

Respiratory Monitoring

Dean R. Hess

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OUTLINE

Pulse Oximetry
Capnography
Transcutaneous Monitoring
Respiratory Rate and Pattern
Brain Tissue Po_2
Near-Infrared Spectroscopy

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 how pulse oximetry can be used to assess carboxyhemoglobin, methemoglobin, and respiratory rate.
6. Describe methods used to measure carbon dioxide in the exhaled gas.
7. Compare sidestream and mainstream capnography.
8. Compare time-based and volume-based capnography.
9. Draw a normal capnogram and a capnogram for a patient with obstructive lung disease.
10. Discuss the physiologic issues related to end-tidal Pco_2 and how they affect the relationship between end-tidal and arterial Pco_2 .
11. Explain how volume-based capnography can be used to measure carbon dioxide production and cardiac output.

12. Discuss the principle of operation of transcutaneous blood gas monitors.
13. Discuss the limitations of transcutaneous blood gas monitoring.
14. List techniques that can be used to measure respiratory rate.
15. Describe how minute ventilation can be monitored noninvasively.
16. Discuss the use of brain Po_2 monitoring.
17. Describe near-infrared spectroscopy.

KEY TERMS

absorption	penumbra effect
acoustic monitoring	perfusion index (PI)
Beer-Lambert law	piezoelectric
bradypnea	plethysmography
brain tissue Po_2 (Pbto_2)	plethysmographic
capnogram	variability index (PVI)
capnography	pulse oximetry
capnometry	Raman spectroscopy
end-tidal Pco_2	respiratory inductance
fiberoptic plethysmography	plethysmography (RIP)
impedance pneumography	spectrophotometry
mass spectrometer	thermistor
near-infrared	thermocouple
spectroscopy (NIRS)	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. Monitoring is also used to assess patient response to such clinical interventions, as well as to ensure patient safety. This chapter discusses respiratory monitoring of oxygenation and ventilation.

Pulse Oximetry

Pulse oximetry noninvasively estimates the hemoglobin oxygen saturation of arterial blood.¹⁻³ It is based on **spectrophotometry**, a process that identifies substances based on 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):

$$A = L \times C \times \epsilon$$

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 (HbO₂) 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 HbO₂ and Hb differ in their 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

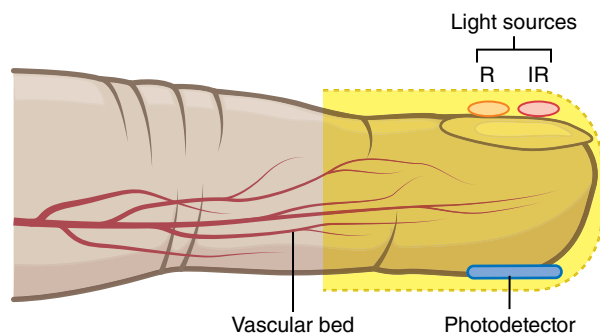


FIGURE 2-1 Pulse oximeter probe fitted over the patient's finger, showing the position of the light sources and detector.

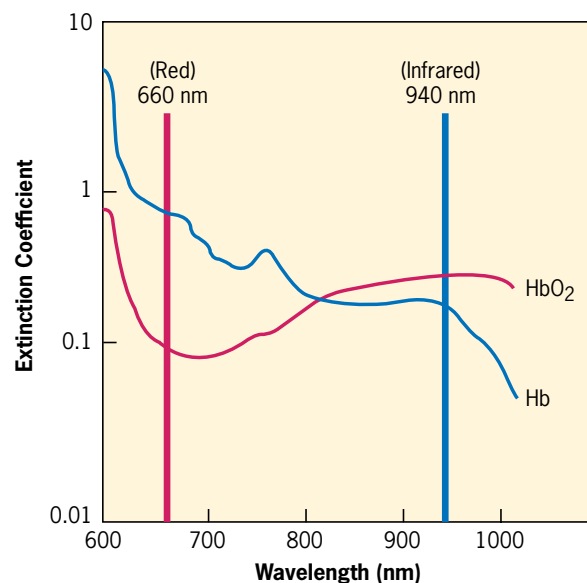


FIGURE 2-2 Absorption spectra for oxyhemoglobin and deoxyhemoglobin for the range of wavelengths relevant to pulse oximetry.

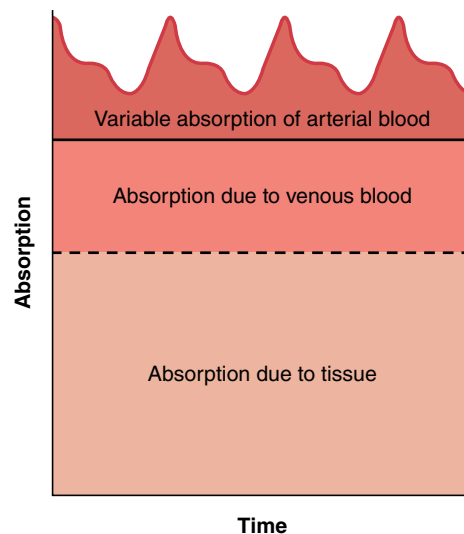


FIGURE 2-3 Dynamic and static light absorption during pulse oximetry.

Courtesy of Philips Respironics.

pulsatile absorption eliminates the effects of nonpulsatile components such as tissue, bone, and venous blood.

Oxygen saturation (SpO₂) is related to the ratio of minimum and maximum absorption at each wavelength (Figure 2-4). In the pulse oximeter, a calibration curve for the pulse-added absorption at the two wavelengths is calculated and stored in a software algorithm. Devices vary by manufacturer in the type of LED, photodiode, and microprocessor used. Because the SpO₂ 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

SpO ₂	660 nm (R)	940 nm (IR)	R/IR
0%			~3.4
85%			1.0
100%			0.43

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

arterial bed to a photodetector on the opposite side. With *reflectance spectrophotometry*, pulse oximeter sensors place the light source and the detector on the same side of the arterial bed.

Pulse oximeter measurements have an accuracy of $\pm 4\%$ at SpO₂ greater than 80%. Note that $\pm 4\%$ is greater than the accuracy level claimed by manufacturers. Manufacturers publish accuracy at one standard deviation, but two standard deviations are necessary to cover 95% of measurements. Thus, an accuracy of $\pm 2\%$ (one standard deviation) will be more likely $\pm 4\%$ in practice. Pulse oximeters are less accurate at SpO₂ less than 80%, but the clinical importance of this finding is questionable. The calibration curves are developed from studies on healthy volunteers; they vary by manufacturer depending on the range of concentrations achieved by the volunteers and the accuracy of the comparison co-oximeter. The output of the LEDs also varies from

