Pulse Oximetry in Emergency Medicine

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• Pulse oximetry • Oxygenation • Hypoxia • Patient monitoring

In 1945, Comroe and Bothello[1] first reported on the inability of practitioners to recognize hypoxemia based on the presence of cyanosis until oxygen saturation reached dangerously low levels. Clinical cyanosis is not evident until there is at least 5 g/100 mL of desaturated hemoglobin. By this point, patients have arterial oxygen saturation rates around 80% or less depending on the concentration of hemoglobin in their blood. This is on the steepest part of the oxygen dissociation curve and puts the patient at risk of significant complications related to hypoxia. Since then, repeated attempts were made to develop methods and technologies to promote the early recognition of hypoxemia in patients.

In the early 1970s, significant progress was made in the development of reliable, relatively portable and affordable equipment, which made noninvasive monitoring of oxygen saturation possible in a variety of clinical settings. Pulse oximetry was quickly and widely accepted. A myriad of uses have been described in a wide variety of clinical settings. The value of pulse oximetry in patient care has been so great that pulse oximetry has been referred to as the "fifth vital sign"[2–4] and "…arguably the greatest advance in patient monitoring since electrocardiography."[5]

The emergency physician encounters pulse oximetry on a daily basis. It is imperative that the emergency physician has a firm understanding of the principles of how pulse oximetry works. Armed with this knowledge, the emergency physician is able to use this important technology appropriately, troubleshoot problems, and be aware of its limitations. This report reviews the history and principles underlying the development of pulse oximetry. Proper procedures for its application and use and indications for its use in emergency settings are discussed. Pitfalls and complications are highlighted and new advances reviewed. Pulse oximetry has become the fifth vital sign in many settings and many patient populations. The emergency physician must be ready to use this tool to its fullest potential.

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HISTORY AND PRINCIPLES

Attempts to develop noninvasive oximeters date back to the 1930s and 1940s when there was a special interest in being able to monitor oxygenation in pilots flying at high altitudes.[6] Early devices were not very portable, difficult to use, and did not accurately reflect arterial oxygen levels. Heating of tissues in which oximetry was to be measured contributed to improvements in accuracy of measurement when compared with actual blood oxygen saturation. In 1974, Aoyagi developed the first oximeters that used the pulsatile nature of blood flow in tissues to lead to a more accurate representation of arterial oxygen saturation levels.[7] This is the basis for the technology used in today's pulse oximeters.

Pulse oximeters use the principles of the Beer-Lambert Law, which states that the concentration of an absorbing substance in a solution is related to the intensity of light transmitted through that solution.[8] Pulse oximeters consist of two light-emitting diodes, one in the red range and one in the infrared range, and a detector. These are connected to a microprocessor that determines pulse oximetry (SpO_2) based on the relative amount of light transmitted through the tissue at these two wavelengths and an empirically derived algorithm of oxygen saturation levels based on the ratio of the transmitted light.

Oxygenated and deoxygenated hemoglobin absorb light at different wavelengths differently. Deoxygenated or "blue" blood absorbs light maximally in the red band, whereas oxygenated or "red" blood absorbs light maximally in the infrared band.[5,9,10] The pulse oximeter emits light at two wavelengths, 660 nm (red) and 940 nm (infrared). The emitter is placed so that it faces a detector through tissue that experiences the pulsatile flow of blood. The amount of light absorbed varies with each pulse, and the difference between the measurement of absorption at two points in the pulse wave will be caused by arterial blood alone.[5]

Approximately 600 individual measurements are made each second by rapidly switching the diodes on and off. The ratio of absorption of the two wavelengths of light are then compared with an algorithm in the microprocessor generated by empirically measuring the absorption in healthy volunteers at varying degrees of directly measured arterial oxygen saturation.[5,10] The display of the pulse oximeter usually includes values for the heart rate displayed as beats per minute as well as the oxygen saturation displayed as a percentage. The displayed value is usually an average based on the previous 3 to 6 seconds of recording.[5] Most models also show a plethysmographic representation of the arterial pulsation, which is useful in judging how accurately the device is detecting blood flow. This may be helpful in detecting problems in using the device.

