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Pulse Oximetry in Pediatric Practice

Sotirios Fouzas, Kostas N. Priftis and Michael B. Anthracopoulos

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Pulse Oximetry in Pediatric Practice

abstract

The introduction of pulse oximetry in clinical practice has allowed for simple, noninvasive, and reasonably accurate estimation of arterial oxygen saturation. Pulse oximetry is routinely used in the emergency department, the pediatric ward, and in pediatric intensive and perioperative care. However, clinically relevant principles and inherent limitations of the method are not always well understood by health care professionals caring for children. The calculation of the percentage of arterial oxyhemoglobin is based on the distinct characteristics of light absorption in the red and infrared spectra by oxygenated versus deoxygenated hemoglobin and takes advantage of the variation in light absorption caused by the pulsatility of arterial blood. Computation of oxygen saturation is achieved with the use of calibration algorithms. Safe use of pulse oximetry requires knowledge of its limitations , which include motion artifacts, poor perfusion at the site of measurement, irregular rhythms, ambient light or electromagnetic interference, skin pigmentation, nail polish, calibration assumptions, probe positioning, time lag in detecting hypoxic events, venous pulsation, intravenous dyes, and presence of abnormal hemoglobin molecules. In this review we describe the physiologic principles and limitations of pulse oximetry, discuss normal values, and highlight its importance in common pediatric diseases, in which the principle mechanism of hypoxemia is ventilation/perfusion mismatch (eg, asthma exacerbation, acute bronchiolitis, pneumonia) versus hypoventilation (eg, laryngotracheitis, vocal cord dysfunction, foreign-body aspiration in the larynx or trachea). Additional technologic advancements in pulse oximetry and its incorporation into evidence-based clinical algorithms will improve the efficiency of the method in daily pediatric practice. *Pediatrics* 2011;128: 740–752

AUTHORS: Sotirios Fouzas, MD,[a] Kostas N. Priftis, MD,[b] and Michael B. Anthracopoulos, MD[a]

[a]Respiratory Unit, Department of Pediatrics, University Hospital of Patras, Patras, Greece; and [b]Third Department of Pediatrics, "Attikon" Hospital, University of Athens School of Medicine, Athens, Greece

KEY WORDS

pulse oximetry, children, hemoglobin oxygen saturation

ABBREVIATIONS

$Sa0_2$—arterial blood oxygen saturation
$SP0_2$—arterial hemoglobin oxygen saturation by pulse oximetry
ODC—oxyhemoglobin dissociation curve
COHb—carboxyhemoglobin

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Address correspondence to Sotirios Fouzas, MD, Respiratory Unit, Department of Pediatrics, University Hospital of Patras, Rio, 265 04 Patras, Greece. E-mail: sfouzas@gmail.com

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The clinical assessment of hypoxemia is notoriously unreliable because it depends on many factors, including ambient lighting, skin pigmentation, tissue perfusion, and hemoglobin concentration.[1] Even under optimal conditions, arterial blood oxygen saturation (Sa_{O_2}) of ~75% is required before central cyanosis becomes clinically detectable.[1,2]

The introduction of pulse oximetry in clinical practice has led to a revolutionary advancement in patient assessment and monitoring, because it allows for a simple, noninvasive, and reasonably accurate estimation of arterial oxygen saturation. Pulse oximeters have become available for widespread application in pediatric care, and oxygen saturation has even been proposed as the "fifth vital sign."[3,4] However, clinically relevant principles and inherent limitations of pulse oximetry are not always well understood by health care professionals.[5,6]

In this review we describe the physiologic principles, limitations, and common applications of pulse oximetry in daily pediatric practice.

HISTORY OF PULSE OXIMETRY

The theoretical background for noninvasive assessment of blood oxygenation was set in the early 1900s when it was observed that spectral changes of light absorbance in vivo are related to tissue perfusion.[7] Great advancements in the development of related instruments occurred during World War II in an effort to monitor oxygenation of military pilots.[7] In 1940, Squire[8] reported on a "blood-oxygen-meter" for use on the hand, and in 1942, Millikan[9] coined the word "oximeter" for a portable ear device that read energy absorption in the red and infrared light spectra. Important subsequent work was presented by Wood,[10] who managed to measure oxygen saturation by suspending tissue perfusion. However, all these "early" oximeters relied either on compression and reperfusion of the measuring site or on the "arterialization" of capillary blood through heating; consequently, they were inconveniently large, difficult to use, and, most importantly, inaccurate.[7,11]