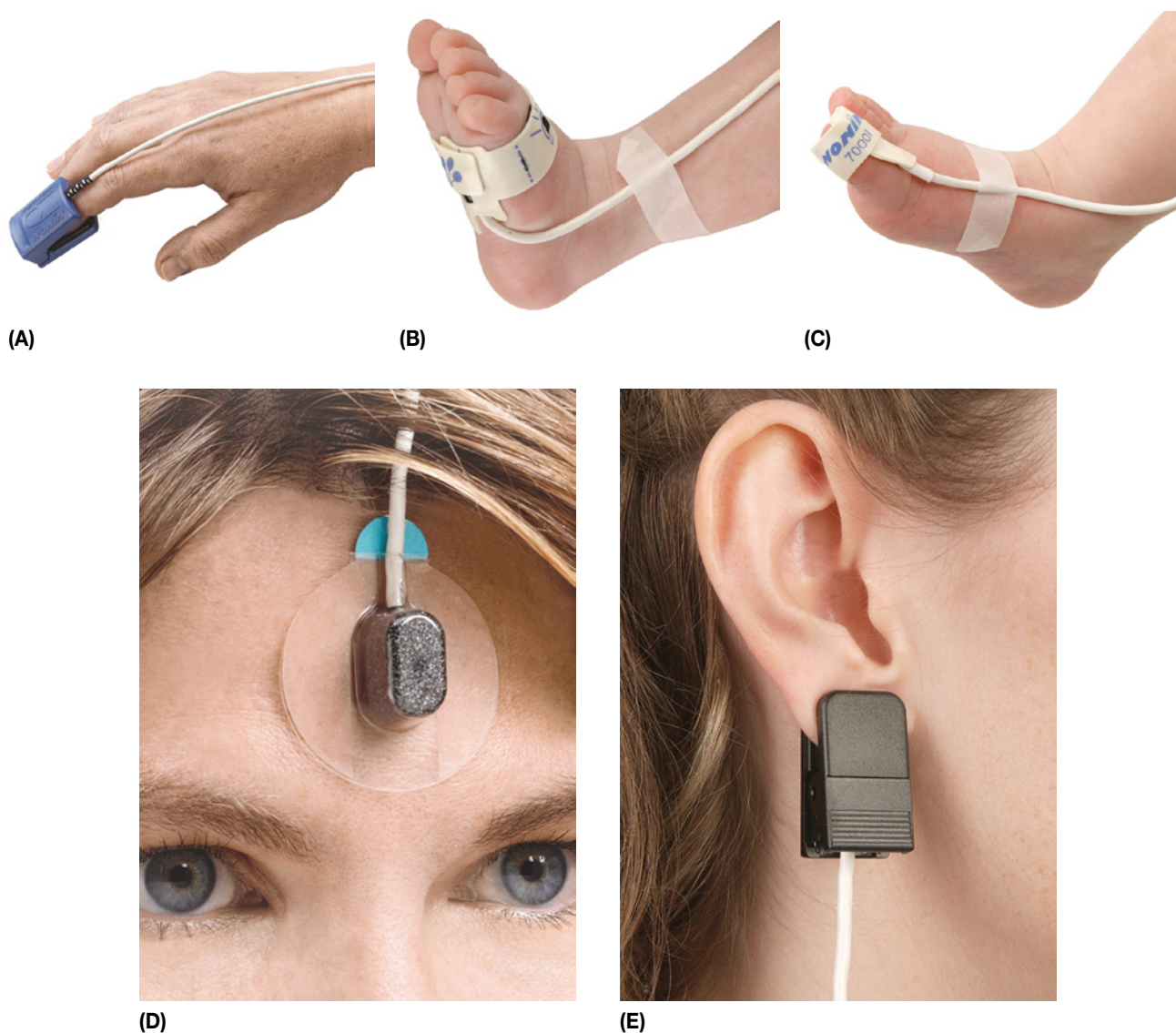


FIGURE 2-5 Examples of pulse oximetry probes. (A) Finger probe. (B) Foot probe. (C) Toe probe. (D) Forehead probe. (E) Ear probe.

Courtesy of Nonin Medical, Inc.

probe to probe, so 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 dissociation curve. If the pulse oximeter displays an SpO_2 of 95%, the true saturation 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 approximately 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, respiratory acidosis will cause the curve to shift to the right, resulting in a decreased SpO_2 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 practice of spot-checking 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.

Respiratory Recap

Pulse Oximetry

- Pulse oximetry measures oxygen saturation by applying a variation of the Beer-Lambert law.
- The accuracy of pulse oximeters is $\pm 4\%$ and can be affected by abnormal hemoglobin, motion, and low perfusion.
- Some pulse oximeters measure hemoglobin, carboxyhemoglobin, methemoglobin, and respiratory rate.
- Some pulse oximeters display the perfusion index and plethysmogram variability index.

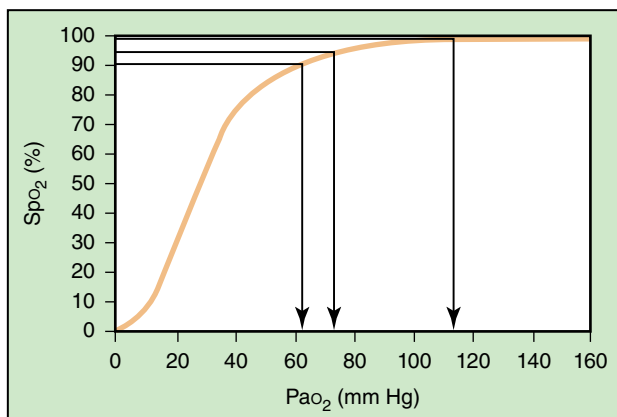


FIGURE 2-6 If the pulse oximeter displays an SpO_2 of 95%, the arterial oxygen saturation could be as low as 91% or as high as 99%. Note that this translates to a wide range of PaO_2 .

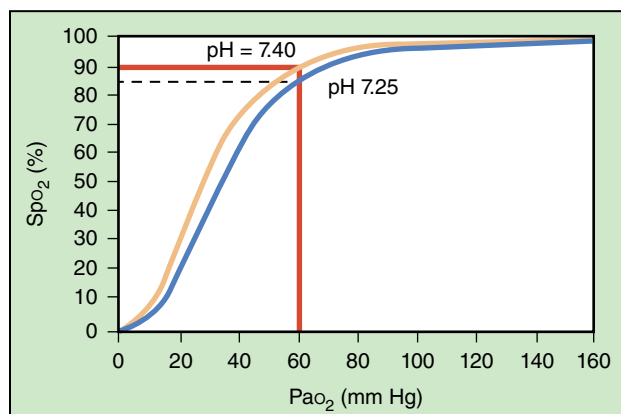


FIGURE 2-7 Note that a shift in the oxyhemoglobin equilibration curve results in a change in SpO_2 without a change in PaO_2 .

Limitations

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

$$\text{SpO}_2 (\%) = \frac{\text{HbO}_2}{(\text{HbO}_2 + \text{Hb})} \times 100$$

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.⁴ For methemoglobin (HbMet), the light absorption for red and infrared light is nearly identical, resulting in an 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%, but causes the SpO_2 to be inaccurately high for an oxygen saturation less than 85%. Fetal hemoglobin and sickle cell anemia 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%—an error 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 initiating pulse oximetry.⁶ Intravascular dyes (methylene blue and indocyanine green) also cause an underestimation

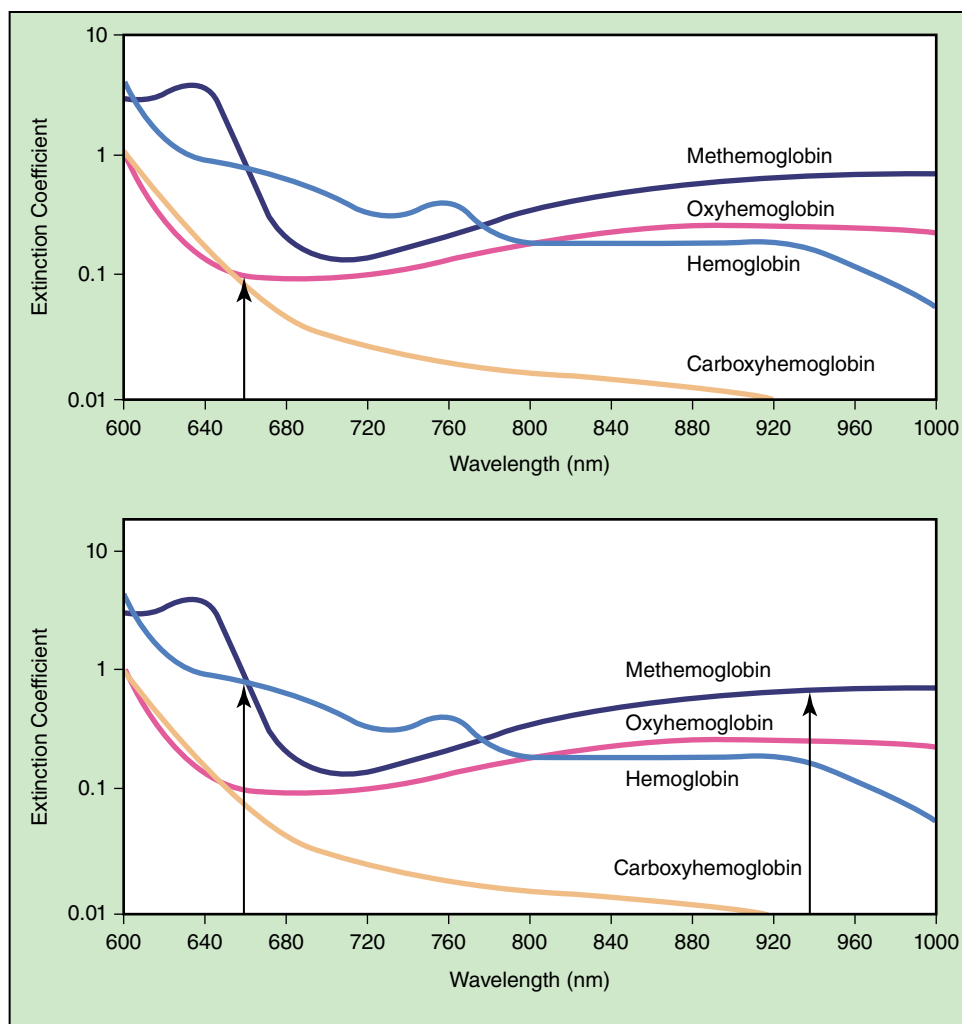


FIGURE 2-8 (A) At 660 nm, the absorptions for oxyhemoglobin and for carboxyhemoglobin are nearly identical. (B) The absorption for methemoglobin is nearly identical at 660 nm and 940 nm.

of SpO_2 . Hyperbilirubinemia has no effect on the accuracy of pulse oximetry 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. In such a case, 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. In rare cases, 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 no other absorbers appear between the LEDs and the 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 Low perfusion leads to 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 in an effort to eliminate motion artifacts from the pulse signal. 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 so as 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 them 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, such that the parts of the waveform that are synchronous with the heart rate remain unattenuated and therefore contribute more to the calculated SpO_2 . Because these algorithms are proprietary, details on how each manufacturer's technology identifies and processes the incoming signals are not available. The clinical performance of the new-generation pulse oximeters is better than that of earlier devices, although the performance of any single new-generation device does not appear to be superior to that of any of the others.

