Editorial

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Pulse Oximetry Revisited

K.K. Mubarak

Oximetry is the measurement of transmitted light through a translucent measuring site to determine the oxygen status. Pulse oximeter is used for arterial hemoglobin oxygen saturation and pulse rate monitoring. Under normal physiological conditions arterial blood is 97% saturated, and venous blood 75% saturated.

History

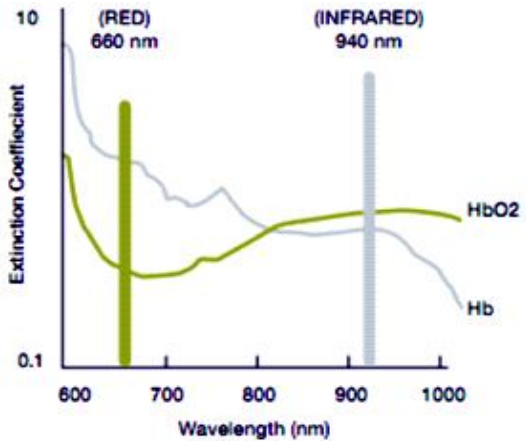
In 1930's German investigators used spectrophotometers to research light transmission through human skin. Kramer (1934) measured oxygen saturation in blood flowing through vessels in animals using photocell. In 1939, German researchers used "ear oxygen meter" that used red and infrared light. British researcher Millikan in 1940 used two wavelengths of light to produce ear oxygen meter for which he coined the word "oximeter". In 1964, Robert Shaw, San Francisco surgeon developed a self-calibrating ear oximeter. In 1972, Takuo Aoyagi, Japanese bioengineer, found that pulsating changes in the light transmission through the ear could measure arterial oxygen saturation and invented the first pulse oximeter in 1975. It was first clinically used by Japanese anaesthesiologist Yoshiya (1980) to monitor oxygen saturation during surgery. In 1980's, there were advances in size reduction, cost, and development of multiple site probes. During 1990's 'new generation' pulse oximeters with better accuracy of readings became popular.

In 1994, American Association of Respiratory Care released the guidelines for the use of pulse oximetry as the 5th vital sign, along with heart rate, respiratory rate, temperature and blood pressure.

Principle

Pulsatile signal generated by arterial blood, is relatively independent of non-pulsatile arterial, venous and capillary blood, and other tissues. Oxyhemoglobin (O_2Hb) and reduced hemoglobin (Hb) have different absorption spectra. Oxygen saturation is the amount of oxygen dissolved in blood, based on the detection of Hemoglobin and Deoxyhemoglobin. Bloodstream is affected by the concentration of O_2Hb and Hb, and their absorption coefficients are measured using wavelengths 660 nm (red light spectra) and 940 nm (infrared light spectra). Deoxygenated hemoglobin has a higher absorption at 660 nm and oxygenated hemoglobin has a higher absorption at 940 nm. Isobestic point is the wavelength at which the absorption by the two forms of the molecule is the same.

Absorption Ppectra of Hb and HbO2



Beer-Lambert law relates the concentration of a solute to the intensity of light transmitted through a solution. It estimates the concentration of a light absorbing substance in a clear solution from the intensity of light transmitted through it. The concentration of a solute in clear solution can be calculated from the intensity of transmitted and incident light of known wave lengths. If there is one solute, the absorption is a product of the path length, the concentration and the extinction coefficient (a constant for a given solute at a specified wave length). If more than one solute is present, the absorption is the sum of for each solute. The absorbance of different wavelengths is dependent on the different solute concentrations (reduced and oxygenated hemoglobin), and is detected by transmitting light of specific wavelengths across thesolution and measuring the intensity.

Conventional pulse oximetry uses two

Author's Affiliation: Professor & HOD Anaesthesia Govt. Med. College, Thrissur, Kerala.

Corresponding Author:
K.K. Mubarak, Professor & HOD Anaesthesia Govt. Med. College, Thrissur, Kerala.
E-mail: mubarakdr@yahoo.co.in

wavelengths of light (red and infrared) transmitted through the finger which is sensed by a photodetector. The pulse oximeter uses the red-to-infrared signal ratio and proprietary calibration tables to calculate SpO_2. The photodetector in the sensor perceives the non-absorbed light from the LEDs. This signal is inverted using an inverting operational amplifier.