A true revolution in the development of noninvasive oximetry occurred after the work of the Japanese electrical engineer Aoyagi.[12] In an experiment aimed to develop a dye-dilution technique to measure cardiac output, he realized that the untoward changes in tissue light absorption caused by the pulsatile nature of the arterial blood flow could be used to compute oxygen saturation. Thus, the "noise" in his experiment became the "signal" for a different application, which led to the development of the first "pulse" oximeter in late 1974.[11,12] In the next 2 decades, after the explosive development of technologies in light emission and signal processing, pulse oximeters underwent astonishing improvements and became available for widespread application throughout medical practice.[11,13]

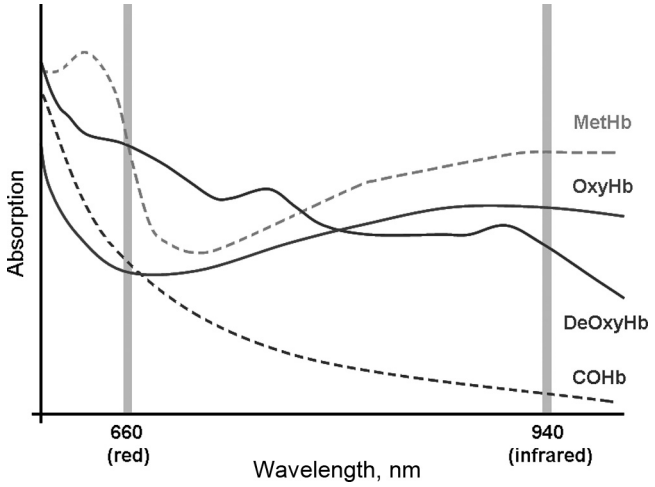

FIGURE 1
Reference spectra depicting the absorption coefficients of oxygenated hemoglobin (OxyHb), deoxygenated hemoglobin (DeoxyHb), methemoglobin (MetHb), and COHb as a function of wavelength. The vertical lines indicate the wavelengths (red and infrared) commonly used in pulse oximetry.

PRINCIPLES OF OPERATION

The estimation of arterial hemoglobin oxygen saturation by pulse oximetry (SP_{O_2}) is based on the specific characteristics of oxygenated and deoxygenated hemoglobin (oxyhemoglobin and deoxyhemoglobin, respectively) with regard to light absorption in the red and infrared spectra. Deoxyhemoglobin is characterized by greater red-light absorption (wavelength range: 600–750 nm) in comparison to oxyhemoglobin, whereas oxyhemoglobin exhibits higher absorption in the infrared spectrum (850–1000 nm)[14,15] (Fig 1). By obtaining the ratio of light absorption in the red and infrared spectra and then calculating the ratio of these 2 ratios (ratio of absorption ratios), the percentage of oxyhemoglobin can be calculated.[12,15]

Light absorption in vivo depends on the characteristics of the tissues across the site of measurement.[16,17] During short time periods, the absorption by skin, subcutaneous fat, muscles, bones, and capillary and venous blood remains practically constant (constant absorbers). Therefore, any change in light absorption should be attributed to

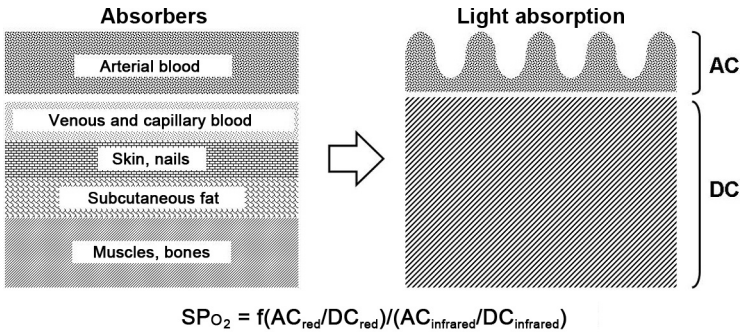

FIGURE 2

Principle of operation of pulse oximetry. Shown is a schematic representation of the layers of human tissues that absorb light energy at the measuring site (left) and the components of light absorption (constant—DC and variable—AC) by distinct tissue characteristics (right). A simplified version of the ratio of absorption ratios equation used to calculate SpO_2 is shown also.

the variations of the arterial blood volume related to the cardiac cycle[12,17–19] (Fig 2; Supplemental Movie 1).

Currently available pulse oximeters are equipped with 2 light-emitting diodes (LEDs), 1 emitting at the red spectrum and the other at the infrared spectrum, most commonly at wavelengths of 660 and 940 nm, respectively. Emission of these 2 wavelengths alternates at frequencies of 0.6 to 1.0 kHz,[15,20,21] and the nonabsorbed energy is detected by a semiconductor. A microprocessor subtracts the absorption by constant absorbers, thus rendering the final signal, which is displayed electronically as a plethysmographic wave form. The SpO_2 is calculated from the conversion of the ratio of absorption ratios by using dedicated calibration algorithms stored in the microprocessor of the device. These algorithms are derived through SaO_2 measurements in healthy volunteers breathing mixtures of decreased oxygen concentrations and are usually unique for each manufacturer.[15,17–21]

