial airways.

The sidestream capnometer uses small-bore tubing to aspirate gas from or adjacent to the airway. The tubing

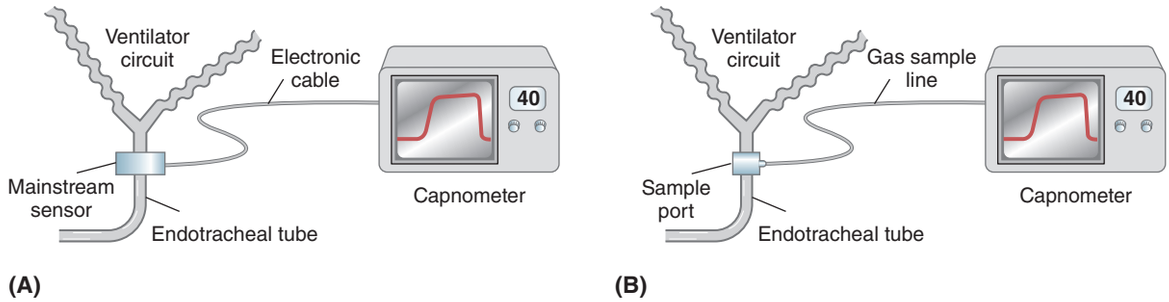


FIGURE 2-11 (**A**) Mainstream capnometry. (**B**) Sidestream capnometry.

aspirates the respiratory gases to a remote measuring chamber for analysis. Moisture and secretions must be removed from the tubing with traps, filters, purging, or reverse flow maneuvers before the sample enters the analysis cell. Some tubing is designed to be water vapor permeable, allowing moisture to escape by diffusion and evaporation. There is always an analysis delay when sidestream monitors are used because of the time required to move the sample from the airway to the sensor. The delay depends on the length of the tubing, its diameter, and the rate at which the gas is aspirated. Sidestream capnometers can be incorporated into nasal cannula designs for nonintubated patients (**Figure 2-12**).

The CO_2 infrared absorption peak (4.26 µm) lies between two peaks for water and very close to a peak for nitrous oxide (**Figure 2-13**). The latter poses an interference problem during the administration of nitrous oxide (N_2O) as an anesthesia gas. Correction factors and filters can be used to address this problem.

TABLE 2-1
Mainstream and Sidestream Capnometers

Advantages	Disadvantages
Mainstream Capnometer	
Sensor at patient airway Fast response (crisp waveform) Short lag time (real-time readings) No sample flow to reduce tidal volume	Secretions and humidity block sensor Sensor heated to prevent condensation Bulky sensor at patient airway Does not measure N_2O Difficult to use with nonintubated patients Cleaning and sterilization of reusable sensor
Sidestream Capnometer	
No bulky sensors or heaters at airway Ability to measure N_2O Disposable sample line Can be used with nonintubated patients	Secretions block sample tubing Water trap required Slow response to CO_2 changes Sample flow may decrease tidal volume

Conventional sidestream infrared analyzers must be calibrated on a regular basis. Room air (zero) and 5% CO_2 are used to perform a two-point calibration. Newer commercially available capnometers allow self-zeroing and calibration features. Until recently, the infrared radiation technique used for capnography was nondispersive blackbody technology. Molecular correlation spectroscopy is also available, which uses a radiation source that emits only CO_2-specific radiation and uses a small sample cell (15 µL) and a low flow rate.

The **mass spectrometer** is used to measure respiratory and anesthetic gases. Multichannel units are available to monitor several patients simultaneously. A mass spectrometer aspirates sample gas into a vacuum chamber, where an electron beam ionizes it. The charged molecules are accelerated through a magnetic field and disperse according to their mass and charge. This dispersion allows them to be separated before they reach a panel of detectors. Because even molecules of similar mass (N_2O and CO_2) ionize to different species (N_2O^+ and CO_2^+), this technique allows accurate measurement of several gases. Mass spectrometers have the advantage of being able to measure all respiratory gases

FIGURE 2-12 Nasal cannula designed for CO_2 sampling and oxygen administration (Smart CapnoLine, Oridion). The cannula samples CO_2 from both the nares and the mouth while oxygen is delivered through pinholes directed toward both the nose and mouth.

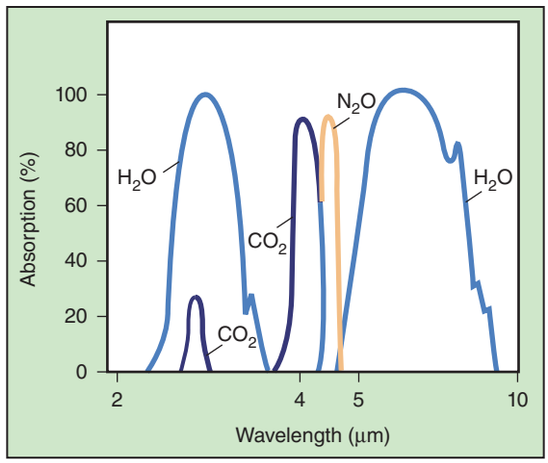


FIGURE 2-13 Carbon dioxide absorption spectra.
Adapted from Decker M, Strohl K. *Pulse Oximetry. Biophysical Measurement Series: Respiration.* SpaceLabs Medical, 1994.

FIGURE 2-15 Colorimetric CO_2 sensor designed to confirm nasogastric tube placement.
Courtesy of Covidien. Used with permission.

breath by breath and are the most accurate analyzers in clinical use. However, they generally are too expensive and cumbersome for use outside the operating room or research settings.

Another method that can be used to measure CO_2 is **Raman spectroscopy**. When ultraviolet or visible light strikes gas molecules, energy is absorbed and reemitted at the same wavelength and direction. A small fraction of the absorbed energy is reemitted at new wavelengths in a phenomenon known as *Raman scattering*. Raman scattering results in reemission at a longer wavelength to produce a red-shifted spectrum. The wavelength shift and amount of scattering can be used to measure the constituents of a gas mixture.