Pulse oximeters need to be placed where the emitters and detectors face each other through approximately 5 to 10 mm of tissue that experiences pulsatile blood flow. The probes are most commonly placed on finger tips and ear lobes. Other sites where they may be applied include the bridge of the nose or nares, the cheek or tongue, and the toes in infants and small children. In neonates, especially low-birth-weight infants, they may be placed across the palms of the hand or soles of the feet.[11] It is important to be sure that the detector experiences minimal interference from ambient light and that the light from the emitter travels through tissue before reaching the detector. Failure to achieve these conditions can cause inaccurate pulse oximeter readings (see Pitfalls and Complications below).

APPLICATIONS IN EMERGENCY MEDICINE AND IMPACT ON CLINICAL CARE

Pulse oximetry is useful wherever hypoxemia could occur, and its detection would aid in the care of the patient. Pulse oximetry can also be helpful in monitoring the

hemodynamic status of the patient. Multiple studies show its efficacy in detecting hypoxemia in a variety of patient populations and settings in emergency medicine. Other studies have shown a variety of other applications that provide other important information. In certain situations, regulatory and professional organizations mandate or strongly encourage its use.

Prehospital Care and use by Emergency Medical Services Personnel

Use of pulse oximetry in the prehospital setting has been prevalent for more than 20 years. Aughey and colleagues[12] showed that pulse oximetry performed in the field was accurate in the measurement of oxygen saturation when compared with co-oximetry measurement of saturation in arterial blood gas samples. Their sample showed outstanding correlation when the SpO_2 was $\geq$88%. They also showed excellent correlation between heart rates measured by pulse oximeter and electrocardiogram in a prehospital setting. Bota and Rowe showed that the sensitivity of physical examination by ambulance attendants for the recognition of hypoxemia in adult patients with serious complaints (many with chest pain or shortness of breath) was only 28%.[13] Even when oxygen was delivered, many patients remained hypoxemic. Pulse oximetry use in the prehospital setting has the potential to increase the recognition of hypoxemia and guide oxygen therapy.

However, Cydulka and colleagues[14] showed that paramedics were more likely than emergency medical technicians to use the pulse oximeter to guide the institution of oxygen therapy in hypoxic patients but that neither group used pulse oximetry to appropriately modify oxygen therapy in patients with SpO_2 $\geq$97%. Although pulse oximetry appears accurate in the prehospital setting, prehospital personnel should receive adequate instruction in the use of pulse oximetry, and modification of oxygen therapy could be better guided with its use.

During prehospital rapid sequence intubation (RSI), patients frequently experience desaturation.[15,16] Many times this, as well as bradycardia, is unrecognized by the personnel performing the intubation.[15] Use of pulse oximetry and attention to it in the development of preoxygenation strategies may be an important step in the development of prehospital RSI programs. The same group showed that the SpO_2 before intubation attempt was predictive of which patients would desaturate. In prehospital programs that use RSI, pulse oximetry and attention to it seem to be prerequisites for safety.

Use in Patient Triage

The use of pulse oximetry as a fifth vital sign in triage has been shown to significantly impact the care provided to a wide variety of patients. Recognition of hypoxemia is improved, patient care is more efficient, and appropriate care is instituted more rapidly when pulse oximetry is used in triage. The noninvasive nature of pulse oximetry allows for rapid, painless, and accurate evaluation of large numbers of patients.

In pediatric patients presenting to an emergency department (ED), clinical assessment had a sensitivity of only 33% and a negative predictive value of only 85% in determining hypoxia in pediatric patients.[17] In this same study, patient management was changed 91% of the time when the SpO_2 was known. Mower and colleagues[3] also showed that the use of pulse oximetry as a fifth vital sign in triage led to important changes in management in a small but significant number of patients, including changes in patient disposition. In pediatric patients with bronchiolitis, use of pulse oximetry in triage has been shown to decrease emergency department length of stay.[18] This study also showed that the presence of respiratory distress for predicting hypoxia had a sensitivity of only 74%.