The displayed SpO_2 represents the mean of the measurements obtained during the previous 3 to 6 seconds, whereas the data are updated every 0.5 to 1.0 second.[15,18–20] The performance of each device is strictly related to the reliability and complexity of the algorithms used in signal processing and to the speed and quality of the microprocessor. There are numerous studies of the accuracy and precision of pulse oximeters in various adult[22–24] and pediatric[25–27] populations. Most manufacturers claim mean differences (bias) of $\leq$2% with SDs (precision) of $\leq$4%.[15,18–20,28] It should be noted, however, that these results have been reported in subjects with SaO_2 levels that exceed 80%[15,18–20,28]; the performance of pulse oximeters deteriorates remarkably when SaO_2 decreases to $<$80%.[17,24,29]

The probe of the device must be positioned in such manner that the emitter and the detector are exactly opposite to each other with 5 to 10 mm of tissue between them.[15,30] Typical measuring sites include the finger, the toe, the pinna, and the lobe of the ear, whereas for neonates and infants measurements are commonly obtained from the palm or the sole by using specially designed probes.[28,30–32] Less commonly used sites are the cheek and the tongue.[30]

MISCONCEPTIONS

Safe use of pulse oximetry requires comprehension of the information that the method offers.[33] SpO_2 is, in fact, an estimate of SaO_2 as derived by arterial blood gas analysis, which in turn does not accurately reflect partial oxygen tension of the arterial blood (PaO_2). Indeed, although SaO_2 and PaO_2 are related through the oxyhemoglobin dissociation curve (ODC), their relation is not linear. Moreover, a series of factors can further influence the shape of the ODC (Fig 3). Hence, SpO_2 (as well as SaO_2) does not necessarily provide reliable information regarding the oxygenation status of tissues.[30,34,35]

SpO_2 represents an estimate of functional arterial hemoglobin saturation,

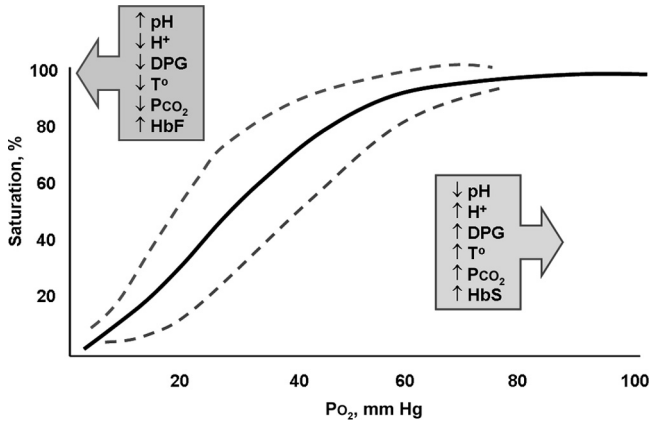

FIGURE 3

ODC (continuous line) and factors that influence its shape. The ODC is shifted to the right (lower dotted line) by increased hydrogen ion (H^+) concentration (acidosis), increased 2,3-diphosphoglycerate (DPG), increased temperature (T°), increased partial pressure of carbon dioxide (PCO_2), and the presence of hemoglobin S (HbS) (sickle cell disease). Decreased H^+ (alkalosis), DPG, T°, and PCO_2 and the presence of fetal hemoglobin (HbF) shift the curve to the left (upper dotted line).

which refers only to the arterial hemoglobin that is capable of transporting oxygen (functional hemoglobin = oxyhemoglobin/[oxyhemoglobin + deoxyhemoglobin]). Functional saturation differs from fractional hemoglobin saturation (Fractional hemoglobin = oxyhemoglobin/total hemoglobin), which can be measured by most blood gas analyzers with co-oximetry. The total hemoglobin denominator in the calculation of fractional hemoglobin might include abnormal or variant hemoglobin molecules with limited oxygen-carrying properties.[30,35,36] Therefore, the terms "functional" and "fractional" hemoglobin saturation are not interchangeable.[36] In situations such as dyshemoglobinemias, pulse-oximetry readings do not adequately reflect the oxygen-carrying properties of arterial blood.[15,28,35,37] It should be noted also that pulse oximetry does not provide information regarding ventilation or acid-base status.[30,38–40]

LIMITATIONS OF PULSE OXIMETRY

The limitations of pulse oximetry can be generally classified as safe or potentially unsafe (Table 1). Safe limitations refer to those circumstances in which the inaccuracy in the displayed SpO_2 can be suspected, and its cause is recognizable. In this case the observer is usually warned by the device (alarm) about the pitfall. A potentially unsafe limitation is considered to be any situation in which the inaccuracy is difficult to recognize; the displayed SpO_2 is erroneous, but the observer is not warned about the pitfall.