A portable non-electronic single-patient-use device (**Figure 2-14**) is commonly used to produce a color change (colorimetric end-tidal CO_2 detection) in the presence of exhaled CO_2 (i.e., tracheal intubation). The color changes from purple with a low CO_2 concentration to yellow when exposed to a CO_2 concentration of 2.0% to 5.0%. This device is commonly used to confirm the correct position of the endotracheal tube. A color change indicates correct position in the trachea, as opposed to esophageal intubation, in which there is no color change. This technique can also be used to detect accidental tracheal placement of a nasogastric tube (**Figure 2-15**). In this case, a color change indicates incorrect placement of the tube in the trachea.[20]

FIGURE 2-14 Colorimetric CO_2 sensor designed to confirm endotracheal intubation. It fits between the endotracheal tube and the manual bag-valve-O_2 device.
Courtesy of Covidien. Used with permission.

Time-Based Capnography

The traditional **capnogram** plots P_{CO_2} on the vertical axis and time on the horizontal axis. During inhalation, P_{CO_2} at the airway equals zero. At the beginning of exhalation, it remains low as the anatomic dead space empties. As the alveolar gas begins to mix with the dead space, CO_2 rises rapidly. A plateau, representing alveolar gas, develops, rising gently, presumably because of CO_2 added to the alveoli from capillary blood during exhalation (**Figure 2-16**). Peak exhaled P_{CO_2} or **end-tidal P_{CO_2}** (P_{ETCO_2}) represents the alveolar P_{CO_2}.

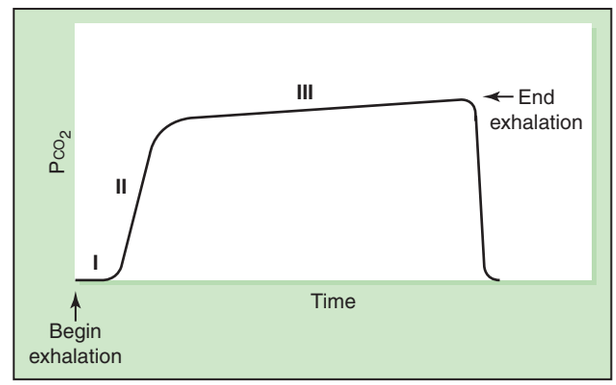


FIGURE 2-16 Time-based capnogram.

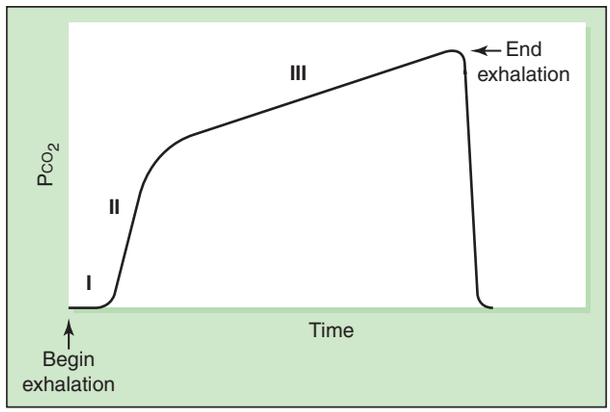


FIGURE 2-17 Capnogram produced with airflow obstruction.

The capnographic waveform can be inspected for specific abnormalities or patterns. In patients with airways obstruction, the slope of the alveolar plateau increases because of inhomogeneous alveolar emptying (**Figure 2-17**). Regions of the lung with delayed emptying caused by increased resistance (long time constants) continue to add CO_2 to expired gas during the latter part of exhalation.

End-Tidal P_{CO_2}

End-tidal P_{CO_2} is determined by the production of CO_2, its subsequent delivery to the lungs by cardiac output, alveolar ventilation, and proper sampling and equipment performance. **Table 2-2** lists causes of an increase or decrease in the P_{ETCO_2}. P_{ETCO_2} is used clinically to ensure that the tracheal tube or mask ventilates the lungs, to estimate the P_{aCO_2}, to detect changes in pulmonary blood flow or dead space ventilation, and to detect the addition of excess CO_2 to the systemic circulation.

TABLE 2-2
Causes of Increased and Decreased P_{ETCO_2}

Increased P_{ETCO_2}	Decreased P_{ETCO_2}
Increased CO_2 production and delivery to the lungs: Fever, sepsis, bicarbonate administration, increased metabolic rate, seizures	*Decreased CO_2 production and delivery to the lungs*: Hypothermia, low pulmonary perfusion, cardiac arrest, pulmonary embolism, hemorrhage, hypotension
Decreased alveolar ventilation: Respiratory center depression, muscular paralysis, hypoventilation, COPD	*Increased alveolar ventilation*: Hyperventilation
Equipment malfunction: Rebreathing, exhausted CO_2 absorber, leak in ventilator circuit	*Equipment malfunction*: Ventilator disconnect, esophageal intubation, complete airway obstruction, poor sampling, leak around endotracheal tube cuff

STOP AND THINK

A patient has a P_{aCO_2} of 55 mm Hg, but the P_{ETCO_2} is 30 mm Hg. Why is there such a large difference between the P_{aCO_2} and P_{ETCO_2}?

The P_{CO_2} of an individual lung unit depends on $\dot{V}/\dot{Q}$ (**Figure 2-18**). Without perfusion (pure dead space; $\dot{V}/\dot{Q} = \infty$), the P_{ACO_2} is similar to the inspired P_{CO_2} (i.e., zero). With a normal $\dot{V}/\dot{Q}$ unit, the P_{ACO_2} is the same as the arterial P_{CO_2} (i.e., 40 mm Hg). With a low $\dot{V}/\dot{Q}$ unit, the P_{ACO_2} increases toward the $P\bar{v}CO_2$ (i.e., 45 mm Hg). The P_{ACO_2}, and thus the end-tidal P_{CO_2}, must always remain between zero and the $P\bar{v}CO_2$. P_{ETCO_2} is normally several mm Hg less than the P_{aCO_2}. However, the relationship between the P_{aCO_2} and P_{ETCO_2} will vary depending on the relative contributions of various $\dot{V}/\dot{Q}$ units comprising the lungs.