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?

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 estimates of HbCO), SpMet (pulse oximeter estimates of HbMet), and SpHb (pulse oximeter estimates of hemoglobin concentration). This technology has several limitations, however. Because it uses the conventional two-wavelength red and infrared algorithm to determine SpO_2 , significant levels of either HbCO or HbMet will leave the displayed SpO_2 subject to the same errors described earlier. However, the high SpCO or SpMet indicator displayed would alert the user to this error. Another limitation is the crosstalk between the HbMet and HbCO measurement channels.⁴ In the presence of significant HbMet levels, the device will identify 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 accuracy of SpCO is $\pm 6\%$; thus, this measurement should not be used for triage or patient

management.^{1,7-9} An elevated SpCO could broaden the diagnosis of CO poisoning in patients without symptoms. In contrast, a low SpCO in patients suspected of CO poisoning should never rule out CO poisoning and should always be confirmed by blood HbCO . Studies evaluating the accuracy of SpHb have reported mixed results.¹⁰⁻¹³

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, thereby indicating the severity of air trapping in patients with obstructive airway disease (Figure 2-9).¹⁴⁻¹⁸ In patients with obstructive lung disease and elevated pulsus paradoxus, an altered pulse oximetry baseline tracing will be 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:

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

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. This noninvasive measure of peripheral perfusion 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 indicate the intrathoracic pressure relative to the intravascular volume. PVI is a measure of the dynamic changes in the PI that occur during the respiratory cycle:

$$\text{PVI} (\%) = 100 \times (\text{PI}_{\text{max}} - \text{PI}_{\text{min}})/\text{PI}_{\text{max}}$$

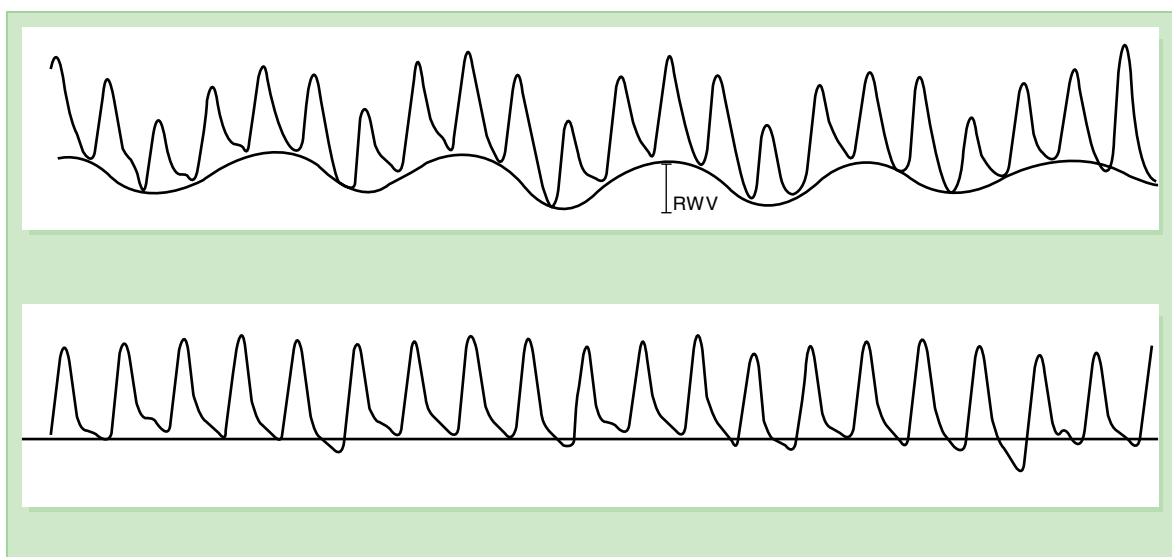


FIGURE 2-9 Pulse oximeter tracings from a 60-year-old woman with an exacerbation of chronic obstructive pulmonary disease who was admitted to the ICU in ventilatory failure. **(A)** The patient's pulse oximetry tracing at the time of admission, revealing the respiratory variability in the pulse oximeter 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(2):475–481. Used with permission from the American College of Chest Physicians.

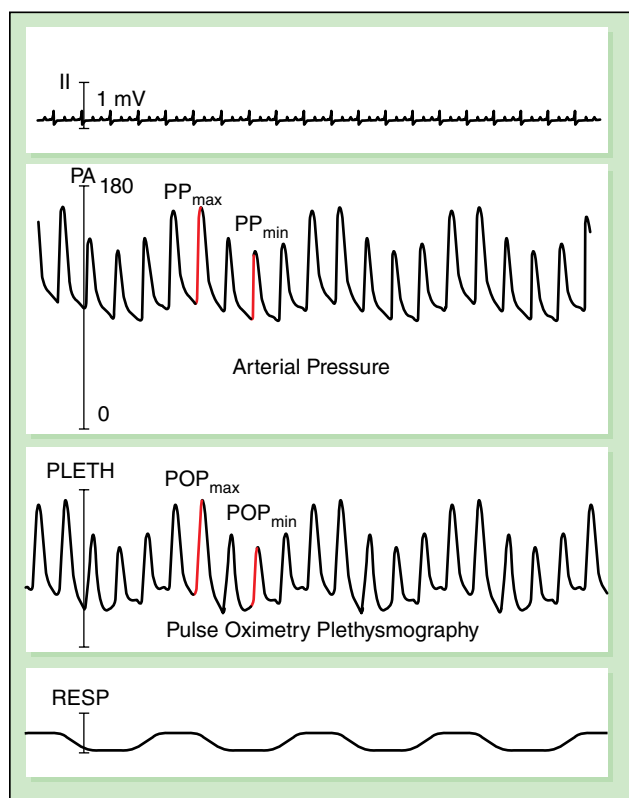


FIGURE 2-10 Comparison of invasive arterial pressure and pulse oximeter plethysmography recordings. Simultaneous recording of electrocardiographic lead (II), systemic arterial pressure (PA), pulse oximetry plethysmography (PLETH), and respiratory signal (RESP) in one illustrative patient. POP, pulse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

Similar to Δ POP, the greater the PVI, the greater variability in the waveform variability over a respiratory cycle.

Respiratory Rate

The alternating current signal of the pulse oximeter plethysmogram indicates the amplitude modulation (Δ POP). The direct current signal indicates the baseline modulation of the plethysmogram at the breathing frequency, which is related to the movement of nonpulsatile venous blood under the probe. The direct current part of the plethysmogram reflects breathing frequency, whereas the alternating current part reflects arterial pulsations. The amplitude of respiratory-induced intensity variations varies with changes in intrathoracic pressure due to tidal breathing. The amplitude of the direct current signal is also affected by breathing frequency, with an amplitude decrease occurring in conjunction with increased breathing frequency. Various companies have developed algorithms to extract the breathing frequency from the pulse oximeter plethysmogram. This technology, which is commercially available, displays the SpO_2 along with the heart rate and respiratory rate.

Capnography

Capnometry and capnography are noninvasive techniques that measure the carbon dioxide levels in expired gas (CPG 2-1).¹⁹ **Capnometry** refers to the numeric display of CO_2 measurements taken from the airway. When the CO_2 level is plotted against time or volume and displayed graphically as a waveform, the result is called **capnography**. Most capnometers measure CO_2

CLINICAL PRACTICE GUIDELINE 2-1

Capnography/Capnometry During Mechanical Ventilation

- Continuous waveform capnography is recommended in addition to clinical assessment as the most reliable method of confirming and monitoring correct placement of an endotracheal tube.
- If waveform capnography is not available, a non-waveform exhaled CO_2 monitor in addition to clinical assessment is suggested as the initial method for confirming correct tube placement in a patient in cardiac arrest.
- PETCO_2 is suggested as a method to guide ventilator management.
- Continuous capnometry during transport of a mechanically ventilated patient is suggested.

- Capnography is suggested to identify abnormalities of exhaled air flow.
- Volumetric capnography is suggested to assess CO_2 elimination and $\text{V}_\text{D}/\text{V}_\text{T}$ to optimize mechanical ventilation.
- Quantitative waveform capnography is suggested in intubated patients to monitor the quality of cardiopulmonary resuscitation (CPR), optimize chest compressions, and detect return of spontaneous circulation during chest compressions or when rhythm check reveals an organized rhythm.