Safe Limitations

Motion Artifacts

Motion artifact represents the most common limitation of pulse oximetry.[13,15,28] Because the normally pulsatile (arterial) component of light absorption represents no more than 5% of the total absorbed energy, any motion that alters the remaining fraction of absorption (especially when due to venous blood) will affect the signal-to-noise ratio and drive SpO_2 to lower than true values.[41,42] Fortunately, motion artifacts can be recognized by motion alarms or distorted plethysmographic waveforms. However, rhythmic motions or vibrations with a frequency similar to heart rate (0.5–3.5 Hz) can be particularly troublesome.[41] Sophisticated read-through-motion and motion-tolerant technologies continue to evolve and have improved the performance of the new-generation oximeters.[30,43–46]

Poor Perfusion

Adequate arterial pulsation at the site of measurement is essential for distinguishing true signal from background noise.[41,42] Low-perfusion states, such as low cardiac output, shock, hypothermia, vasoconstriction, arterial occlusion, or during blood pressure cuff inflation, might impair the functioning of the device and result in lower SpO_2 readings or delayed recognition of acute hypoxemia.[13,28,46–50] For infants with cold extremities, local rubbing or heating before the application of the probe might temporarily improve perfusion; however, for hypothermic patients, monitoring by a forehead probe is an alternative option.[51] New-generation devices are equipped with signal-extraction algorithms and can perform better in low-perfusion states.[30,46–49]

Skin Pigmentation, Nail Polish, and Artificial Nails

In theory, skin pigmentation presents a constant level of absorption that is subtracted in the calculation of SpO_2 and, therefore, should not influence the performance of the device.[12,34] However, dark skin pigmentation has been incriminated for erroneous SpO_2 readings, especially at Sao_2 values of $<80\%$.[21,52,53]

Although data regarding the impact of nail polish are conflicting,[54–58] polish of black, blue, or green color and synthetic nails might interfere with pulse oximetry and result in an underestimation of Sao_2.[54,55,59] This effect can be avoided by mounting the probe on the finger sideways.[34] New-technology pulse oximeters are less susceptible to these limitations.[21,34,56–58]

Bilirubin has no effect on pulse oximetry, because it presents a different spectrum of light absorption (at ~450 nm). Therefore, the method can be used reliably for monitoring jaundiced patients, including neonates.[13,15,20,21,28,30,34] However, patients with severe hemolytic jaundice might also have increased carboxyhemoglobin (COHb) levels, which could potentially lead to erroneous pulse-oximetry readings.[15] In addition, falsely low SpO_2 values have been reported in bronze baby syndrome.[60]

Irregular Rhythms

Inaccurate oximetry readings can be observed with irregular heart rhythms, especially during tachyarrhythmias.[21] These artifacts can usually be recognized by observing the plethysmographic wave form. Currently available devices possess signal-extraction technologies that are capable of recognizing such events.[20,21,34]

Electromagnetic Interference

Electromagnetic energy from electrosurgical cauterization units and cellular phones might interfere with pulse oximeters and lead to erroneous SpO_2 readings.[61] Special devices with fiberoptic technology should be used during MRI to avoid both interference with image quality and potentially dangerous heating of the sensor with consequent thermal injury.[61,62]

Potentially Unsafe Limitations

Calibration Assumptions

As stated already, the displayed SpO_2 is the result of the conversion of the ratio