The presence of CO_2 in exhaled gas usually indicates tracheal intubation. Exhaled CO_2 does not always ensure proper endotracheal tube placement, however, because the tube could be in the main stem bronchus or in the pharynx. Although esophageal intubation generally results in a very low P_{ETCO_2}, falsely elevated readings may occur if the patient ingested antacids or carbonated beverages. The elevated value should diminish with subsequent breaths. Even with proper endotracheal tube placement, the P_{ETCO_2} may remain deceptively low with cardiogenic shock. P_{ETCO_2} is also used to detect tracheal placement of a nasogastric tube. A P_{ETCO_2} near zero suggests that the gastric tube is *not* in the trachea.

Even though P_{ETCO_2} approximates P_{aCO_2} in normal individuals, capnometry cannot routinely be used as a substitute to measure arterial P_{CO_2}. Most critically ill patients have ventilation-perfusion abnormalities, particularly an increased ratio of dead space to tidal volume (V_D/V_T), resulting in a significant $P_{aCO_2} - P_{ETCO_2}$ difference ($P[a-ET]CO_2$) (**Table 2-3**).[21] Even patients whose $P(a-ET)CO_2$ is calibrated by simultaneous arterial blood gas and capnometry measurements do not remain stable enough over time to render the measurement a reliable estimate of P_{aCO_2}.

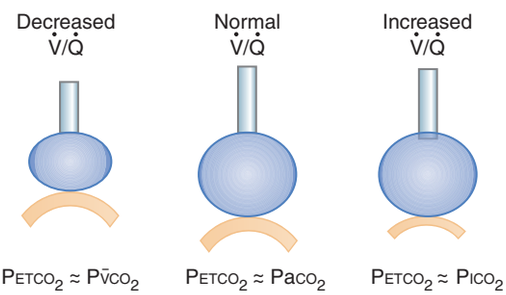


FIGURE 2-18 P_{ETCO_2} with low $\dot{V}/\dot{Q}$, normal $\dot{V}/\dot{Q}$, and high $\dot{V}/\dot{Q}$.

TABLE 2-3
Causes of Increased P[a – ET]CO_2

Pulmonary hypoperfusion
Pulmonary embolism
Cardiac arrest
Positive pressure ventilation (especially excessive PEEP)
High-rate, low-tidal-volume ventilation

With no pulmonary blood flow, $P_{ET}CO_2$ equals zero. Because $P_{ET}CO_2$ is partly determined by the amount of blood flow returning to the lungs from the systemic circulation, it has been used to verify the effectiveness of cardiopulmonary resuscitation (CPR). Adequate CPR is associated with increasing $P_{ET}CO_2$ levels. If $P_{ET}CO_2$ does not rise above 10 mm Hg after 20 minutes of pulseless resuscitation, the prognosis is poor. An abrupt increase in $P_{ET}CO_2$ during CPR indicates a return of spontaneous circulation.

Pulmonary embolism is associated with an increased V_D/V_T. The P(a − ET)CO_2 is increased with pulmonary embolism. Because many conditions increase V_D/V_T, an increased P(a − ET)CO_2 is not specific to pulmonary embolism. However, a normal V_D/V_T suggests that pulmonary embolism is unlikely.

In patients with acute respiratory distress syndrome (ARDS), either too little or too much PEEP increases V_D/V_T and P(a − ET)CO_2. If V_D/V_T is excessive, the minute ventilation requirement might indicate that ventilator liberation is unlikely. As noninvasive monitors during the ventilator discontinuation process, capnometric measurements of the respiratory rate and elevated $P_{ET}CO_2$ are unreliable.

Respiratory Recap

Capnography

- Capnography uses either mainstream or sidestream sampling.
- The CO_2 level is measured by infrared absorption, mass spectrometry, or colorimetric techniques.
- End-tidal P_{CO_2} often is an imprecise reflection of Pa_{CO_2}.
- Capnography is useful in the detection of esophageal intubation.
- End-tidal P_{CO_2} is useful to monitor the effectiveness of cardiopulmonary resuscitation and return of spontaneous circulation.
- Volumetric capnography can be used to measure carbon dioxide production and cardiac output.

Patient safety monitoring during procedural sedation includes pulse rate, blood pressure, respiratory rate, oxygen saturation, ECG, and clinical observation. Noninvasive monitoring of ventilation with capnography is also used in this setting. There are two types of hypoventilation that occur during procedural sedation and analgesia (**Figure 2-19**).[22] An increased $P_{ET}CO_2$ and an increased Pa_{CO_2} characterize bradypneic hypoventilation. Respiratory rate is depressed proportionally greater than tidal volume, resulting in bradypnea, an increase in expiratory time, and an increase in $P_{ET}CO_2$. Bradypneic hypoventilation is commonly observed with opioids. Hypopneic hypoventilation is

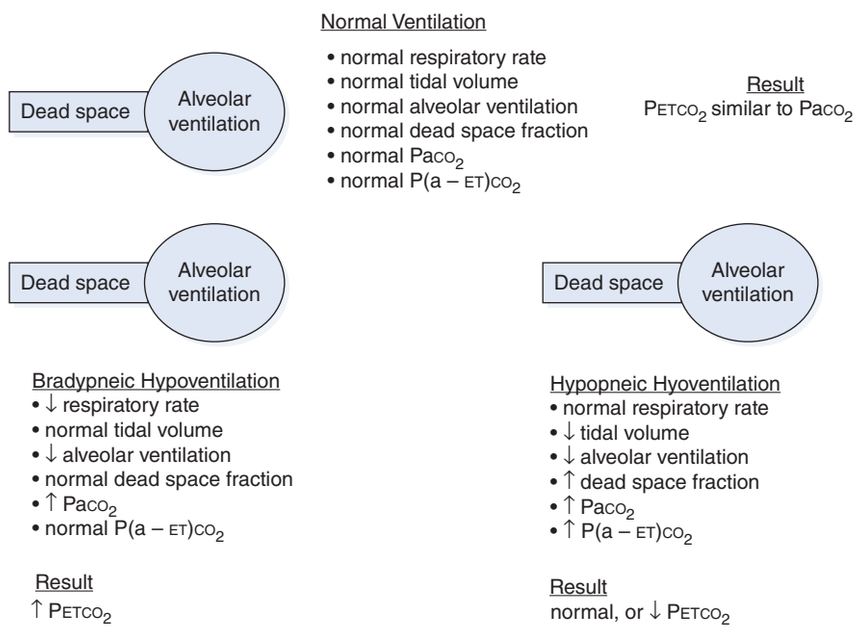


FIGURE 2-19 Physiology of hypoventilation states as related to monitoring of end-tidal P_{CO_2}. $P_{ET}CO_2$ = end-tidal P_{CO_2}, Pa_{CO_2} = arterial P_{CO_2}.
Reproduced from Krauss B, Hess DR. Capnography for procedural sedation and analgesia in the emergency department. *Ann Emerg Med.* 2007;50:172–181, with permission from Elsevier.