The use of pulse oximetry as a fifth vital sign has also been shown to be useful in adult patients in triage. In adult patients, use of triage pulse oximetry was shown to lead to changes in triage classification in a small but significant number of patients[19] while another group showed that providing the triage SpO_2 to treating physicians led to significant changes (including changes in patient disposition) in the medical treatment of these adult patients.[20] The same group showed that similar changes, including changes in disposition, were found when pulse oximetry in triage was included in the care of geriatric patients presenting to emergency departments.[4] In all patients presenting to the emergency department with respiratory complaints or findings, it is clear that pulse oximetry should be used in their triage assessment.

Care of Critically Ill Patients in the Emergency Department

Continuous pulse oximetry is the standard of care in monitoring of patients in the ICU.[9] Care of critically ill patients in the ED is also aided by the use of continuous monitoring of the patient's SpO_2. Intubated patients and patients receiving mechanical ventilation require continuous pulse oximetry regardless of their location in the hospital. In the ED, as in other patient care settings, an abnormal SpO_2 is a sensitive and reliable sign of complications in these patients. In adult patients with respiratory distress, continuous pulse oximetry in the ED detected multiple episodes of clinically unrecognized hypoxemia as well as episodes of hypoxemia during several procedures including tracheal intubation, suctioning, and other treatments.[21]

Continuous pulse oximetry during ED intubation has been shown to decrease the frequency and duration of hypoxemia during emergency intubation attempts.[22] Pulse oximetry has also been shown to decrease use of arterial blood gas (ABG) testing in the ED in one study[23] and especially ''unjustified ABG measurements'' in another study.[24] This means that the use of an inexpensive, noninvasive, instantaneous and essentially painless technology has the ability to decrease ED charges, patient discomfort, and time to availability of essential clinical information.

Oximetry may be less prone to error and more accurate in the assessment of oxygenation in patients with cardiopulmonary disease when compared with ABG measurement.[5] ABG measurement requires correct technique. Practitioners who only rarely perform this procedure may not practice sufficient attention to detail to minimize error. In addition, the pain associated with the procedure may lead to a change in the patient's respiratory pattern and an increase in respiratory effort producing improved oxygenation, which is only transient. Clinicians may be misled by the results they obtain in this way.

Pulse oximetry has also been used to monitor adequacy of interventions during cardiopulmonary resuscitation. High-quality chest compressions often produce excellent pulse oximetry tracings in patients with a lack of spontaneous circulation. In a critical appraisal of use in this setting, the pulse oximeter proved beneficial in the management of primary respiratory arrest but less useful during external chest compressions. However, the availability of a pulse oximeter significantly altered the management in seven of 20 patients. Five of these 7 patients survived.[25]

Pulse Oximeters in Emergency Department Patient Assessment

Pulse oximeters that display pulsatile wave forms can be used to measure systolic blood pressure. Either the reappearance of the waveform with slow cuff deflation or the disappearance of the wave form with cuff inflation may be used. An average of these two measurements has been shown to have good agreement with blood pressures obtained by auscultation or blood pressures obtained by noninvasive measurement devices.[9]

Pulse oximetry wave forms have also been shown to be useful in the detection of pericardial effusions in children[26] and in assessing the degree of airways obstruction in patients with asthma[27,28] through the recognition of a pulsus paradoxus in the oximeter wave form. Frey and Butt showed in an ICU setting that pulse oximetry accurately reflected the pulsus paradoxus documented by invasive monitoring of patients.[29] Further development of the monitoring of pulsus paradoxus in this way may lead to improvements in the assessment and treatment of patients with asthma who present to the ED.[30,31]

Pulse oximetry has been shown to be predictive of the presence of pneumonia in elderly patients.[32] An SpO_2 less than 94% had a sensitivity of 80% and a specificity of 91% for the presence of pneumonia with a positive predictive value of 95%. Even more impressive was if there was a decrease of greater than 3% from the baseline value of the patient's SpO_2 there was a positive predictive value for the presence of pneumonia of 100%. Pulse oximetry has also been shown in children to be predictive of treatment failure in pediatric patients with severe pneumonia.[33]

Pulse oximetry has also been shown to be predictive of respiratory failure in patients with severe exacerbations of asthma. In children, SpO_2 levels of less than 90% to 92% are predictive of severe exacerbations and need for hospitalization and other additional therapies.[34,35] In adults, respiratory failure was rare in patients presenting with SpO_2 greater than 92%.[36] Above this level, the need for arterial blood gas monitoring could be safely avoided.