TABLE 1 Limitations of Pulse Oximetry

Limitations	Mechanism	Bias	Proposed Action
Safe limitations[a]			
Motion	Sensor movement	Lower SpO_2 readings	Evaluate plethysmographic waveform
	Increased noise caused by changes in nonpulsatile component of light absorption	False alarms	Stabilize sensor Change sensor position Use new-generation pulse oximeters
Poor perfusion	Decreased signal caused by decreased pulsatile (arterial) component of light absorption	Lower SpO_2 readings	Evaluate plethysmographic waveform Check and correct skin temperature and peripheral perfusion Place sensor more centrally Use new-generation pulse oximeters[b]
Skin pigmentation	Probably caused by calibration assumptions for dark skin pigmentation	Lower or less reliable SpO_2 readings at lower Sao_2 values	Use new-generation pulse oximeters[b]
Nail polish and artificial nails	Decreased signal because of decreased light absorption with artificial nails or nail polish of black, blue, or green color	Lower SpO_2 readings	Change sensor position
Irregular rhythms	Increased noise caused by tachyarrhythmias	Lower or less reliable SpO_2 readings	Evaluate plethysmographic waveform Use new-generation pulse oximeters[b]
Electromagnetic interference	External electromagnetic energy interference caused by electrosurgical cauterization units, cellular phones, or MRI devices	Lower SpO_2 readings False alarms Heating of the sensor and thermal injury (MRI)	Evaluate plethysmographic waveform Avoid external electromagnetic energy sources Use pulse oximeters with fiber-optic technology (MRI)
Potentially unsafe limitations[a]			
Calibration	Device-specific calibration algorithms derived by correlating light absorption ratios over a Sao_2 spectrum of 80%–100% in healthy young adults Lower SpO_2 values calculated by mathematical equations	SpO_2 readings of <80%–85% are less accurate especially at the extremes of the age spectrum	Use new-generation pulse oximeters[b]
Time lag	Software-related delay between sudden changes in blood oxygenation and SpO_2 readings	Delay in detecting clinically important desaturation, which may exceed 15–20 s	Use new-generation pulse oximeters[b] Do not use pulse oximetry as a substitute for cardiorespiratory monitoring in critically ill patients
Probe positioning	The emitted light energy is projected tangentially to the detector because of inappropriate sensor placement ("penumbra" or "optical shunting" effect)	Lower SpO_2 readings	Place sensor with the emitter and the detector exactly opposite to each other Use probes of appropriate size in neonates and infants
Ambient light interference	Intense external light energy (as in phototherapy) may interfere with the photodetector ("flooding" effect)	Lower SpO_2 readings	Use new-generation pulse oximeters[b] Cover the sensor
Abnormal hemoglobin molecules	COHb presents red-light absorption similar to oxyhemoglobin	In carboxyhemoglobinemia pulse oximetry overestimates blood oxygenation	Check arterial Sao_2 if abnormal hemoglobin molecules are suspected (ie, carbon monoxide intoxication)
	Methemoglobin absorbs equal amount of energy in the red and infrared spectra, which affects the ratio of absorption	In significant methemoglobinemia, SpO_2 tends toward 85%	Suspect abnormal hemoglobin molecules if the Sao_2–SpO_2 difference exceeds 5% Use pulse co-oximetry[c]
Pulsatile veins	Increased noise because of pulsations of venous blood (ie, significant tricuspid regurgitation, hyperdynamic circulation states)	Lower or less reliable SpO_2 readings	Use new-generation pulse oximeters[b]
Intravenous dyes	Intravenous dyes such as methylene blue, indocyanine green, and indigo carmine interfere with light absorption	Lower SpO_2 readings	Do not use pulse oximetry or interpret pulse-oximetry readings with caution Check Sao_2

[a] Safe limitations are circumstances in which a possible inaccuracy in the displayed SpO_2 can be easily suspected; the observer is usually warned by the device (alarm) about the pitfall. Potentially unsafe limitations are those situations in which the inaccuracy is difficult to recognize; the displayed SpO_2 is erroneous but the observer is not warned about the pitfall.

[b] New-generation pulse oximeters are less susceptible to these limitations because of more sophisticated calibration and signal-extraction algorithms.

[c] Pulse co-oximeters are capable of detecting abnormal hemoglobin molecules by using multiwavelength technology.

of absorption ratios into percent saturation by using specific calibration algorithms. These algorithms are derived by correlating the ratio of the absorption ratios with arterial gas $Sa0_2$ measurements in healthy young volunteers over a range of desaturation values. Because it is unethical to desaturate volunteers below $Sa0_2$ levels of ~80%, lower $SP0_2$ values are derived by extrapolation and, therefore, are less accurate.[15,17,24,29,34] Moreover, because the subjects recruited for calibration purposes are healthy young adults, the applicability of calibration data to patients at the age extremes has been questioned.[13,15,25,30,34]

Time Lag in the Detection of Hypoxic Events

Most conventional pulse oximeters present a clinically significant delay between a sudden change in blood oxygenation and the related change in the displayed $SP0_2$ values. This time lag depends on the complexity of the algorithms used and might exceed 15 to 20 seconds.[34,63–65] Although new-generation devices have improved response times, and desaturation events can be detected earlier if the probe is placed more centrally (eg, at the ear lobe),[13,21,63] pulse oximetry should not be used as a substitute for cardiorespiratory monitoring in critically ill patients.[30,34]

Probe Positioning

Lower $SP0_2$ readings might occur when the probe is inappropriately placed, especially on the small fingers of neonates and infants.[13,28] In this case, the emitted light can be projected tangentially to the detector, sometimes without crossing an arterial bed, phenomena which have been described as the "penumbra" and "optical shunting" effects, respectively.[66,67] This pitfall can be avoided by positioning the emitter and the detector exactly opposite to each other and by using probes of appropriate size for neonates and infants.[13,28,34]

Ambient Light Interference

Intense white or infrared light might interfere with pulse oximetry and lead to falsely low $SP0_2$ readings. This phenomenon, known as the "flooding" effect, is caused by the excessive increase of the light energy that literally floods the photodetector and drives the ratio of absorption ratios toward the unit; this corresponds to an $SP0_2$ of 85%.[16] Although new-generation devices can detect light interference,[16,21,34,68] health care professionals, particularly those who handle neonates exposed to phototherapy, must be aware of this potential limitation. Ambient light interference can be avoided by simply covering the sensor with nontransparent material.