STOP AND THINK

During CPR the P_{ETCO_2} is slowly decreasing from 25 mm Hg to 20 mm Hg to 15 mm Hg. Why is this happening and what is the appropriate response?

characterized by a normal or decreased P_{ETCO_2} with an increased P_{aCO_2}. This reflects the relationship between tidal volume and airway dead space, in which dead space is constant and tidal volume is decreasing. Because tidal volume is depressed more than respiratory rate, the result is a low tidal volume that leads to an increase in V_D/V_T. The $P(a-ET)CO_2$ increases with the increase in V_D/V_T. Even though P_{aCO_2} is increasing, P_{ETCO_2} may remain normal or be decreasing. Thus, either an increase or decrease in P_{ETCO_2} might suggest excessive procedural sedation.

Volume-Based Capnography

A normal volume-based capnogram is shown in **Figure 2-20**. It is displayed with the P_{CO_2} on the vertical axis and the volume on the horizontal axis.[23–25] At the beginning of exhalation, the P_{CO_2} remains zero as gas from the anatomic dead space leaves the airway (phase I). The capnogram rises sharply as alveolar gas mixes with dead space gas (phase II). The capnogram then forms a plateau during most of exhalation (phase III). Phase III represents gas flow from the alveoli and therefore is called the *alveolar plateau*. The P_{CO_2} at end-exhalation is the P_{ETCO_2}. Anatomic dead space, alveolar dead space volume, and the volume of exhaled CO_2 ($\dot{V}CO_2$) can be determined from the volume-based capnogram. Volume-based capnography can be measured with stand-alone monitors or with technology incorporated into mechanical ventilators.[26]

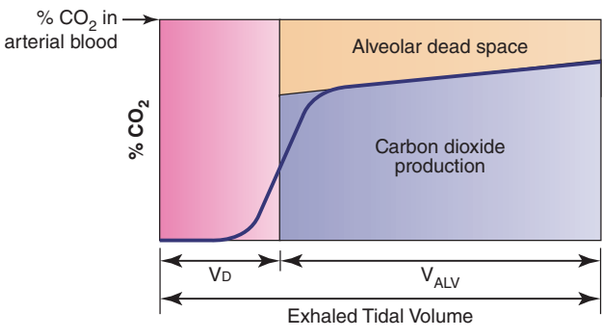


FIGURE 2-20 Components of volume-based capnogram. V_D, anatomic dead space; V_{ALV}, alveolar gas volume.

Reproduced from Longnecker D, Brown D, Newman M, Zapol W. 2008. *Anesthesiology.* McGraw-Hill, New York. (© The McGraw-Hill Companies, Inc.)

Because $\dot{V}CO_2$ is determined by metabolic rate, this can be used to estimate resting energy expenditure (REE):

$$REE = \dot{V}CO_2(L/min) \times 5.52\ kcal/L \times 1440\ min/day$$

Normal $\dot{V}CO_2$ is approximately 200 mL/min (2.8 mL/kg/min).

Using volume-based capnography, it is possible to noninvasively measure cardiac output with the partial CO_2 rebreathing technique (**Figure 2-21**).[27–32] $\dot{V}CO_2$ is calculated on a breath-by-breath basis, and the Fick equation is applied to establish the relationship between $\dot{V}CO_2$ and cardiac output ($\dot{Q}$):

$$\dot{V}CO_2 = \dot{Q} \times (C\bar{v}CO_2 - CaCO_2)$$

where $C\bar{v}CO_2$ represents the CO_2 content of mixed venous blood and $CaCO_2$ represents the CO_2 content of arterial blood. CO_2 rebreathing is performed for 35 seconds every 3 minutes. Assuming that $\dot{Q}$ remains constant during the rebreathing procedure yields the following:

$$\Delta\dot{V}CO_2 = \dot{Q} \times (\Delta C\bar{v}CO_2 - \Delta CaCO_2)$$

where $\Delta\dot{V}CO_2$ is the change in $\dot{V}CO_2$ between normal breathing and rebreathing, $\Delta C\bar{v}CO_2$ is the change in mixed venous carbon dioxide content, and $\Delta CaCO_2$ is the change in arterial carbon dioxide content. If $\Delta C\bar{v}CO_2$ remains constant during rebreathing, the following equation is used:

$$\Delta\dot{V}CO_2 = \dot{Q} \times (-\Delta C\bar{v}CO_2)$$

When end-capillary content ($Cc'CO_2$) is used in place of $CaCO_2$, pulmonary capillary blood flow (PCBF), the blood flow that participates in alveolar gas exchange, is measured rather than $\dot{Q}$, and the following equation is used:

$$\Delta\dot{V}CO_2 = PCBF \times (-Cc'CO_2)$$

Assuming that $-Cc'CO_2$ is proportional to ΔP_{ETCO_2}, the following equation can be used:

$$PCBF = \Delta\dot{V}CO_2/(S \times \Delta P_{ETCO_2})$$

where ΔP_{ETCO_2} is the change in P_{ETCO_2} between normal breathing and rebreathing, and S is the slope of the carbon dioxide dissociation curve from hemoglobin. Because cardiac output is the sum of PCBF and intrapulmonary shunt flow,

$$\dot{Q} = PCBF/(1 - \dot{Q}_S/\dot{Q}_T)$$

The noninvasive method for estimating $\dot{Q}_S/\dot{Q}_T$ is adapted from Nunn's iso-shunt plots, which are a series of continuous curves indicating the relation between