Walsh BW, Crotwell DN, Restrepo RD. Capnography/capnometry during mechanical ventilation: 2011. *Respir Care* 2011;56(4):503–509. Reprinted with permission.

by infrared absorption, although mass spectrometry and Raman spectrometry can also be used. Capnometers can take multiple forms: They can be incorporated into the bedside monitor, can be handheld units (sometimes also incorporating pulse oximetry), can be incorporated into the ventilator, or can be small devices attached directly to the artificial airway (**Figure 2-11**).

Two airway sampling systems are used in capnometry: *mainstream* sensors and *sidestream* sensors (**Figure 2-12**). Each approach has both advantages and

disadvantages (**Table 2-1**). The mainstream capnometer is placed directly into the breathing circuit directly at the airway. 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, these devices may be adversely affected by the accumulation of moisture, secretions, and debris. They also add dead space into the circuit. Mainstream designs are best suited to patients with artificial airways.



FIGURE 2-11 (A) Handheld pulse oximeter and capnograph. (B) CAPNO EMER II from Wuhan Union Medical.

(A) © 2019 Medtronic. All rights reserved. Used with permission of Medtronic; (B) Courtesy of Wuhan Union Medical Technology CO., Ltd.

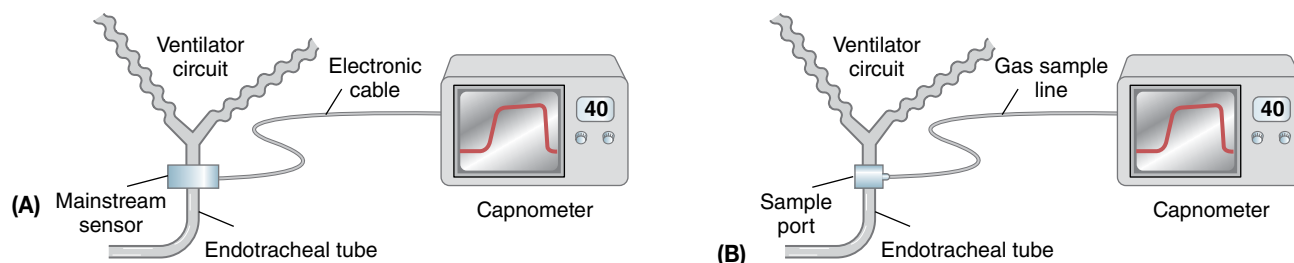


FIGURE 2-12 (A) Mainstream capnometry. (B) Sidestream capnometry.

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 may block sensor Sensor heated to prevent condensation Bulky sensor at patient airway Adds dead space to the circuit Difficult to use with nonintubated patients Cleaning and sterilization of reusable sensor
Sidestream Capnometer	
No bulky sensors or heaters at airway Disposable sample line Can be used with nonintubated patients	Secretions block sample tubing Water trap is required Slow response to CO ₂ changes Sample flow may decrease tidal volume

The sidestream capnometer uses small-bore tubing to aspirate gas from or adjacent to the airway. This tubing delivers aspirated 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 permeable to water vapor, allowing moisture to escape by diffusion and evaporation. An analysis delay always occurs with sidestream monitors because of the time required to move the sample from the airway to the sensor. The length of this 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 2-13).

The CO₂ infrared absorption peak (4.26 μm) lies between two peaks for water and very close to a peak for nitrous oxide (Figure 2-14). The latter poses an interference problem during the administration of nitrous oxide (N₂O) as an anesthesia gas, although correction factors and filters can minimize this problem. Room



FIGURE 2-13 Nasal cannula designed for CO₂ sampling and oxygen administration (Smart CapnoLine, Covidien). The cannula samples CO₂ from both the nares and the mouth while oxygen is delivered through pinholes directed toward both the nose and mouth.
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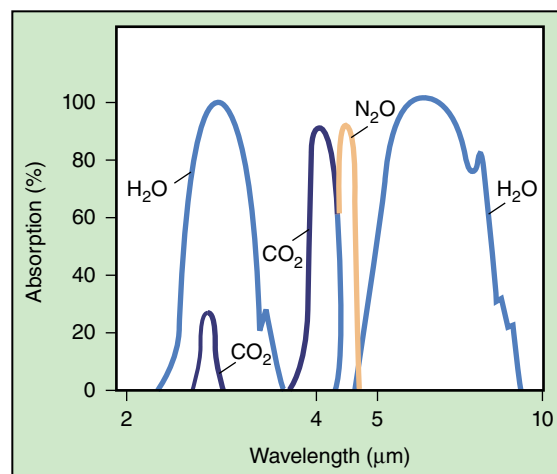


FIGURE 2-14 Carbon dioxide absorption spectra.

Adapted from Decker M, Strohl K. Pulse Oximetry. Biophysical Measurement Series: Respiration. SpaceLabs Medical, 1994.

air (zero) and 5% CO₂ are used to perform a two-point calibration of conventional sidestream analyzers. 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.

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 it is ionized by an electron beam. 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 for accurate measurement of several gases. Mass spectrometers have the advantage of being able to measure all respiratory gases breath by breath and are the most accurate analyzers in clinical use. However, most models are too expensive and cumbersome for routine use.

Another method 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 re-emission of energy 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 2-15**) is 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



FIGURE 2-15 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.



FIGURE 2-16 Colorimetric CO_2 sensor designed to confirm nasogastric tube placement.

Courtesy of Covidien. Used with permission.

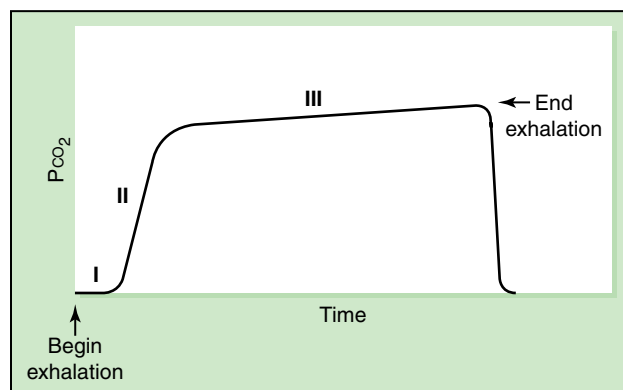


FIGURE 2-17 Time-based capnogram.

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 positioning in the trachea, as opposed to esophageal intubation, in which case no color change occurs. This technique can also be used to detect accidental tracheal placement of a nasogastric tube (**Figure 2-16**). In this case, a color change indicates incorrect placement of the tube in the trachea.²⁰

Time-Based Capnography

The traditional **capnogram** plots Pco_2 on the vertical axis and time on the horizontal axis. During inhalation, Pco_2 at the airway is 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, the CO_2 level 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 2-17**). Peak exhaled Pco_2 or **end-tidal Pco_2** (PETCO_2) represents the alveolar Pco_2 .

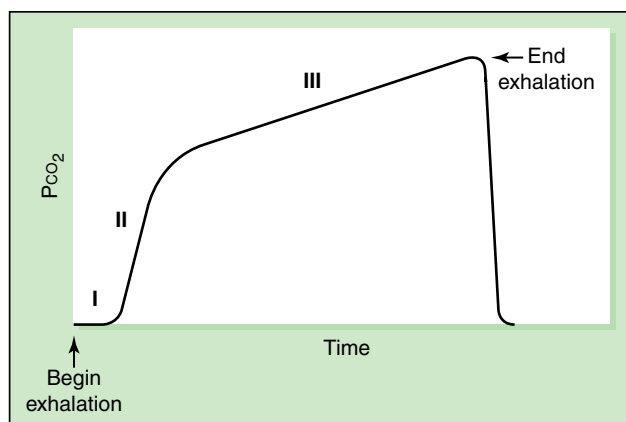


FIGURE 2-18 Capnogram produced with airflow obstruction.

TABLE 2-2
Causes of Increased and Decreased PETCO₂

Increased PETCO ₂	Decreased PETCO ₂
<i>Increased CO₂ production and delivery to the lungs:</i> Fever, sepsis, bicarbonate administration, increased metabolic rate, seizures	<i>Decreased CO₂ production and delivery to the lungs:</i> Hypothermia, low pulmonary perfusion, cardiac arrest, pulmonary embolism, hemorrhage, hypotension
<i>Decreased alveolar ventilation:</i> Respiratory center depression, muscular paralysis, hypoventilation, chronic obstructive pulmonary disease (COPD)	<i>Increased alveolar ventilation:</i> Hyperventilation
<i>Equipment malfunction:</i> Rebreathing, exhausted CO₂ absorber, leak in ventilation circuit	<i>Equipment malfunction:</i> Ventilator disconnect, esophageal intubation, complete airway obstruction, poor sampling, leak around endotracheal tube cuff

The capnographic waveform can be inspected for specific abnormalities or patterns. In patients with airway obstruction, the slope of the alveolar plateau increases because of inhomogeneous alveolar emptying (Figure 2-18). Regions of the lung with delayed emptying caused by increased resistance (long time constants) add CO₂ to expired gas during the latter part of exhalation.