Abnormal Hemoglobin Molecules

Abnormal or variant hemoglobin molecules might interfere with pulse oximetry and lead to inaccurate results that might influence clinical decision-making.[69] Carboxyhemoglobinemia represents the most dangerous limitation of pulse oximetry, because in the presence of COHb the method overestimates arterial oxygenation. This effect is caused by the specific characteristics of COHb, which exhibits red-light absorption similar to that of oxyhemoglobin[14] (Fig 1). Therefore, increased COHb levels affect the ratio of absorption ratios and cause the pulse oximeter to overread by ~1% for every 1% increase of circulating COHb.[70,71] Therefore, $SP0_2$ values should be verified by $Sa0_2$ measurements using a co-oximetry method when the presence of COHb is suspected (eg, carbon monoxide intoxication).[21,69,72,73]

Methemoglobinemia also represents an important but less dangerous limitation of pulse oximetry.[69] Methemoglobin (MetHb) absorbs approximately equal amounts of energy in the red and infrared spectrums[14] (Fig 1). In significant methemoglobinemia (MetHb > 30%), the ratio of absorption ratios will tend toward the unit ($SP0_2$ ~ 85%), thus underestimating high saturation values and overestimating severe hypoxemia.[71,73,74] If the difference between $Sa0_2$ and $SP0_2$ (the "$Sa0_2$–$SP0_2$ gap") exceeds 5%, the presence of abnormal hemoglobin molecules should be investigated by co-oximetry.[72,73] Pulse co-oximeters, by taking advantage of novel multiwavelength technologies, have been shown to accurately measure both COHb and MetHb.[71,75–78]

Fetal hemoglobin and hemoglobin S present light-absorption characteristics similar to those of adult hemoglobin and do not interfere with pulse oximetry.[14,79–81] However, physicians should remember that abnormal hemoglobin molecules affect ODC (Fig 3); thus, the displayed $SP0_2$ value might not reliably reflect tissue oxygenation, particularly for children with sickle cell disease.[30,82]

Anemia does not seem to affect the accuracy of pulse oximetry, at least for hemoglobin levels of >5 g/dL and if cardiovascular function is preserved.[34,80,83,84] Similarly, polycythemia does not seem to interfere with pulse oximetry.[80]

Venous Pulsation

In case of significant tricuspid regurgitation and in hyperdynamic circulation states, the pulsatile variation of venous blood might affect signal-to-noise ratio and result in erroneous $SP0_2$ readings.[85,86]

Intravenous Dyes

Intravenous dyes such as methylene blue (actually used as a first-line treatment for severe methemoglobinemia), indocyanine green, and indigo carmine might cause lower $SP0_2$ readings.[15,34,87,88]

APPLICATIONS OF PULSE OXIMETRY IN PEDIATRIC PRACTICE

Pulse oximetry has become widely available in various aspects of pediatric care. It is routinely found in the emergency department and the pediatric ward, and it is regarded as an essential element of patient monitoring in pediatric intensive and perioperative care. Its use in the assessment of respiratory and hemodynamic parameters in advanced pediatric care settings is beyond the intentions of this review.

Normal Values

Normal pediatric SpO_2 values have not yet been established. Pulse-oximetry readings vary with age and altitude.[89,90] The substantial variation of normal SpO_2 values among studies can be attributed to differences in sample size, instruments used, health of participants, probe positioning, and measurement protocols. Thus, in healthy infants and children, mean SpO_2 values at sea level have been reported to be 97% to 99% (−2 SDs, 95%–96%),[91–93] and they might be lower in neonates and young infants (range: 93%–100%).[93] At moderate altitudes SpO_2 values are somewhat lower (mean: 97%–98%; −2 SDs, 93%–96%)[94,95] and decrease further at high altitudes (>3000 m; mean: 86%–91%; −2 SDs, 74%–82%).[89,90,96–98] Authors of a recent systematic review concluded that supplemental oxygen should be administered to children who reside at altitudes of >3000 m if the SpO_2 is <85%.[99]

Most children also exhibit a progressive fluctuation in SpO_2 during a 24-hour cycle. Maximal values occur in the late afternoon, whereas minimal values appear in the first morning hours. This pattern is evident regardless of whether children are asleep or awake.[100] Basal SpO_2 values reported by polysomnography or home monitoring range from 95% to 100%, but normal saturation nadirs can be as low as 84% to 86%.[101–103] However, although SpO_2 values in the range of 90% to 93% are not uncommon during sleep, they might be associated with poorer academic performance.[104]