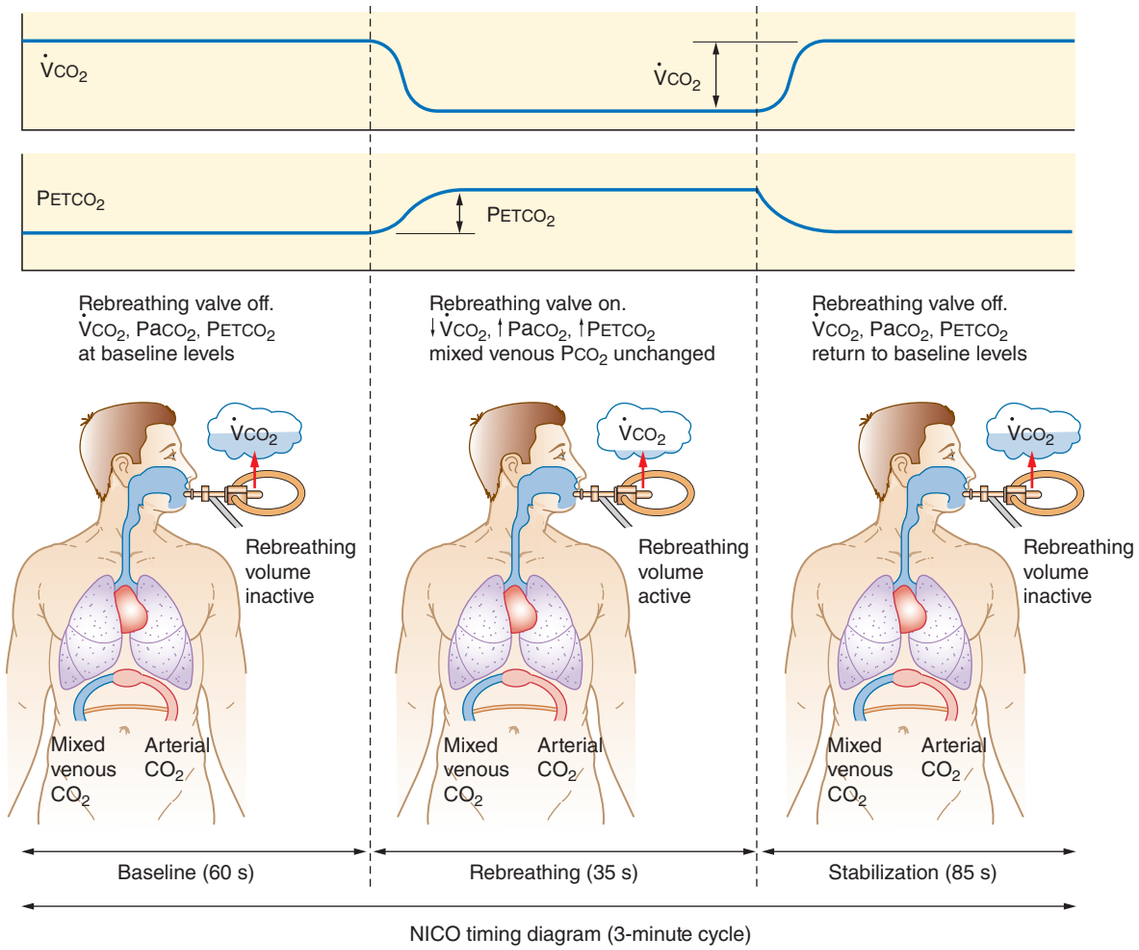


FIGURE 2-21 Rebreathing cycle used to measure cardiac output using the partial CO_2 rebreathing technique.
Modified from Longnecker D, Brown D, Newman M, Zapol W. 2008. *Anesthesiology*. McGraw-Hill, New York. (© The McGraw-Hill Companies, Inc.)

arterial oxygen pressure (Pa_{O_2}) and F_{IO_2} at different levels of right-to-left shunt. Pa_{O_2} is noninvasively estimated using a pulse oximeter.

There are several potential limitations of partial rebreathing for the measurement of cardiac output. In nonparalyzed patients, rebreathing increases the respiratory rate, which reduces the magnitude of the signal and limits the ability to detect changes in P_{ETCO_2} and $\dot{V}CO_2$. Noise is increased by respiratory pattern irregularities that produce an unstable P_{ETCO_2} and $\dot{V}CO_2$, and these may impair accuracy. Additional cardiac output not calculated due to shunt fraction is estimated from Sp_{O_2} and F_{IO_2}, and these may also introduce errors.

Transcutaneous Blood Gas Monitoring

Transcutaneous monitoring of O_2 and CO_2 (Ptc_{O_2} and Ptc_{CO_2}) uses measurements at the skin surface to provide estimates of Pa_{O_2} and Pa_{CO_2} (**CPG 2-2**).[33] This type of monitoring has been used with neonates, infants, small children, and patients with peripheral vascular disease. The devices warm the skin to induce hyperemia, and then electrochemically measure oxygen and carbon dioxide partial pressures at the skin surface, providing a noninvasive means of continuously monitoring arterial oxygenation and ventilation. They have been particularly useful in neonates and infants, in whom arterial sampling is technically difficult. Also, because intact circulation is a prerequisite for successful hyperbaric oxygen therapy, candidates with peripheral vascular disease are screened with transcutaneous O_2 monitors. Because Ptc_{O_2} is affected by perfusion, it may reflect the quantity of oxygen delivered to the skin under the electrode (the product of cardiac output and arterial oxygen content). Ptc_{O_2} has been used in adults to monitor the results of vascular surgery, the intent being to evaluate perfusion rather than Pa_{O_2} per se.

The transcutaneous oxygen electrode uses the polarographic technique. Heating coils surround the

CLINICAL PRACTICE GUIDELINE 2-2

Transcutaneous Blood Gas Monitoring for Neonatal and Pediatric Patients

Indications

- The need to monitor the adequacy of arterial oxygenation and/or ventilation.
- The need to quantitate the response to diagnostic and therapeutic interventions as evidenced by $Ptco_2$ and/or $Ptcco_2$ values.

Contraindications

In patients with poor skin integrity or adhesive allergy, or both, transcutaneous monitoring may be relatively contraindicated.

Hazards and Complications

$Ptco_2$ and $Ptcco_2$ monitoring are considered safe procedures, but because of device limitations, false-negative and false-positive results may lead to inappropriate treatment of the patient. In addition, tissue injury may occur at the measuring site (e.g., erythema, blisters, burns, skin tears).