End-Tidal Pco₂

End-tidal Pco₂ is determined by the production of CO₂, its 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 PETCO₂. In clinical settings, PETCO₂ is used to ensure that the tracheal tube or mask ventilates the lungs, to

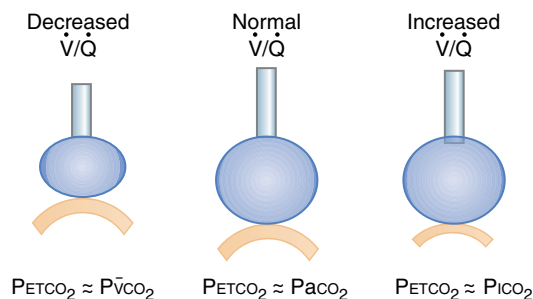


FIGURE 2-19 PETCO₂ with low $\dot{V}/\dot{Q}$, normal $\dot{V}/\dot{Q}$, and high $\dot{V}/\dot{Q}$.

Stop and Think

A patient has a PACO₂ of 55 mm Hg, but the PETCO₂ is 30 mm Hg. Why is there such a large difference between the PACO₂ and the PETCO₂?

estimate the PACO₂, to detect changes in pulmonary blood flow or dead space ventilation, and to detect the addition of excess CO₂ to the systemic circulation.

The PCO₂ of an individual lung unit depends on $\dot{V}/\dot{Q}$ (Figure 2-19). Without perfusion (pure dead space; $\dot{V}/\dot{Q} = \infty$) the PACO₂ is similar to the inspired PCO₂ (i.e., zero). With a normal $\dot{V}/\dot{Q}$ unit, the PACO₂ is the same as the PACO₂ (i.e., 40 mm Hg). With a low $\dot{V}/\dot{Q}$ unit, the PACO₂ increases toward the $\bar{P}\dot{V}\text{CO}_2$ (i.e., 45 mm Hg). The PACO₂, and thus the end-tidal PCO₂, is always between zero and the $\bar{P}\dot{V}\text{CO}_2$. Although the PETCO₂ is normally several mm Hg less than the PACO₂, the relationship between these measures will vary depending on the relative contributions of the various $\dot{V}/\dot{Q}$ units making up the lungs.

The presence of CO₂ in exhaled gas usually indicates tracheal intubation. Exhaled CO₂ does not always ensure proper endotracheal tube placement, however, because the tube could be inadvertently placed into the main stem bronchus or in the pharynx. Although esophageal intubation generally results in a very low PETCO₂, falsely elevated readings may occur if the patient ingested antacids or carbonated beverages. In such a case, the elevated value should diminish with subsequent breaths. Even with proper endotracheal tube placement, the PETCO₂ may remain deceptively low with cardiogenic shock. PETCO₂ is also used to detect tracheal placement of a nasogastric tube. A PETCO₂ near zero suggests that the gastric tube is *not* in the trachea.

Even though PETCO₂ approximates PACO₂ in normal individuals, capnometry cannot routinely be used as a substitute to measure arterial PCO₂. Most critically ill patients have $\dot{V}/\dot{Q}$ abnormalities, particularly an

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

increased ratio of dead space to tidal volume (V_D/V_T), resulting in a significant $Paco_2 - PETCO_2$ 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 $Paco_2$.

With no pulmonary blood flow, $PETCO_2$ is zero. Because $PETCO_2$ is partly determined by the amount of blood flow returning to the lungs from the systemic circulation, this measure has been used to verify the effectiveness of cardiopulmonary resuscitation (CPR). Adequate CPR is associated with increasing $PETCO_2$. If $PETCO_2$ does not rise above 10 mm Hg after 20 minutes of pulseless resuscitation, the patient's prognosis is poor. An abrupt increase in $PETCO_2$ during CPR indicates a return of spontaneous circulation (Figure 2-20).

Pulmonary embolism is associated with an increased V_D/V_T ; consequently, $P(a - ET)CO_2$ is

increased. Because many conditions increase V_D/V_T , an increased $P(a - ET)CO_2$ is not specific to pulmonary embolism. Nevertheless, a normal $P(a - ET)CO_2$ 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 $P(a - ET)CO_2$. An elevated $P(a - ET)CO_2$ suggests that V_D/V_T is excessive and, in turn, the minute ventilation requirement might suggest that ventilator liberation is unlikely.

Respiratory Recap

Capnography

- Capnography uses either mainstream or side-stream sampling.
- The CO_2 level is measured by infrared absorption, mass spectrometry, or colorimetric techniques.
- $PETCO_2$ often is an imprecise reflection of $Paco_2$.
- Capnography is useful in the detection of esophageal intubation.
- $PETCO_2$ 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.

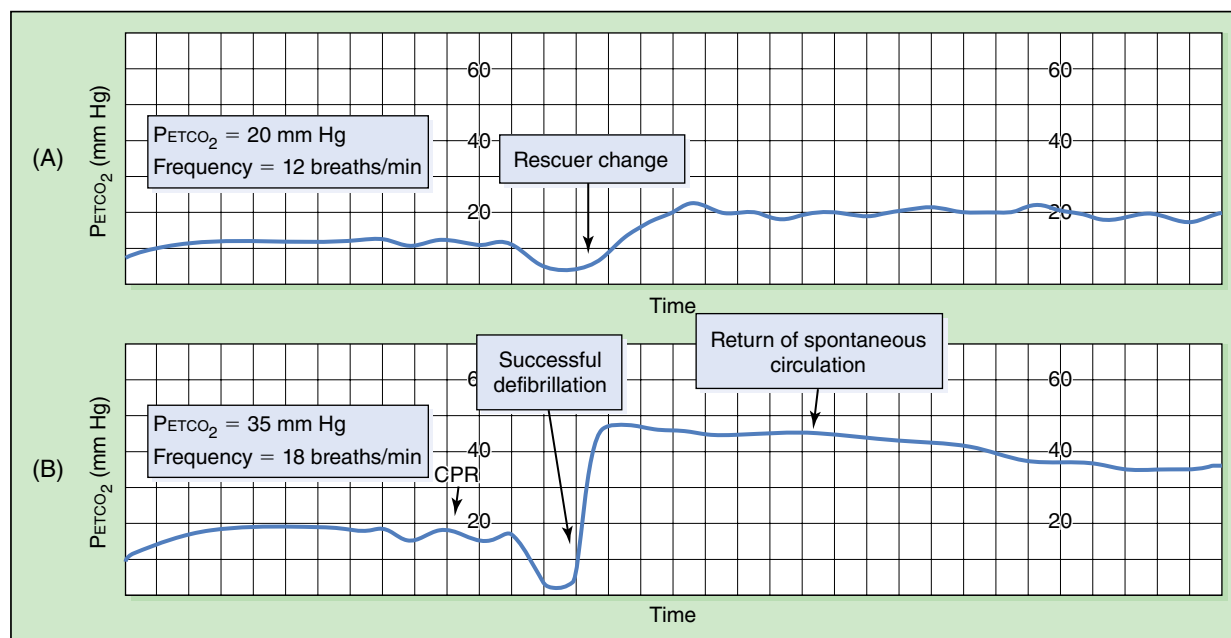


FIGURE 2-20 Time-based capnograms of $PETCO_2$ during CPR showing ineffective cardiac compressions or rescuer fatigue (A) and return of spontaneous circulation (B).

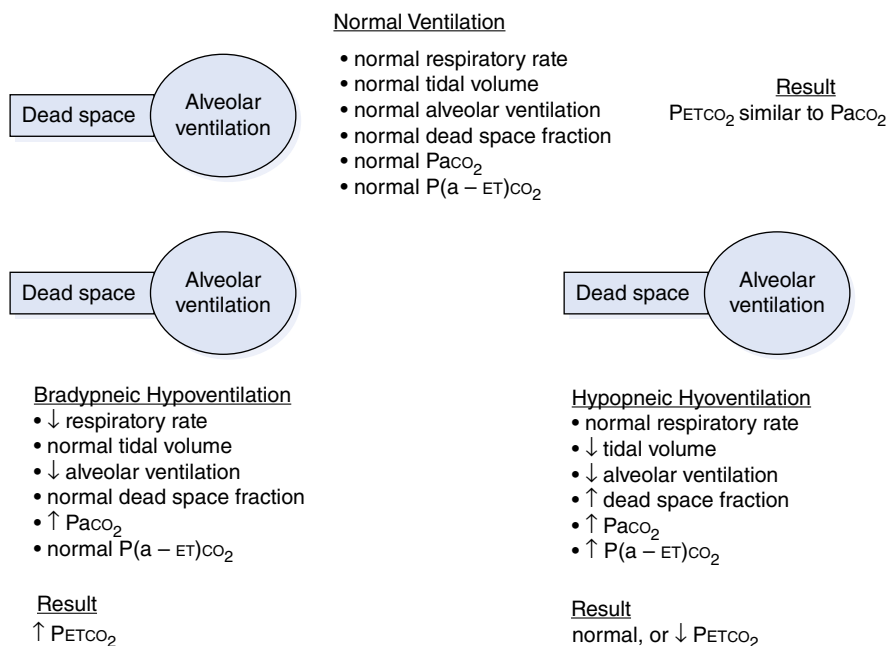


FIGURE 2-21 Physiology of hypoventilation states as related to monitoring of end-tidal PCO_2 .
 $PETCO_2$ = end-tidal PCO_2 , P_{aCO_2} = arterial PCO_2 .

