18 Continuous Monitoring Techniques

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I. *Transcutaneous partial pressure of oxygen ($PTcO_2$) monitoring*
   A. Principle of operation

      Electrodes consist of a platinum cathode and silver reference anode, encased in an electrolyte solution and separated from the skin by an O_2-permeable membrane. Electrodes are heated to improve oxygen diffusion and to arterialize the capillary blood. Oxygen is reduced at the cathode, generating an electric current proportional to the O_2 concentration in the capillary bed underneath the sensor. Sensors need calibration every 4–8 h. Fluorescence quenching, a new optical technique to measure $PTcO_2$, does not require calibration. With either technique, sensors require a 10–15 min. Warm-up period after application.

   B. Factors influencing measurements
      1. Sensor temperature. Good agreement with PaO_2 only at 44 ° C, but then frequent (2–4 hourly) repositioning necessary. The above optical method may already show good agreement with PaO_2 at 43 °C.
      2. Probe placement. $PTcO_2$ will underread PaO_2 if sensor is placed on bony surface, if pressure is applied on sensor, or if too much contact gel is used. With patent ductus arteriosus and right-to-left shunt, $PTcO_2$ will be higher on upper than on lower half of the thorax.
      3. Peripheral perfusion. $PTcO_2$ depends on skin perfusion. If the latter is reduced, e.g., from hypotension, anemia, acidosis (pH <7.05), hypothermia, or marked skin edema, $PTcO_2$ will be falsely low. If underreading of PaO_2 occurs, check patient for the above conditions.
      4. Skin thickness. Close agreement with PaO_2 only in neonates; beyond 8 weeks of age, $PTcO_2$ will usually only be 80% of PaO_2.
      5. Response times. In vivo response time to a sudden fall in PaO_2 is 16–20 s.

   C. Detection of hypoxemia and hyperoxemia

      Sensitivity to these conditions (at 44 ° C sensor temperature) is approximately 85%.

   D. Technique is better for trending than determining absolute value.

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II. *Pulse oximetry (SpO_2)* (Chap. 19)

A. Principle of operation

The ratio of the absorbances of red and infrared light sent through a tissue correlates with the ratio of oxygenated to deoxygenated hemoglobin in the tissue. Early devices determined arterial absorption component by identifying the peaks and troughs in absorbance over time, thereby obtaining a "pulse-added" value that is independent of the absorbance characteristics of the non-pulsating parts of the tissue. Current instruments use additional techniques, e.g., scan through all red-to-infrared ratios found, determine the intensity of these, and choose the right-most peak of these intensities, which will correspond to the absorbance by the arterial blood in the tissue. Some instruments also use frequency analysis, time domain analysis, and adaptive filtering to establish a noise reference in the detected physiologic signal, thereby improving the ability to separate between signal and noise. All instruments have built-in calibration algorithms to associate their measured light absorbances with empirically determined arterial oxygen saturation (SaO_2) values.

B. Factors influencing measurements

1. Probe placement. Light receiving diode must be placed exactly opposite emitting diode; both must be shielded against ambient light and not be applied with too much pressure. Light bypassing the tissue can cause both falsely high and falsely low values. Sensor site must be checked every 6–8 hours. Highly flexible sensors (usually disposable) provide better skin contact and thus better signal-to-noise ratio.
2. Peripheral perfusion. Oximeters require a pulsating vascular bed; performance at low perfusion may be impaired. Some manufacturers provide continuous information about perfusion conditions so that users can check signal quality.
3. Response and averaging times. The former largely depends on the latter. Longer averaging times will increase response times and may reduce alarm rates, although the latter are more effectively reduced by introducing an alarm delay (e.g., 10 sec). The relationship between desaturation rate and averaging time has been described mathematically, so that rates observed with one averaging time can be translated into those theoretically obtained with another averaging time.
4. Movement artifact. Most frequent cause of false alarms. May be identified from analysis of the pulse waveform signal or via a signal quality indicator displayed by some instruments.
5. Other hemoglobins and pigments. Methemoglobin (MetHb) will cause SpO_2 readings to tend toward 85%, independent of SaO_2. Carboxyhemoglobin (COHb) will cause overestimation of SaO_2 by 1% for each percent COHb in the blood. Fetal hemoglobin (HbF) and bilirubin do not affect pulse oximeters but may lead to an underestimation of SaO_2 by co-oximeters. In patients with dark skin, SpO_2 values may be falsely high, particularly during hypoxemia.
6. Calibration algorithms. These may vary between brands and even between different software versions from the same manufacturer. Recently, the discovery of a shift in the in-built calibration curve used in one manufacturer's instruments revealed a reduction in the number of SpO_2 readings between 87 and 90% and was subsequently corrected by the manufacturer.

C. Detection of hypoxemia and hyperoxemia

In the absence of movement, pulse oximeters have a high sensitivity for the detection of hypoxemia. Because of the shape of the O_2 dissociation curve, they are less well suited for detecting hyperoxemia. The upper alarm setting at which a $PaO_2 > 80$ mmHg (10.7 kPa) can be reliably avoided is at 95–96%.