Limitations

- $Ptco_2$ is an indirect measurement Pao_2 and $Ptcco_2$ is an indirect measurement of $Paco_2$.
- The procedure may be labor intensive, although newer designs have made it quicker and simpler.
- A prolonged stabilization period is required after placement.
- Manufacturers state that electrodes must be heated to produce valid results; however, clinical studies suggest that valid results may be obtained with $Ptcco_2$ electrodes operated at lower-than-recommended temperatures.
- The theoretic basis for mandatory heating of the $Ptco_2$ electrode has not been established.
- Improper calibration, trapped air bubbles, and damaged membranes are possible and may be difficult to detect.
- Hyperoxemia ($Pao_2 > 100$ mm Hg).
- Hypoperfused state (shock, acidosis).
- Improper electrode placement or application.
- Use of vasoactive drugs.
- Nature of the patient's skin and subcutaneous tissue (skinfold thickness, edema).

Modified from AARC clinical practice guideline: transcutaneous blood gas monitoring for neonatal and pediatric patients—2004 revision and update. *Respir Care*. 2004; 49:1069–1072. Reprinted with permission.

anode, and the platinum cathode is centered inside the anode ring. The heating coil induces local hyperemia to arterialize the skin surface. A flat membrane separates the electrode from the skin. Oxygen diffuses from the blood vessels to the skin surface and through the membrane into the electrode.

Respiratory Recap

Transcutaneous Blood Gas Monitors

- Warmed electrodes are placed on the skin to measure $Ptco_2$ and $Ptcco_2$ and estimate Pao_2 and $Paco_2$.
- The electrodes operate on the same principles as blood gas electrodes.
- A miniaturized single sensor combines measurement of pulse oximetry (Spo_2) and $Ptcco_2$.

Transcutaneous carbon dioxide electrodes use a flat glass membrane permeable to CO_2. A pH electrode is positioned behind the membrane in a bicarbonate buffer. Carbon dioxide diffuses from the skin through the membrane and reacts with the buffer to produce a change in $[H^+]$. Similar to the Pco_2 blood gas electrode, the $Ptcco_2$ electrode detects changes in $[H^+]$ but is calibrated to display Pco_2. Unlike the $Ptco_2$ electrode, a reasonably good correlation with $Paco_2$ can be obtained at a temperature of 37° C (98.6° F). Because $Ptcco_2$ is consistently greater than $Paco_2$, manufacturers incorporate a correction factor so that the $Ptcco_2$ that is displayed approximates the $Paco_2$. Like $Ptco_2$, the proximity with which $Ptcco_2$ approximates $Paco_2$ is the result of a complex set of physiologic events, and thus it is incorrect to believe that $Ptcco_2$ is the $Paco_2$. For example, decreased tissue perfusion causes the $Ptcco_2$ to increase.

A miniaturized single sensor combines the measurement of pulse oximetry (Spo_2) and $Ptcco_2$ (**Figure 2-22**).[34–37] It uses a heated Severinghaus electrode combined with a pulse oximetry sensor and is attached to the earlobe with a clip. The sensor is calibrated using a one-point dry gas calibration with 7% CO_2 when the sensor is placed in its calibration chamber. The sensor is heated to 42° C to induce local vasodilation and enhance skin permeability for CO_2 to improve gas diffusion at the site of measurement. A drop of contact gel is applied in the center of the attachment clip before the sensor is applied. The sensor is removed after 8 hours, recalibrated, and fixed on the other earlobe.

A limitation in the use of transcutaneous blood gas monitoring is the need for a heated electrode. This carries the risk of skin burns and requires that the sensor be rotated among monitoring sites on a regular basis. The reliability of transcutaneous monitoring for accurately estimating arterial blood gases is often questioned, which has led to limited use of this technology.

(A)

(B)

FIGURE 2-22 A sensor for noninvasive monitoring of transcutaneous carbon dioxide and oxygen saturation.
Courtesy of SenTec AG.

STOP AND THINK

The $Ptcco_2$ suddenly drops to zero. What is the best explanation for this and what is the appropriate clinical response?

Respiratory Rate and Pattern

The respiratory rate is one of the four vital signs. It is a core component of monitoring, because respiratory rate slowing (***bradypnea*** or *apnea*) or increasing (*tachypnea*) may warn of clinical deterioration or impending respiratory arrest. In sleep laboratories, sophisticated respiratory rate and pattern monitoring are required during polysomnography. Respiratory (apnea) monitors are also used for infant studies in the home.

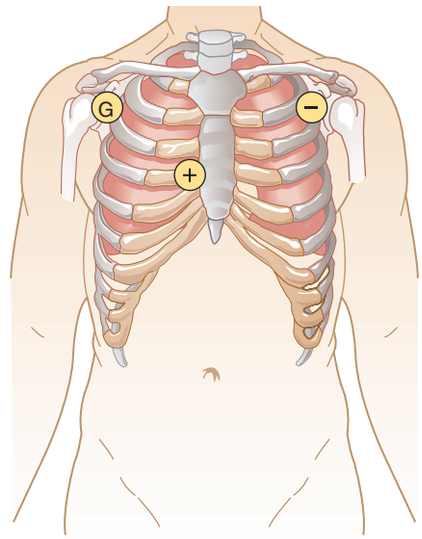
The respiratory rate is easily measured at the bedside by counting chest excursions for 30 seconds (and multiplying by 2 to obtain breaths/min) or for 60 seconds. However, this method may be inaccurate, perhaps because clinicians underestimate the importance of this vital sign.