Reproduced from Krauss B, Hess DR. Capnography for procedural sedation and analgesia in the emergency department. Ann Emerg Med 2007;50(2):172–181, with permission from Elsevier.

Patient safety monitoring during procedural sedation includes pulse rate, blood pressure, respiratory rate, SpO_2 , electrocardiography (ECG), and clinical observation. Noninvasive monitoring of ventilation with capnography is also used in this setting. Two types of hypoventilation may occur during procedural sedation and analgesia: bradypneic and hypopneic (Figure 2-21).²² Bradypneic hypoventilation features an increased $PETCO_2$ and an increased P_{aCO_2} . The respiratory rate is depressed proportionally greater than the tidal volume, resulting in bradypnea, an increase in expiratory time, and an increase in $PETCO_2$. Use of opioids commonly leads to bradypneic hypoventilation. Hypopneic hypoventilation is characterized by a normal or decreased $PETCO_2$ with an increased P_{aCO_2} . This condition reflects the relationship between tidal volume and airway dead space, in which dead space is constant and tidal volume is decreasing. Because the tidal volume is depressed more than the respiratory rate, the result is 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, $PETCO_2$ may remain

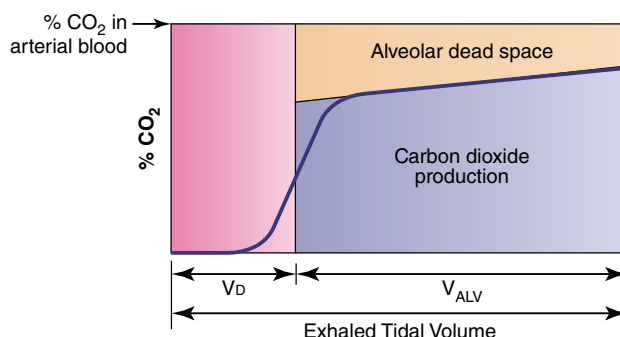


FIGURE 2-22 Components of volume-based capnogram. V_D , anatomic dead space; V_{ALV} , alveolar gas volume.

Courtesy of Hamilton Medical Group.

normal or decrease. Thus, either an increase or decrease in $PETCO_2$ might suggest excessive procedural sedation.

Volume-Based Capnography

Figure 2-22 shows a normal volume-based capnogram, in which the PCO_2 appears on the vertical axis and the volume on the horizontal axis.^{23–26} At the beginning of exhalation, the PCO_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). It then forms a plateau during most of exhalation (phase III). Phase III represents gas flow from the alveoli; thus, it is called the *alveolar plateau*. The PCO_2 at end-exhalation is the $PETCO_2$. Anatomic dead space volume, alveolar dead space volume, and the volume of exhaled CO_2 ($\dot{V}_{CO_2}$) can be determined from

Stop and Think

During CPR, the patient's $PETCO_2$ slowly decreases from 25 mm Hg to 20 mm Hg to 15 mm Hg. Why is this happening, and what is the appropriate response?

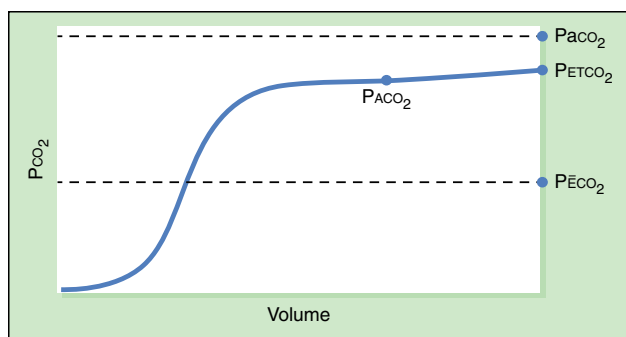


FIGURE 2-23 Volumetric capnogram showing the relationship between PaCO_2 , PACO_2 , PETCO_2 , and PECO_2 .

Republished with permission of Daedalus Enterprises, Inc. From Siobal MS. Monitoring exhaled carbon dioxide. *Respir Care* 2016;61(10):1397–1416. Permission conveyed through Copyright Clearance Center, Inc.

the volume-based capnogram, as can PACO_2 (used to calculate VD/VT), and PETCO_2 (Figure 2-23).

Using volume-based capnography, it is possible to noninvasively measure cardiac output with the partial CO_2 rebreathing technique (Figure 2-24).²⁷ $\dot{V}\text{CO}_2$ is calculated on a breath-by-breath basis, and the Fick

equation is applied to establish the relationship between $\dot{V}\text{CO}_2$ and cardiac output ($\dot{Q}$). Several potential limitations arise when partial rebreathing is used 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 PETCO_2 and $\dot{V}\text{CO}_2$. Noise is increased by respiratory pattern irregularities that produce an unstable PETCO_2 and $\dot{V}\text{CO}_2$, which then may impair accuracy. Additional cardiac output not calculated due to shunt fraction is estimated from SpO_2 and FIO_2 , and this might introduce errors.

Transcutaneous Monitoring

Transcutaneous monitoring of O_2 and CO_2 (PtcO_2 and PtcCO_2) uses measurements at the skin surface to provide estimates of PaO_2 and PaCO_2 (CPG 2-2).²⁸ This type of monitoring has been used with neonates, infants, children, and adults. The devices warm the skin to induce hyperemia and then electrochemically measure oxygen and carbon dioxide partial pressures at the

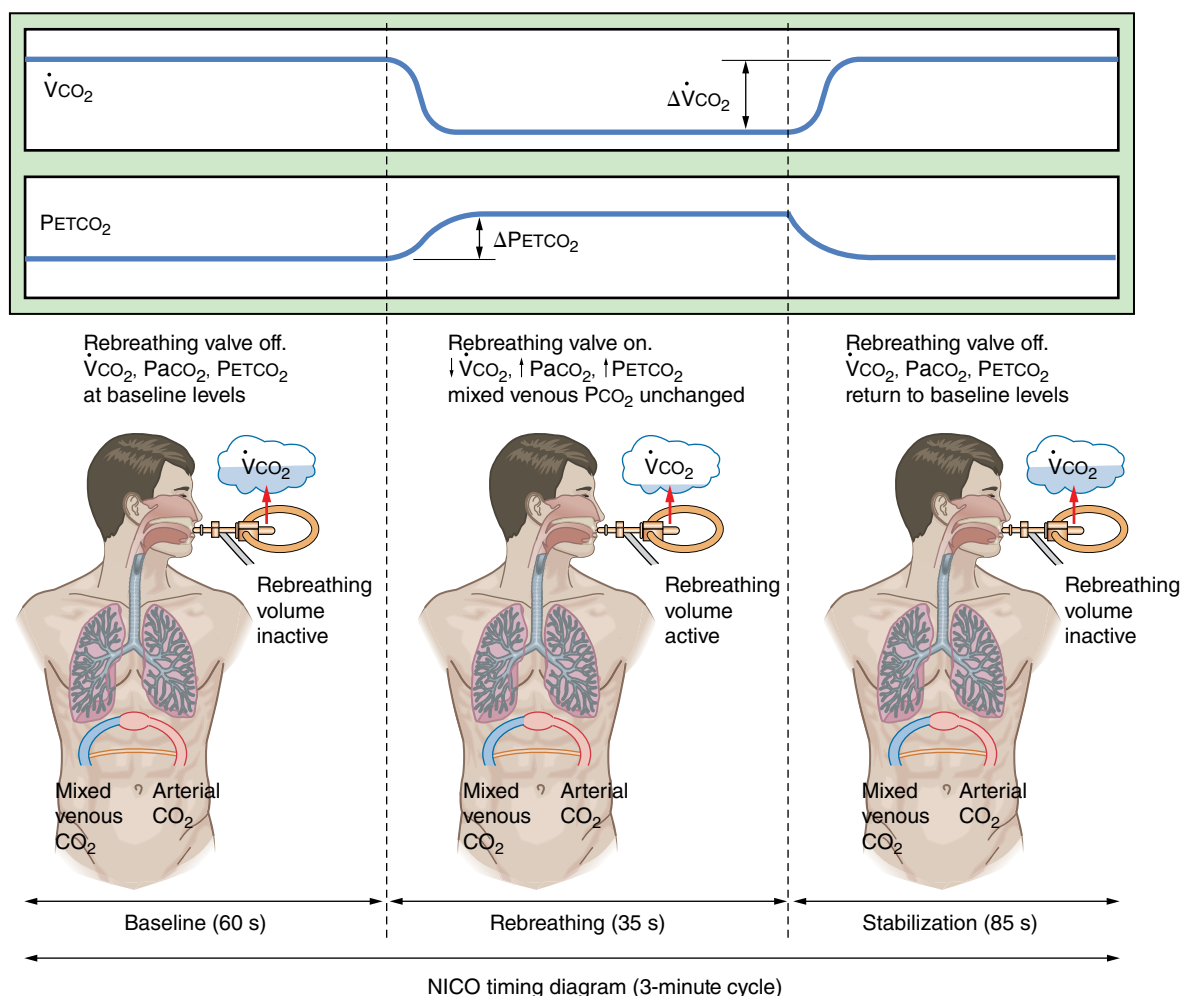


FIGURE 2-24 Rebreathing cycle used to measure cardiac output using the partial CO_2 rebreathing technique.