Sedation and Analgesia in the Emergency Department

Pulse oximetry is routine and mandatory in the monitoring of patients undergoing procedural sedation and analgesia in the ED. The American Academy of Pediatrics, American College of Emergency Physicians, American Society of Anesthesiologists, American Medical Association, and Joint Commission on the Accreditation of Healthcare Organizations all call for continuous pulse oximetry in patients receiving procedural sedation and analgesia in the ED or other settings.[37–42] Although the most important ''monitor'' for these patients is someone whose only role is to monitor and record the patient's vital signs, level of alertness, and respiratory effort, the pulse oximeter remains a vital piece of equipment that should be in place and watched carefully. Recognition of hypoxemia based on cyanosis is no better here than in any other setting. Most adverse events in this setting are related to a failure to adequately monitor and then rescue patients who have received these interventions.[43]

LIMITATIONS AND COMPLICATIONS

Pulse oximetry is an amazing technology that is invaluable in the everyday practice of emergency medicine. However, as with any technology, it is only as good as the practitioner who is using it. The emergency physician must be aware of the limitations of this technology and the complications associated with it. Unfortunately, many physicians have limited understanding of pulse oximetry.[9] One study found that less than 50% of physicians were aware that motion, arrhythmias, and things like nail polish could affect pulse oximetry readings.[44] Ultimately, the clinician must look at the patient, and if the pulse oximeter (or any other monitor) does not seem to be behaving in a way that is consistent with the clinical picture that is presented, the clinician must determine the cause of the discrepancy and act in a way that is in the best interest of the patient.

It is important to remember that pulse oximetry only reflects the state of oxygenation of the patient. It does not provide any information regarding the patient's ventilation,

carbon dioxide level, or acid–base status. Especially when patients are receiving supplemental oxygen, they may have normal SpO_2 levels but be in respiratory failure with hypercapnia and respiratory acidosis. If information about ventilation is needed, capnography or blood gas measurements are needed. Likewise, if the acid–base status of the patient is in question, blood gas testing should be performed.

Pulse oximetry may be affected by physical factors, physiologic factors, and interference from substances that affect the transmission or absorption of light in the path of the oximeter's diode.

Physical Factors Affecting Pulse Oximetry

The pulse oximeter will only function if the transmitted light is detected by the detector, and there is an adequate change in the amount of light transmitted (because of the arterial pulsation in the tissue of that area of the body). Anything that interferes with this relationship will make the device susceptible to malfunction. If there is an inadequate pulse caused by decreased perfusion secondary to hypotension, hypothermia, or vasoconstriction, a satisfactory signal will not be detected, and no reading or a potentially inaccurate reading will be obtained.[5,7,9] Usually the pulse oximeter will display oxygen saturations that are falsely low in this setting. More worrisome is that poor perfusion will lead to a lack of a reading, and hypoxemia will go unrecognized until perfusion is improved or another means of determining the oxygenation status of the patient is used. Adult systolic blood pressures of less than 80 mm Hg have been associated with poor pulse oximetry performance.[7] The SpO_2 level displayed should only be assumed to be accurate when there is a high-quality plethysmographic tracing displayed on the monitor. Ideally, the display will show a pulse wave with a demonstrable dicrotic notch.