With **impedance pneumography**, the respiratory rate and excursion can be measured by use of two electrodes placed on the chest wall. A high frequency (20 to 100 Hz) and low ampere alternating current (less than 100 μA) is passed between the electrodes on the chest surface (this is, of course, a current too small to be felt by the patient). The strength of the current when it reaches the receiving electrode varies according to the *impedance,* or effective resistance of the tissue between the electrodes. During chest expansion, as the distance between the electrodes increases, impedance increases, causing the current to decrease. The change in current is electronically processed to calculate the respiratory rate (**Figure 2-23**). During normal tidal breathing, the signal can also be calibrated to measure tidal volume. However, volume measurements deteriorate with patient movement or a change in position. Moreover, an obstructive apnea cannot be detected with this method, because the chest wall continues to move despite cessation of airflow. These systems usually are configured as

Respiratory Recap

Techniques to Measure the Respiratory Rate

- Counting by inspection at the bedside
- Impedance pneumography
- Respiratory inductance plethysmography
- Fiberoptic plethysmography
- Nasal temperature- and pressure-sensing devices
- Piezoelectric plethysmography
- Acoustic technology
- Capnography



(A)

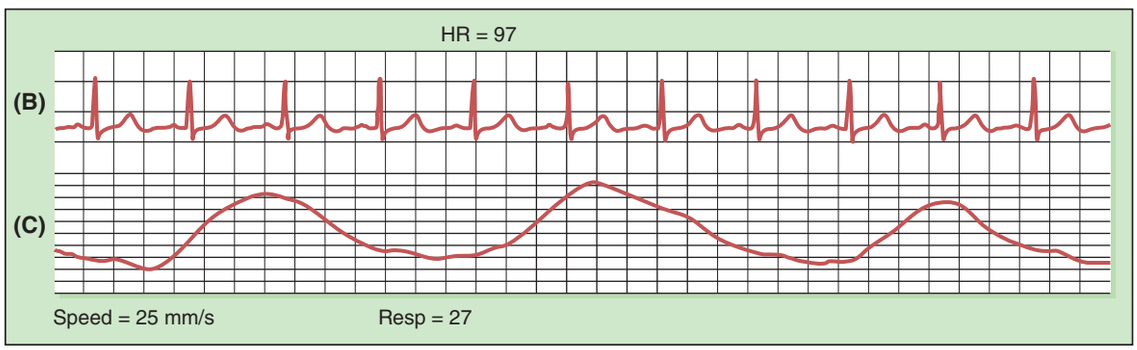


FIGURE 2-23 (**A**) Electrode placement for three-lead array. (**B**) Cardiac rate and rhythm recorded from a single ECG lead. (**C**) Respiratory impedance plethysmography tracing obtained from the same electrode array.

a plug-in module for bedside monitoring of the respiratory rate in the ICU. They use the same electrodes that generally are applied to the patient for cardiac rhythm monitoring. Infant home apnea monitors are based on this technology.

The most accurate method for indirect measurement of tidal volume is **respiratory inductance plethysmography (RIP)**. Inductance sensors use a circuit of coiled wire woven into an elastic band and excited by an AC current. *Inductance* results from alternating electrical currents that create magnetic fields around themselves and the changes in those magnetic fields that alter other electrical currents they encounter. During tidal breathing, the bands stretch and relax. As the belt is displaced during chest expansion, changes in the magnetic fields around the wire coils result in changes in the excitation current. Variations in the excitation current caused by the expansion and contraction of the belt are electronically processed to provide a display of the ventilatory pattern, rate, and change in volume.

When rib cage and abdominal bands are used simultaneously, respiratory motion is described more completely, resulting in tidal volume measurements that correlate well with spirometry (±10%). RIP is stable and comfortable despite patient movement, which makes it suitable for use in sleep laboratories. This noninvasive technique has also been used in the ICU to monitor noninvasive ventilation and to conduct studies of the effect of PEEP on the functional residual capacity. Because it is more expensive than impedance pneumography, its use in the ICU usually is reserved for cases in which noninvasive measurements of tidal volume or changes in functional residual capacity are desired.

A modification of inductance plethysmography, **fiberoptic plethysmography**, uses optical fibers woven into elastic belts. Light is passed through the fibers into a photodetector. When rib cage or abdominal displacements stretch the elastic belt, large changes in light transmission through the fibers result. The change in light transmission is electronically processed to provide

data similar to RIP. This technique has the advantage of being free of electrical interference and electrically safe for patients. It also is more sensitive than conventional RIP to small changes in lung volume. Clinical experience with this device is limited.

Temperature and pressure probes can be used to measure the rate and pattern of airflow. Disordered breathing, hypopneas, and apneas are characterized in this way. **Thermistors** and **thermocouples** detect bidirectional airflow at the nose and mouth by sensing the temperature difference between inspired room air and exhaled air that has been warmed to body temperature (**Figure 2-24**). The ability of these devices to detect airflow diminishes if the room air temperature approaches body temperature. Likewise, if the sensor touches skin and rises to body temperature, airflow cannot be detected. Other limitations of thermally based sensors are that they cannot be calibrated in terms of airflow and provide only qualitative information, that moisture condensing on the probe compromises temperature-sensing capabilities, and that loss of signal may occur if the sensor becomes dislodged from the airstream.

To simplify the plethysmography apparatus, the wire coils have been removed from the elastic belts and replaced by a piezoelectric buckle (**piezoelectric plethysmography**). This reduces the cost and allows for belts that can be adjusted to different-size patients. The buckle encloses a sensor, which generates a voltage in response to stretch passed through the ends of the belts. The sensor is not calibrated, however, and provides only a qualitative record of chest or abdominal movement, hence the term *effort belts*. Effort belts based on piezoelectric sensors do not require a battery. As with all belt-type transducers, the quality and interpretability of the respiratory signal are affected if the belt loosens or slips out of the original position.

Most modern mechanical ventilators have integrated airflow transducers designed to monitor and display the respiratory rate. Capnography can also be used to assess respiratory rate. This uses the fact that CO_2 is only present in the exhaled breath. Thus, each decrease in CO_2 to zero represents a respiratory cycle.

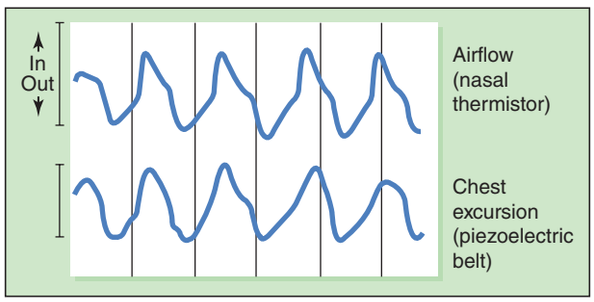


FIGURE 2-24 Airflow and chest and abdominal excursion waveforms are used to monitor respiratory rate and pattern during sleep studies.

Adapted from materials from Pro-Tech Services, Woodinville, WA.