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CLINICAL PRACTICE GUIDELINE 2-2

Transcutaneous Monitoring of Carbon Dioxide and Oxygen

- Although $PtCO_2$ has a good agreement with $Paco_2$ and can reliably evaluate plasma CO_2 levels, it is recommended that arterial blood gas values be compared to transcutaneous readings taken at the time of arterial sampling, so as to verify the transcutaneous values, and periodically as dictated by the patient's clinical condition.
- It is suggested that $PtCO_2$ may be used in clinical settings where monitoring the adequacy of ventilation is indicated.
- It is suggested that $PtCO_2$ and $PtCCO_2$ may be used in determining the adequacy of tissue perfusion and monitoring of reperfusion.

- It is suggested that transcutaneous monitoring should be avoided in the presence of increased thickness or edema of the skin and/or subcutaneous tissue where the sensor is applied.
- It is recommended that sites used for a transcutaneous monitoring be changed as often as necessary and that they be alternated and observed to avoid thermal injury. The manufacturer's recommendations should be followed.

Restrepo RD, Hirst KR, Wittnebel L, Wettstein R. AARC clinical practice guideline: transcutaneous monitoring of carbon dioxide and oxygen: 2012. *Respir Care* 2012; 57(11):1955–1962. Reprinted with permission.

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 $PtCO_2$ 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). This measure has been used in adults to monitor the results of vascular surgery, with the intent being to evaluate perfusion rather than PaO_2 per se.

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

Transcutaneous carbon dioxide electrodes use a flat glass membrane that is 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 $PtCO_2$ electrode detects changes in $[H^+]$ but is calibrated to display PCO_2 . Unlike with the $PtCO_2$ electrode, a reasonably good agreement with $Paco_2$ can be obtained at a temperature of $37^\circ C$ ($98.6^\circ F$). Because $PtCCO_2$ is consistently greater than $Paco_2$, manufacturers incorporate a correction factor so that the $PtCCO_2$ displayed approximates the $Paco_2$. Like $PtCO_2$, the accuracy with which $PtCCO_2$ approximates $Paco_2$ is the result of a complex set of physiologic events; thus, $PtCCO_2$ is not synonymous with $Paco_2$. For example, decreased tissue perfusion causes the $PtCCO_2$ to increase without a change in $Paco_2$.

A miniaturized single sensor combines the measurement of pulse oximetry (SpO_2) and $PtCCO_2$ (Figure 2-25).^{29–31} This device, which uses a heated Severinghaus electrode combined with a pulse oximetry sensor, 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 $42^\circ C$ to induce local vasodilation and to enhance skin permeability for CO_2 , thereby improving 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.

Respiratory Recap

Transcutaneous Blood Gas Monitors

- Warmed electrodes are placed on the skin to measure $PtCO_2$ and $PtCCO_2$ and to 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 $PtCCO_2$.

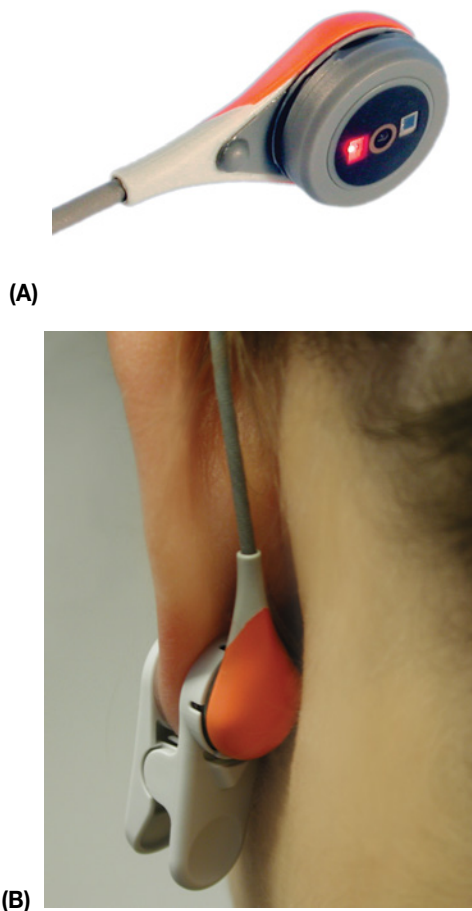


FIGURE 2-25 A sensor for noninvasive monitoring of transcutaneous carbon dioxide and oxygen saturation. Courtesy of SenTec AG.

The reliability of transcutaneous monitoring for accurately estimating arterial blood gases is often questioned, which has led to limited use of this technology.

Stop and Think

The patient's $PtCO_2$ suddenly drops to zero. What is the best explanation for this decrease, and what is the appropriate clinical response?

Respiratory Rate and Pattern

Respiratory rate is one of the four vital signs. It is a core component of monitoring, because slowing (**bradypnea** or *apnea*) or acceleration (*tachypnea*) of respiratory rate may warn of clinical deterioration or impending respiratory arrest. 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), low-ampere (less than 100 μ A) alternating current is passed between the electrodes on the chest surface (such a current is 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 2-26**). Obstructive apnea cannot be detected with this method, because the chest wall continues to move despite cessation of flow. In the ICU, the same electrodes that are applied for cardiac rhythm monitoring measure the respiratory rate by this method. Infant home apnea monitors are based on this technology as well.

With **respiratory inductance plethysmography (RIP)**, 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 rate, pattern, and change in volume. When rib cage and abdominal bands are used with RIP, respiratory motion is described more completely, resulting in tidal volume measurements that correlate well with spirometry ($\pm 10\%$).

A modification of inductance plethysmography, **fiberoptic plethysmography**, uses optical fibers woven into elastic belts. Light passes through the fibers and into a photodetector. When rib cage or abdominal displacements stretch the elastic belt, changes in light transmission through the fibers results. The change in light transmission is electronically processed to provide data similar to those obtained with 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.

To simplify the plethysmography apparatus, the wire coils may be removed from the elastic belts and replaced by a piezoelectric buckle (**piezoelectric plethysmography**). This reduces the cost and allows for adjustable belts that can accommodate different-size patients. The buckle encloses a sensor, which