Disease-Specific Applications

Respiratory Applications

In pediatric practice, pulse oximetry must be readily available in any situation associated with hypoxemia. Oxygen saturation is a particularly sensitive indicator of disease severity in conditions associated with ventilation/perfusion (V/Q) mismatch, such as exacerbations of asthma or chronic lung disease of prematurity, acute bronchiolitis, and pneumonia.[3,4,21,26,105–108] Conversely, SpO_2 is not a reliable indicator of disease severity in proximal (laryngeal or tracheal) airway obstruction such as acute laryngotracheitis, foreign-body aspiration, and vocal chord dysfunction.[34] The principle mechanism of hypoxemia in such cases is hypoventilation, which primarily leads to an increase in $Paco_2$. These patients might not present with particularly low SpO_2 readings,[38–40] because, per the alveolar gas equation,[109] an SpO_2 of <90% requires a $Paco_2$ of ~80 mm Hg. It should be noted that coexistent diffuse peripheral airway obstruction (eg, laryngotracheobronchitis) might cause V/Q mismatch leading to a lower SpO_2 level. In the later scenario, however, hemoglobin desaturation reflects a secondary pathophysiological process rather than the primary mechanism of the disorder.

Current guidelines state that oxygen saturation should be monitored by pulse oximetry during asthma exacerbations to assess severity of the disease and response to treatment.[110,111] Mild asthma exacerbations are associated with SpO_2 values of >95%, moderate exacerbations with values of 90% to 95%, and severe exacerbations with values of <90%.[110,111] Although SpO_2 values of <92% at presentation have been suggested to predict hospitalization or return to the hospital,[112] more recent studies have not confirmed this finding.[113–116] Instead, a 1-hour posttreatment SpO_2 of <92% to 94% has been shown to be a better predictor of the need for hospitalization.[113–115]

To date, there is no consensus on the SpO_2 thresholds that should be used to admit, treat, and discharge infants with acute bronchiolitis.[117–120] The American Academy of Pediatrics guideline recommends administration of supplemental oxygen if SpO_2 values fall to <90%.[117] The Scottish Intercollegiate Guidelines Network (SIGN) recommends admission for all symptomatic infants with SpO_2 values of ≤92%, whereas the decision to admit and/or treat patients with an SpO_2 value of 93% to 94% should be made on an individual basis.[118] Intermittent is preferred over continuous SpO_2 monitoring in hospitalized infants, and patients should be considered for discharge when the SpO_2 is >94% in room air after an observation period of 8 to 12 hours.[118] SpO_2 values of <94% have been shown to increase the likelihood of admission and to predict longer hospital stay[121–123]; however, small differences in SpO_2 (92% vs 94%) might significantly influence the decision to admit or discharge.[124] Therefore, it is evident that, on the basis of SpO_2 values alone, many infants with bronchiolitis will be hospitalized and treated for prolonged periods of time while all other problems have resolved.[125,126]

Pulse oximetry is essential for prompt detection and management of pediatric pneumonia, because infants and children might not appear cyanotic despite significant hypoxemia.[127] The British Thoracic Society guideline for the management of community-acquired pneumonia recommends that symp-

tomatic infants and children with an SPO_2 of ≤92% should be treated with oxygen and admitted to the hospital.[128] However, despite its very good positive predictive value, the method cannot reliably exclude the disease in emergency settings.[127,129] Pulse oximetry is mandatory for monitoring hospitalized patients with pneumonia to guide management and to assess response to treatment. It is recommended that the SPO_2 be maintained at >92% with a fraction of inspired oxygen of <0.6; otherwise, transfer to intensive care should be considered.[128]

Cardiovascular Applications

Pulse oximetry can be used for heart rate monitoring or might serve more specialized applications, such as the assessment of peripheral perfusion and hemodynamic status.[130,131] The plethysmographic waveform has been shown to be useful in the estimation of blood pressure when manometry fails.[131] It can also offer a semiquantitative evaluation of "pulsus paradoxus" by identifying an exaggerated decrease of pulse-wave amplitude during inspiration.[132]

Neonatal Resuscitation

Assessment of skin color is not a reliable indicator of oxygenation status during the immediate postnatal period.[133] Moreover, the optimal management of oxygenation during neonatal resuscitation is critical, because there is strong evidence that both hypoxia and hyperoxia can be harmful.[134] The feasibility and reliability of pulse oximetry during neonatal resuscitation have been proven in several studies.[135–138] Thus, SPO_2 monitoring in the delivery room is currently recommended for neonates with persistent cyanosis, when assisted ventilation and supplementary oxygen administration are required, or when neonatal resuscitation is anticipated (high-risk deliveries).[133] Under acceptable conditions of peripheral perfusion, SPO_2 values can be reliably measured ~2 minutes after birth.[137,139,140] Use of new-generation devices and sensors of appropriate size, as well as probe attachment to a preductal location (ie, right upper extremity), preferably before connecting the probe to the device, might result in more accurate and timely readings.[133,134] However, health care professionals should be aware that, even in uncompromised neonates, an increase in SPO_2 at levels of >90% might take >10 minutes to achieve.[135–140] Therefore, pulse oximetry should be used in conjunction with, but not as a substitute for, clinical assessment during the transitional period after birth.[133,134]