Patient movement can make it difficult for the detector to adequately ''sense'' light that is transmitted. Motion artifact is usually caused by motion of the probe relative to the patient's skin.[5] Sometimes, taping the pulse oximeter cable to the back of the extremity to which it is attached will minimize the amount of motion artifact. Having the patient rest their hand on a flat surface may also help.[5]

Ambient light may also interfere with pulse oximeters. Excessive exposure of the detector to ambient light may lead to inaccurate readings. In most cases of ambient light overexposure the SpO_2 level will tend toward 85% (the reading dictated by the algorithm in the microprocessor when the ratio of the absorbance of the two wavelengths of light is one) and therefore will be falsely low.[10] However, there have also been reports of falsely high readings when probes are exposed to high levels of ambient light, or probe displacement is not recognized and the probe is completely exposed to ambient light.[45,46] Making sure that the light from the diode is only sensed by the detector after it has passed through the tissue and that the detector is protected from ambient light is important. If light from the diode reaches the detector without passing through the tissues as is the case when probes are malpositioned or oversized, a *penumbra effect* may occur leading to a calculated saturation in the low 80s.[47] This will usually lead to an underestimation of the patient's SpO_2 level unless the patient is already hypoxemic.[11]

Physiologic Factors Affecting Pulse Oximetry

The major physiologic factor affecting pulse oximetry is the oxygen–hemoglobin dissociation curve. SpO_2 is an estimation of arterial oxygen saturation of hemoglobin (SaO_2), which is related to the partial pressure of oxygen in arterial blood (PaO_2). Because the oxygen–hemoglobin dissociation curve is sigmoidal in shape, at high PaO_2, or on the ''flat part of the curve,'' large changes in PaO_2 level will lead to only

minor changes in SpO_2 level. This is the major reason pulse oximetry is not the ideal technology for monitoring patients in whom hyperoxia is a major concern.

At lower levels of PaO_2, relatively small decreases in oxygen tension can lead to rapid decreases in oxygen saturation. It is therefore important to realize that a PaO_2 of 75 mm Hg usually is associated with an SpO_2 level of about 90%. However, an SpO_2 level of 80% usually is associated with a PaO_2 level of less than 50%. It is important to have a sense of the relationships between oxygen tension and saturation.

Substances that Interfere with Pulse Oximetry

Skin pigmentation is one factor that may affect the accuracy of pulse oximetry. In critically ill patients, readings that were more than 4% different from actual measured SaO_2 were found in 27% of black patients compared with only 11% of white patients.[9] Intravenous dyes such as methylene blue, indocyanine green, and indigo carmine can cause falsely low SpO_2 readings for up to 20 minutes after administration.[9]

Older pulse oximeters were prone to interference from nail polish.[7] However, newer work showed that even the nail polish colors that most affected the accuracy of the readings (black, purple, and dark blue) did not affect accuracy enough to be clinically significant.[48] The investigators also showed that rotation of the sensor probe by 90° did not completely eliminate the error in measurement. Despite these findings, the investigators state that removing nail polish might be helpful in some cases.

Abnormal Hemoglobins

Patients with abnormal hemoglobins are at risk of having inaccurate pulse oximetry results. Fetal hemoglobin does not seem to affect pulse oximetry.[7] Patients with sickle hemoglobin usually have readings similar to those with normal hemoglobin.[7] However, there have been reports of both falsely low and falsely high readings in patients with sickle cell disease.[7,49,50] These patients are at significant risk for pulmonary complications that are life threatening in addition to sepsis. In this population, oximetry data are extremely useful. In practice, it is very useful to keep a file of patients with sickle cell disease who use an ED and be sure part of the file is a baseline SpO_2 value obtained at a time when they are relatively well. Past medical records may be able to provide this information, and many patients with sickle cell disease or their families may be aware of this value. Significant deviations from their baseline SpO_2 level must be treated aggressively in terms of finding the etiology and in providing supplemental oxygen to decrease further complications.