This signal represents the light that has been absorbed by the finger and is divided into DC and AC components. DC component represents the light absorption of the tissue, venous blood, and non-pulsatile arterial blood and AC component, the pulsatile arterial blood. Pulse oximeter analyzes the light absorption of two wavelengths from the pulsatile-added volume of oxygenated arterial blood (AC/DC) and calculates the absorption ratio using the equation.

(AC660)/(DC660)

(AC940)/(DC940)

SpO2 is taken out from a table stored on the memory calculated with empirical formulas.

For more reliability, the table is based on measurements on healthy persons. The photoplethysmographic waveform is used to determine the pulse rate.

Errors in Pulse Oximetry

As pulse oximeters are dual-wavelength devices, presence of Hb species other than Hb and O_2Hb result in false reading.

Carboxyhemoglobin

At 920 nm, COHb has low absorbance and does not contribute to total absorbance. At 660 nm, COHb has an absorbance similar to that of O_2 Hb; therefore, SpO_2 will be falsely high. Each % increase in COHb results in 1 % increase in SpO_2 reading.

Methemoglobin (MetHb) has larger absorbance than either of the two major species of Hb at 940 nm, but simulates Hb at 660 nm. Therefore, at high SaO_2 levels (>85%) the reading underestimates the true value; at low SaO_2 levels (<85%) the value is falsely high. In high MetHb concentrations, SpO_2 approaches 85 percent, independently of the actual arterial oxygenation.

Other Hemoglobin Species

Sufhemoglobinemia can produce errors in oximetry, usually with a false reading of methemoglobin. Hemoglobin F in neonates has almost the same absorption spectrum as hemoglobin A, hence no measurable effect on SpO_2. During sickle cell crisis SpO_2 overestimates SaO_2 by 6.9 percent. Patients with sickle cell disease have rightward shift of the O_2 dissociation curve and therefore at any given PaO_2 value, SpO_2 is lower than the normal Hb-O_2 dissociation curve would predict.

Hemoglobin Concentration

At normal oxygenation levels, over a range of hemoglobin 2.3 to 8.7 g/dL, SpO_2 accurately reflects SaO_2. During hypoxia, SpO_2 underestimate SaO_2 to a degree that increases linearly as Hb concentration falls. Polycythemia has no apparent effect on the reading.

Dyes

Methylene blue results in decrease in measured SpO_2. Indocyanine green causes less decrease than methylene blue. Fluorescein injection has no measurable effect. Isosulfan blue, dye used to visualize lymphatics for surgical procedures is associated with prolonged reduction in SpO_2.

Nail Polish and Nail Pigments

Blue nail polish, with absorbance near 660 nm, has the greatest effect, an artifactual decrease. Other

colors have smaller effects. Red henna has no significant effect, but black henna can block the light to prevent a correct reading. *Bilirubin* have no significant effect on pulse oximeter readings.

Skin Pigment

Deeply pigmented skin can result in inability to pick up arterial pulsations.

Ambient Light

particularly fluorescent light can falsely elevate SpO_2 reading. Poor contact of the sensor with the skin can result in direct "optical shunting" of light from source to detector, either directly or by reflection from the skin, resulting in a falsely low SpO_2 reading.

Electrical interference from electrosurgical unit can give incorrect pulse rate or decrease in oxygen saturation. This is more in patients with weak pulse signals. Steps to minimize electrical interference include locating the grounding plate close to the oximeter sensor and far from the surgical field as possible.

Motion Artifacts

Motion may produce prolonged detection time for hypoxaemia. It can be significant in shivering or during patient transport.

Evoked potential monitors and nerve stimulators can produce motion artifacts if the pulse oximeter sensor is on the same extremity.

Pressure on the sensor may result in inaccurate SpO2 readings without affecting pulse rate. *Reduced blood flow* results in a diminished signal and can cause inability to obtain SpO_2 reading or low reading, due to greater fractional tissue consumption of arterial oxygen. This results in lower saturation in the pulsatile blood component. There may be a slight reduction in measured SpO_2 during the reactive hyperemia after ischemia in the arms. *Vasoconstriction or hypotension* can cause loss of SpO_2 signal. Topical nitroglycerin ointment has been used to restore the signal, but can worsen hypotension. Digital block is often successful. Topical Emla cream (lidocaine 2.5%, prilocaine 2.5%) to the earlobe covered by an occlusive plastic dressing for 30 minutes may facilitate the signal.

Irregular Heart Rhythms

During aortic balloon pulsation, the augmentation of diastolic pressure exceeds that of systolic pressure. This leads to a double or triple-packed arterial pressure waveform that confuses the pulse oximeter so that it may not provide a reading. Pulse oximetry is unreliable in atrial fibrillation and fast cardiac rhythms.