III. *Transcutaneous partial pressure of carbon dioxide ($PTcCO_2$) monitoring*
   A. Principle of operation
      $PTcCO_2$ sensor consists of a pH-sensing glass electrode and a silver-silver chloride reference electrode, covered by a hydrophobic CO_2-permeable membrane from which they are separated by a sodium bicarbonate-electrolyte solution. As CO_2 diffuses across the membrane, there is a pH change of the electrolyte solution ($CO_2 + H_2O$ / $HCO3^- + H^+$), which is sensed by the glass electrode. All instruments have built-in correction factors since their uncorrected measurements will be 50% higher than arterial PCO_2. They must also be calibrated at regular intervals and require a 10–15 min. Run-in time following repositioning.
   B. Factors influencing measurements
      1. Sensor temperature. Optimal sensor temperature is 42 ° C, but if sensors are used in combination with a $PTcO_2$ sensor, a sensor temperature of 44 ° C can be used without jeopardizing the precision of the $PTcCO_2$ measurement.
      2. Sensor placement and skin thickness. $PTcCO_2$ measurements are relatively independent of sensor site or skin thickness, but $PTcCO_2$ may be falsely high if pressure is applied onto the sensor.
      3. Peripheral perfusion. $PTcCO_2$ may be falsely high in severe shock. Precision may already be affected if $PaCO_2$ is >45 mmHg (6 kPa) and/or arterial pH is <7.30, but there is no systematic over- or underestimation of $PaCO_2$ under these conditions.
      4. Response times. 90% response time to a sudden change in $PaCO_2$ is between 30 and 50 sec.
   C. Detection of hypocarbia and hypercarbia
      Sensitivity to both hypocarbia and hypercarbia is 80–90%.
   D. Technique is better for trending than determining absolute value.

IV. *End-tidal carbon dioxide ($ETCO_2$) monitoring (capnometry)* (Chap. 21)
   A. Principle of operation
      An infrared beam is directed through a gas sample and the amount of light absorbed by the CO_2 molecules in the sample measured; this is proportional to the CO_2 concentration in the sample.
   B. Factors influencing measurements
      1. Gas sampling technique. Two approaches exist: (1) with mainstream capnometers, the CO_2 analyzer is built into an adapter which is placed in the breathing circuit. Advantage: fast response time (10 ms), therefore reliable even at high respiratory rates. Disadvantage: 1–10 ml extra dead space; risk of tube kinking. (2) Sidestream capnometers aspirate the expired air via a sample flow. Advantages: no extra dead space; can be used in non-intubated patients. Disadvantages: risk of dilution of expired gas by entrainment of ambient air at the sampling tube-patient interface; longer response time; falsely low values at high respiratory rates (>60/min.).
      2. Influence of V/Q mismatch. $ETCO_2$ will only approximate $PaCO_2$ if (i) CO_2 equilibrium is achieved between end-capillary blood and alveolar gas, (ii) $ETCO_2$ approximates the average alveolar CO_2 during a respiratory cycle, and (iii) ventilation/perfusion relationships are uniform within the lung. These conditions are rarely achieved in patients with respiratory disorders. The reliability of an $ETCO_2$ measurement can be assessed from the expiratory signal: this must have a steep rise, a clear end-expiratory plateau, and no detectable CO_2 during inspiration.

V. *Chest wall movements*
   A. Impedance plethysmography. Changes in the ratio of air to fluid in the thorax, occurring during the respiratory cycle, create changes in transthoracic impedance. Cannot be used to quantify respiration. May be heavily influenced by cardiac and movement artifacts.
   B. Inductance plethysmography. Changes in the volume of the thoracic and abdominal compartment create changes in inductance, which is registered via abdominal and thoracic bands. The sum of these changes is proportional to tidal volume, and several methods have been developed to calibrate the systems so that tidal volume can be quantified. Also provides information on thoraco-abdominal asynchrony during spontaneous breathing. This, however, only works as long as the patient does not shift position.
   C. Strain gauges (usually mercury in silicon rubber) sense respiratory efforts by measuring changes in electrical resistance in response to stretching. These measurements, however, are not reproducible enough to quantify tidal volume.
   D. Pressure capsules detect movements of an infant's diaphragm by means of an air-filled capsule that is taped to the abdomen and connected to a pressure transducer via a narrow air-filled tube. The outward movement of the abdomen during inspiration compresses the capsule to produce a positive pressure pulse that is interpreted as a breath. The technique is predominantly used in apnea monitors and in trigger devices for infant ventilators; it is not suitable for quantifying tidal volume.

VI. *Regional lung aeration using electrical impedance tomography (EIT)*
   A. EIT calculates cross-sectional (i.e., tomographic) images of the chest.
   B. Very small alternating electrical currents are applied through electrode pairs and the resulting voltages measured on the remaining electrodes.
   C. By repeating this process at a rate of about 50 images/sec, information on lung function under dynamic conditions can be sampled, as the method is sensitive to changes in conductivity in the tissue underneath the electrodes. For example, a higher lung volume reduces conductivity, while more blood or fluid volume increases it.
   D. Using this technique, continuous information about local tidal volumes, the spatial distribution of the inspired gas within the thorax or the effects of changes in PEEP on lung aeration can be obtained.

VI. *Electrocardiography (ECG)*

The ECG records electrical depolarization of the myocardium. During continuous monitoring, only heart rate can be determined with sufficient precision; any analysis of P and T waves, axis, rhythm, or QT times requires a printout and/or a 12-lead ECG.