Carboxyhemoglobin

Standard pulse oximeters that use only two wavelengths of light are prone to significant errors when abnormal hemoglobins are present. The most common causes of these types of errors are elevated levels of carboxyhemoglobin (COHb) and methemoglobin. COHb absorbs light in the red wavelength (eg, 660 nm) almost identically to oxyhemoglobin. Therefore, it is understandable how the standard pulse oximeter will interpret carboxyhemoglobin as oxyhemoglobin. This leads to a falsely elevated absorption ratio (red or oxygenated versus infrared or deoxygenated) that is sensed by the oximeter. Therefore, the reported SpO_2 level is an overestimation of the true SaO_2. This has been shown in several clinical studies, and, in fact, the pulse oximeter tends to overestimate the SaO_2 by the amount of COHb present except at extremely high levels of COHb.[51–53] In patients with suspected, known, or possible CO poisoning, it is important to directly measure CO levels as well as oxyhemoglobin levels by co-oximetry in addition to ABGs.[53] A new eight-wavelength pulse oximeter has

been introduced that seems to accurately measure COHb and methemoglobin levels.[54]

Methemoglobin

Methemoglobin (MeHb) absorbs light equally well at both wavelengths used in standard pulse oximeters (660 nm and 940 nm). In the presence of MeHb, SpO_2, although somewhat reduced initially, overestimates actual SaO_2.[55,56] As the level of MeHb increases to 30% to 35%, the ratio of absorbance at the two wavelengths reaches a plateau and approximates one. At this ratio, the algorithm in the microprocessor gives a calculated SpO_2 value of 85%, and most pulse oximeters plateau at SpO_2 levels of 82% to 85%.[55,56] In light of MeHb levels by this time of 30% to 35%, this is a marked overestimation of actual SaO_2. Pulse oximetry must be interpreted with extreme caution in patients with known or suspected methemoglobinemia. The newer eight-wavelength oximeter seems to measure MeHb accurately as well and may represent a real advance in oximetry technology.[54]

Complications

Most complications related to pulse oximetry use are caused by a lack of understanding of the technology on the part of the clinician using the device. Recognition that the pulse oximeter only gives you information about oxygenation and not ventilation or acid–base status is often lacking or not thought about. A normal SpO_2 level provides a clinician with a false sense of security. Failure to consider the possibility of a dyshemoglobinemia may allow a patient with a seemingly acceptable SpO_2 level to actually remain hypoxic for a prolonged period of time. However, there have been actual complications related to pulse oximeters reported as well.

Digital injury has been reported when continuous pulse oximetry is used for prolonged periods especially in the setting of hypoperfusion or the use of vasopressor medications.[57] There have also been multiple reports of burns to digits and other body parts when non–magnetic resonance imaging (MRI) compatible pulse oximeter probes have been used in patients undergoing MRI scanning.[58,59] Ferrous portions of the probes become extremely hot in the setting of the scanner's electromagnetic field causing severe thermal injury.

NEW TECHNOLOGY

Newer pulse oximeters are more successful at dealing with several of the limitations that have plagued these devices since they first enjoyed widespread use 25 years ago. Motion causes fewer disturbances in pulse oximeter readings in newer models because of improved algorithms;[11] units have become smaller, lighter, and less expensive; and the development and clinical use of devices that measure COHb and MeHb will make oximetry even more useful in the ED setting.[11,54]

The development of reflectance oximeters, which do not rely on transmitted light but on reflected light, is underway. These are not yet reliable enough for clinical use but once perfected may address several other shortcomings of current oximeters. Other technologies are being developed that may be useful in assessing tissue oxygenation and brain oxygenation and perfusion.[11]

SUMMARY

Since first introduced into widespread clinical use 25 to 30 years ago, pulse oximeters have become so commonplace in clinical medicine that they are seen as providing an all-important ''fifth vital sign.'' The pulse oximeter is a noninvasive, safe, essentially

painless, and relatively inexpensive device that provides valuable and usually reliable clinical information rapidly. The value of oximetry is recognized by professional and regulatory organizations. It should be available in all settings in which emergency physicians care for patients and used frequently.

However, as with any technology, the device is only as good as the clinician who is using it. The emergency physician must have an understanding of the principles underlying the technology to understand its limitations and potential complications. Although the recognition of hypoxemia is greatly enhanced through the proper and informed use of the pulse oximeter, the device can never be relied on to take the place of the clinician at the bedside who makes sure that the data provided matches the clinical picture with which he or she is presented.

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