Neonates

Pulse oximeters are unreliable in the newborn, as minor changes in skin temperature, and minor adjustments in contact can cause motion artifacts and poor signal.

Delayed Detection of Hypoxia

There may be a delay between change in alveolar oxygen tension and change in the oximeter reading. Desaturation is detected earlier when the sensor is more central. Lag time will be increased with poor perfusion and decrease in blood flow. Neural block may cause the lag time to decrease while venous obstruction, vasoconstriction, hypothermia and motion artifacts delay detection of hypoxaemia.

Loss of Accuracy at Low Values

SpO2 is less accurate at low values. 70% saturation is generally taken as the lowest accurate reading.

Recent advances include analysis of photo plethysmographic waveform (respiratory variations, perfusion index, and venous pulse) use of multiple wavelengths of light to quantify methemoglobin, carboxyhemoglobin and total hemoglobin in blood and use of electronic processes to improve pulse oximeter signal processing during low signal-to-noise ratio.

Morphological Analysis of Photo Plethysmographic Waveform

The waveform is based on a signal proportional to infrared light absorption between the emitter and photo detector in the probe. The raw waveform has DC and AC components. Photo plethysmography measures changes in volume of the finger. The larger the blood volume in the finger, the more light is absorbed by the finger. Thus, less light passes through the finger and current generated by the photodetector is smaller. So, during systole the amount of light transmitted is less than diastole, and the original plethysmograph signal resembles a mirror image of an arterial blood pressure waveform. To make it easier for interpretation, the plethysmograph waveform is

inverted and auto-scaled to fit the display area.

Changes in the AC and DC components are related to the vasomotor tone. The DC component is also influenced by respiration and is related to the fluid status.

Perfusion index(PI) is defined as AC / DC × 100% of the plethysmograph waveform. It reflects the peripheral vasomotor tone. Low PI suggests peripheral vasoconstriction (severe hypovolemia) and high PI suggests vasodilation. PI is also sensitive to temperature of the finger, vasoactive drugs, sympathetic activity (pain, anxiety) and stroke volume.

Pleth Variability Index (PVI)

It quantifies the variability in plethysmograph waveform due to respiration and is a measure of intravascular volume. It is defined as $(PI_{max} - PI_{min}) / PI_{max} \times 100\%$.

Monitoring Intravascular Volume Status

In 2005, the respiratory variation in pulse oximeter waveform amplitude (ÄPOP) was described. ÄPOP was shown to be sensitive to venous return in mechanically ventilated patients and an accurate predictor of fluid responsiveness by noninvasive method. PVI is a clinically available continuous measurement of the respiratory variations of the plethysmographic waveform amplitude. Future studies will define the utility of PVI to guide intravascular volume management.

Pulse Oximetery for Regional Anaesthesia

Local anesthetic-induced sympathectomy during regional anesthesia causes peripheral vasodilation. This can be quantified by the plethysmograph waveform (PI). PI has been evaluated as a predictor of the success of regional anesthesia. Studies have shown that PI was a good indicator of intravascular epinephrine injection which induced significant decrease in PI.

Other morphological Analysis

Morphological analysis of the waveform can provide information regarding venous pulsation or analgesia (analysis of the slope of the plethysmographic waveform ascending portion). Use of waveform amplitude and pulse rate can be used to estimate the nociception-antinociception balance of the anesthetized patient. This reflects the sympathetic nervous system activation and level of analgesia, which can be used to guide the intra-operative analgesic requirements.

Carboxyhemoglobin and Methemoglobin Measurements

Conventional pulse oximeter measure only oxyhemoglobin and reduced hemoglobin in the blood. Other hemoglobins such as methemoglobin, carboxyhemoglobin, also absorb light in the blood. Recently developed pulse oximeter uses multiple wavelengths of light to analyze several different hemoglobins, which can also measure carboxyhemoglobin and methemoglobin concentrations.

Motion Artifacts, Low Perfusion

Motion artifacts result in a low signal-to-noise ratio, with SpO_2 lower due to venous motion. This venous component is exacerbated by low perfusion. Technological advances are being made to overcome these defects.

Conclusion

Despite problems and limitations, pulse oximetry remains the standard of care in most clinical situations and patients under anaesthesia. As with all monitors one must be familiar

with its performance, advantages and limitations. Intelligent use of pulse oximetry can save lives and prevent hypoxic events.

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