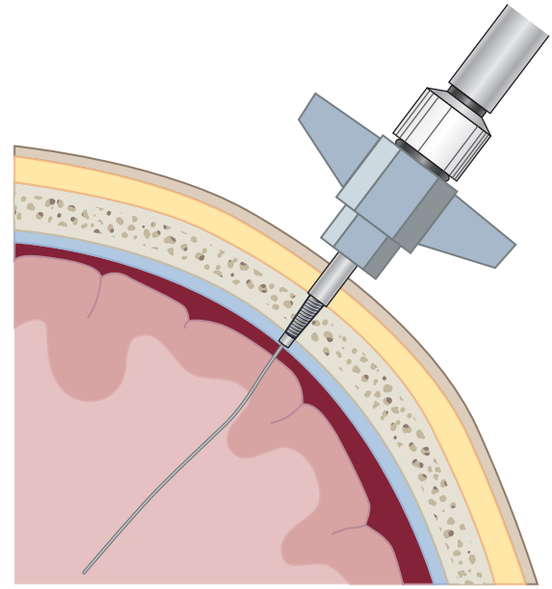


FIGURE 2-25 Coronal section illustrating the placement of the brain tissue oxygenation probe in the brain parenchyma.

Reproduced from Martini RP, Deem S, Treggiari MM. Targeting brain tissue oxygenation in traumatic brain injury. *Respir Care.* 2013;58:162–172.

Acoustic monitoring noninvasively and continuously measures respiration rate using an adhesive sensor with an integrated acoustic transducer applied to the patient's neck. Using acoustic signal processing, the respiratory signal is separated and processed to display continuous respiration rate. This technology is commercially available on the Masimo Rainbow SET Acoustic Monitoring device.

Brain Tissue Po_2

The **brain tissue Po_2 ($Pbto_2$)** measures dissolved oxygen in a small area of brain tissue (**Figure 2-25**).[38] The $Pbto_2$ probe contains polarographic Clark electrodes covered in a semipermeable membrane at the tip of a flexible microcatheter. It is a highly localized measurement, with a sampling area of 7 to 15 mm^2. The probe can be placed through the same burr hole as used with a monitor for intracranial pressure. The location of placement affects the values of $Pbto_2$ measured. Placement into an area of damaged brain, compared to placement into a relatively normal area, will result in data that fail to reflect global dissolved oxygen. Interventions to improve $Pbto_2$ are similar to those used to decrease intracranial pressure. Treatment generally becomes indicated for $Pbto_2$ <20 mm Hg. Periodically, the reliability of measured $Pbto_2$ is assessed by a brief increase in FIo_2 to 1. $Pbto_2$ should rise in tandem with the Pao_2. It is unclear whether targeting strategies to improve $Pbto_2$ result in better outcomes for

brain-injured patients, and for this reason monitoring of $Pbto_2$ has not become widespread.

Near-Infrared Spectroscopy

Near-infrared spectroscopy (NIRS) is a technique for noninvasive monitoring of peripheral tissue oxygenation (Sto_2).[39–41] It measures muscle oxygen metabolism and microvascular dysfunction in critically ill patients. NIRS uses the differential absorption properties of oxygenated and deoxygenated hemoglobin. The near-infrared light (700–850 nm) crosses biological tissues, which have a low absorption power, and is absorbed only by hemoglobin, myoglobin, and oxidized cytochrome. The contribution of myoglobin and cytochrome to the light attenuation signal is small and thus the NIRS signal is derived predominantly from hemoglobin present within the volume of tissue crossed by the near-infrared light. The NIRS signal is limited to vessels that have a diameter less than 1 mm (e.g., arterioles, capillaries, and venules).

Commercially available NIRS monitors can provide fractions of oxyhemoglobin and deoxyhemoglobin, used to calculate Sto_2 as well as the total tissue hemoglobin (TTH) and the absolute tissue hemoglobin index (THI), two indicators of blood volume in the region of microvasculature sensed by the probe and expressed in arbitrary units. Light tissue penetration is directly related to the spacing between illumination and detection fibers. At 25 mm spacing, approximately 95% of the detected optical signal is from a depth of 0 to 23 mm. NIRS monitors vary in terms of wavelength selection, number of wavelengths, optode spacing, and algorithms used to calculate data from the absorption data. The NIRS probes in current use measure reflected light and thus the NIRS light source is placed beside the light sensor.

Thenar Sto_2 (**Figure 2-26**) is determined real time at the bedside and may be useful to guide the early resuscitation of critically ill patients, especially in hypodynamic state. However, Sto_2 may be normal in patients with severe sepsis or septic shock, which limits its utilization during resuscitation of septic patients. By inducing an occlusion stress, a variety of dynamic variables can be defined that provide a measure of local metabolic demand and microvascular reactivity. Due to anatomic conditions, both the brachioradial muscle and the muscles of the thenar eminence can be easily subjected to the vascular obstruction test. Alterations in these NIRS-derived dynamic variables are common in patients with severe sepsis and are associated with a poor outcome.

FIGURE 2-26 Near-infrared spectroscopy probe to measure thenar Sto_2.
Courtesy of Hutchinson Technology.

Key Points

- Pulse oximetry measures oxygen saturation by passing two wavelengths of light through a pulsating vascular bed.
- The accuracy of pulse oximetry is ±4%.
- A number of factors can affect the accuracy and performance of pulse oximetry.
- New designs of pulse oximeters measure SpHb, SpCO, and SpMet; the clinical utility of these measures is yet to be determined.
- Capnometry measures the concentration of carbon dioxide exhaled from the lungs.
- Capnography can be useful for detection of esophageal intubation, the adequacy of chest compressions, and the return of spontaneous circulation during CPR.
- End-tidal PCO_2 may not be an accurate reflection of $PaCO_2$.
- Volumetric capnography can be used to measure carbon dioxide production and cardiac output.
- Transcutaneous PO_2 and PCO_2 are measured with a heated electrode placed on the skin.
- The respiratory rate and pattern can be monitored through observation of chest wall motion, monitoring of nasal airflow, and measurement of chest wall motion.
- A polarographic electrode can be used to measure $Pbto_2$, but it is unknown whether this monitor affects outcomes in patients with traumatic brain injury.
- Near-infrared spectroscopy is a technique for noninvasive monitoring of peripheral tissue oxygenation in various tissues.

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