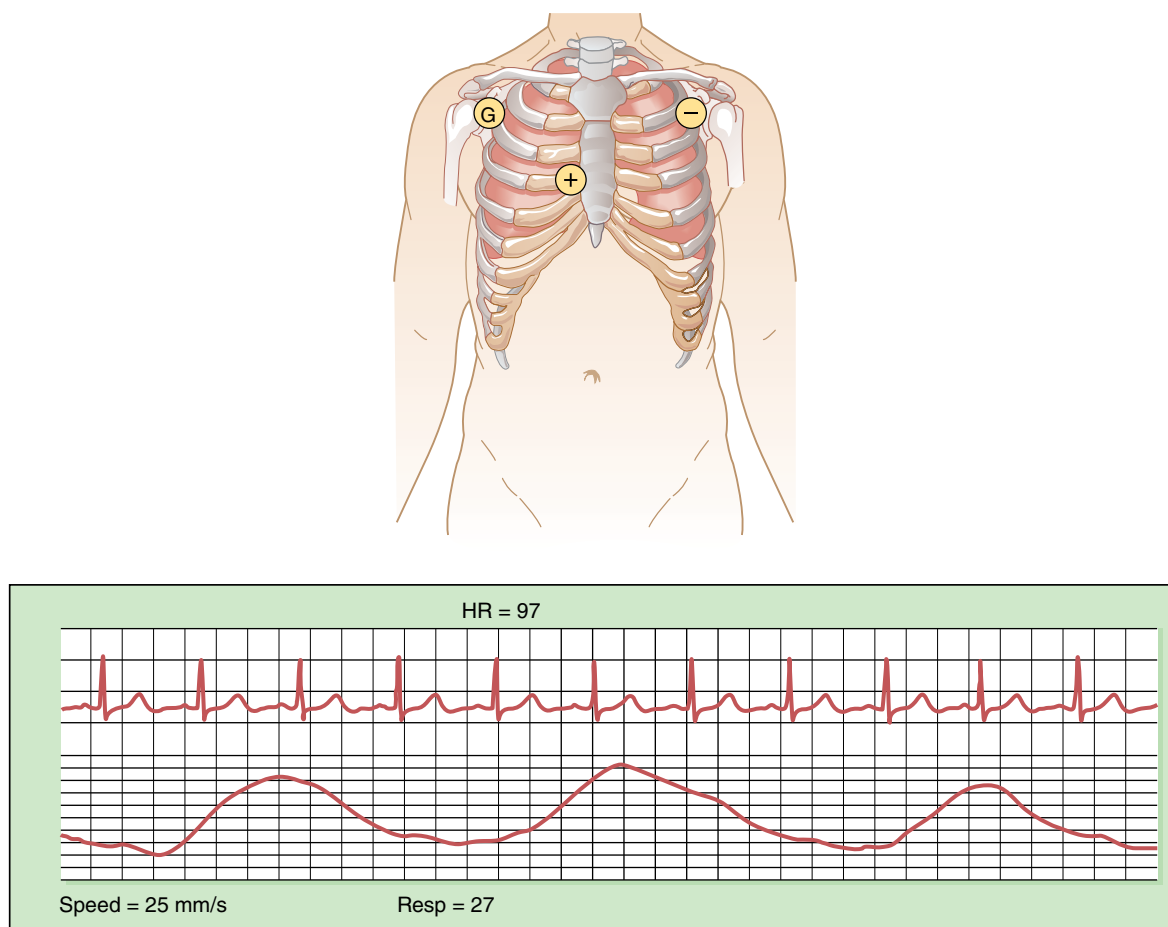


FIGURE 2-26 (A) Electrode placement for three-lead array. (B) Cardiac rate and rhythm recorded from a single ECG lead. (C) Respiratory impedance plethysmography tracing obtained from the same electrode array.

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.

A noninvasive respiratory volume monitor has been developed to continuously measure and display minute ventilation, tidal volume, and respiratory rate in a variety of clinical settings.³² Two electrode pads are used: One electrode pad comprising three electrodes is placed along the sternum, and the other electrode pad comprising three electrodes is placed across the right midaxillary line at the level of the xiphoid (**Figure 2-27**). Minute ventilation, tidal volume, and respiratory rate are displayed as well as the real-time respiratory volume curve and trends of the measurements.

Temperature and pressure probes can be used to measure the rate and pattern of airflow, thereby facilitating the identification of disordered breathing, hypopneas, and apneas. **Thermistors** and **thermocouples**



FIGURE 2-27 Respiratory volume monitor illustrating electrodes on chest.

ExSpiron, Non Invasive Respiratory Monitor, Quadromed, <https://www.quadromed.com/fr/produit/minute-ventilation-monitor-minute-respiratory-monitor/>.

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 2-28**). The ability of these devices to detect flow diminishes if room air temperature

approaches body temperature. Likewise, if the sensor touches the skin and rises to body temperature, airflow cannot be detected. Other limitations of thermally based sensors are that they provide only qualitative information, that moisture condensation on the probe compromises temperature-sensing capabilities, and that loss of signal may occur if the sensor becomes dislodged from the airstream.

Acoustic monitoring noninvasively and continuously measures respiration rate through an adhesive sensor with an integrated acoustic transducer applied to the patient's neck (**Figure 2-29**).³³ Using acoustic signal processing, the respiratory signal is separated and processed to display continuous respiratory rate. Capnography and pulse oximetry can also be used to assess respiratory rate. Most modern mechanical ventilators have integrated flow transducers that monitor respiratory rate.

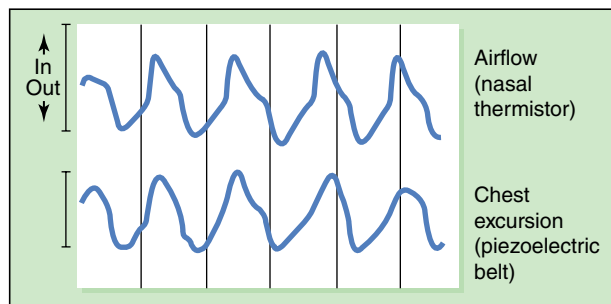


FIGURE 2-28 Airflow and chest and abdominal excursion waveforms are used to monitor respiratory rate and pattern during sleep studies.

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



FIGURE 2-29 Acoustic monitor placement on a patient's neck.

Rainbow Acoustic Monitoring, Masimo, <http://www.masimo.com/technology/ventilation-and-respiration/rra/>.

Respiratory Recap

Techniques to Measure the Respiratory Rate

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

Brain Tissue P_{O_2}

Brain tissue P_{O_2} (P_{bto_2}) measures dissolved oxygen in a small area of brain tissue (**Figure 2-30**).³⁴ The P_{bto_2} probe contains polarographic Clark electrodes covered in a semipermeable membrane at the tip of a flexible microcatheter. This device provides a highly localized measurement, with a sampling area of 7 to 15 mm². The probe can be placed through the same burr hole used for an intracranial pressure monitor, although the location of placement affects the P_{bto_2} values measured. For example, 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

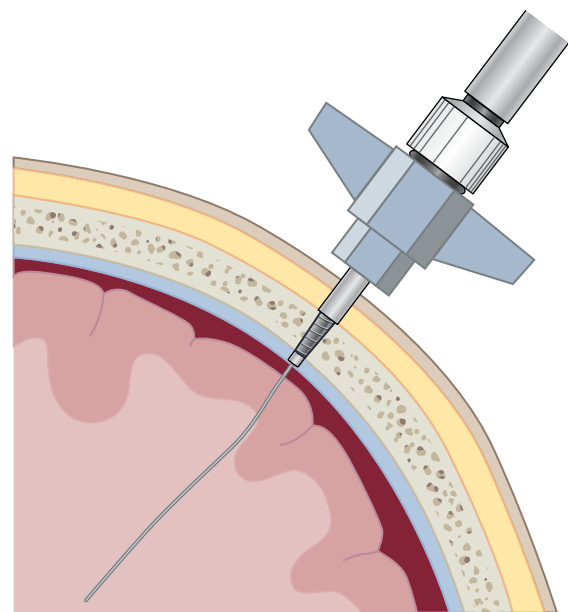


FIGURE 2-30 Coronal section illustrating the placement of the brain tissue oxygenation probe in the brain parenchyma.

Reproduced from Martini RP, Deem S, Treggiari MM. Targeting brain tissue oxygenation in traumatic brain injury. *Respir Care* 2013;58(1):162–172.

oxygen. Interventions to improve $Pbto_2$ are similar to those used to decrease intracranial pressure, with treatment generally indicated for patients with $Pbto_2 < 20$ mm Hg. Periodically, the reliability of measured $Pbto_2$ is assessed by briefly increasing the FIO_2 to 1: The $Pbto_2$ should rise in tandem with the Pao_2 . It is unclear whether implementing strategies to improve $Pbto_2$ result in better outcomes for brain-injured patients; consequently, $Pbto_2$ monitoring has not become a widespread practice.

Near-Infrared Spectroscopy

Near-infrared spectroscopy (NIRS) is a technique used for noninvasive monitoring of peripheral tissue oxygenation (Sto_2).^{35–37} 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. Because myoglobin and cytochrome make only small contributions to the light attenuation signal, 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); TTH and THI are both indicators of blood volume in the region of microvasculature sensed by the probe and are 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 comes 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; thus, the NIRS light source is placed beside the light sensor.

Thenar Sto_2 (**Figure 2-31**) is determined in real time at the bedside and may be useful to guide the early resuscitation of critically ill patients, especially those in a hypodynamic state. However, Sto_2 may be normal in patients with severe sepsis or septic shock, which limits this measure's 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



FIGURE 2-31 Near-infrared spectroscopy probe to measure thenar Sto_2 . Courtesy of Hutchinson Technology Inc.

obstruction test. Alterations in these NIRS-derived dynamic variables are common in patients with severe sepsis and are associated with a poor outcome.

Key Points

- Pulse oximetry measures oxygen saturation by passing two wavelengths of light through a pulsating vascular bed.
- The accuracy of pulse oximetry is $\pm 4\%$.
- A number of factors can affect the accuracy and performance of pulse oximetry.
- Pulse oximeters can measure $SpHb$, $SpCO$, and $SpMet$; the clinical utility of these measures has yet to be determined.
- The plethysmographic waveform from pulse oximeters can be used to assess pulsus paradoxus, fluid responsiveness, and respiratory rate.
- Capnometry measures the concentration of carbon dioxide exhaled from the lungs.
- Capnography can be useful for detecting esophageal intubation, adequacy of chest compressions, and return of spontaneous circulation during CPR.
- End-tidal PCO_2 may not accurately reflect $Paco_2$.
- 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, pulse oximetry, capnography, acoustic technology, 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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