Neonatal Screening for Congenital Heart Disease

Pulse oximetry has been proposed as a reasonable screening tool for the early detection of asymptomatic newborns with critical congenital heart disease (CCHD).[141,142] Single lower-extremity SPO_2 values obtained after 24 postnatal hours seem to be convenient for large-scale screening.[142] An SPO_2 threshold of ≤95% at low altitudes seems to be appropriate.[142] Although the method has been shown to have excellent specificity and negative predictive value, its sensitivity and false-positive rate might vary substantially.[142–144] The cost/benefit balance of routine universal screening has not been well quantified; however, important cost savings could emerge because of early diagnosis and treatment of infants with CCHD.[141] Future studies, designed to assess the impact of routine neonatal screening by pulse oximetry on morbidity, mortality, and hospital costs related to CCHD, are expected to clarify this issue.[144]

Prevention of Hyperoxia

Although for ventilator-dependent patients pulse oximetry can assist in the titration of inspired oxygen concentration, it cannot reliably prevent hyperoxic events.[13,19,30,34] SPO_2 values of >92% do not accurately correlate with PaO_2, as is clearly depicted by the shape of the ODC (Fig 3). At such high SPO_2 values, small variations of SPO_2 might relate to disproportionally wider variations of PaO_2.[145] Therefore, caution is required when interpreting pulse-oximetry readings in situations in which hyperoxia is to be avoided, especially in case of preterm and low birth weight neonates for whom excessive oxygen administration can be particularly harmful.[146–151] Although a single best range has not been established yet, there is convincing evidence that SPO_2 values between 85% and 93% are sufficient to maintain normoxemia[152] and to decrease the incidence of retinopathy of prematurity in infants receiving supplemental oxygen.[148–151] In extremely preterm neonates, however, lower SPO_2 targets (ie, 85%–89%) have been associated with an increased risk of mortality compared with higher SPO_2 levels (ie, 91%–95%).[153] Further ongoing trials on this issue are expected to resolve the uncertainties surrounding optimum SPO_2 range in premature neonates receiving supplemental oxygen.[154]

NOVEL TECHNOLOGIES AND FUTURE DIRECTIONS

Pulse oximetry has been proven to be an extremely useful tool in patient assessment and monitoring in pediatric practice. However, its widespread use over the last 3 decades has also revealed its inherent limitations.

The theoretical model of conventional pulse oximetry assumes that the arterial blood is the only light-absorbing pulsatile component. However, this assumption has been challenged by SPO_2 readings during motion that fall to <85% (which corresponds to a ratio of absorption ratios equal to 1); this

should not be the case if these desaturations were merely the result of uncharacterized noise. New theoretical models assume that nonarterial absorbers also generate a pulsatile signal when motion occurs and that the ratio of absorption ratios should be considered a composite of arterial and nonarterial pulsatile components. These novel conceptual models are also applicable to situations of low signal-to-noise ratio such as low-perfusion states. Thus, new-generation devices use improved algorithms of signal extraction, which ultimately result in more accurate SpO_2 readings, especially under critical conditions.[155,156] In addition, new theories of multiwavelength pulse oximetry are expected to further improve the performance and applicability of these devices.[157] Reflectance pulse oximeters that are based on absorption analysis of reflected rather than transmitted light have been also introduced into clinical practice.[158] In light of these ongoing technologic advancements, clinical trials on how to incorporate pulse oximetry into evidence-based diagnostic and management algorithms in daily pediatric practice are urgently required.

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HOW MUCH IS ENOUGH?: *Many of my friends exercise all the time, whereas others hardly ever do. When I ask those not exercising why they don't, most say they don't have enough time, that it is too hard to start, or that exercising just a few minutes a day is unlikely to be beneficial. Exercise physiologists and others have long wondered just how much aerobic exercise each day or each week is necessary to produce a health benefit in adults. As reported in* USA Today *(Fitness & Food: August 2, 2011), it turns out that it doesn't take much at all. Federal guidelines suggest that adults should engage in 150 minutes of moderate-intensity activity each week; this is still a reasonable goal. However, new data suggest that almost any amount of exercise may be beneficial. Adults engaging in as little as 10 to 15 minutes/day of moderate-intensity exercise accrue some benefit in the prevention of heart disease. In studies evaluating the risk of heart disease in sedentary and exercising adults, the most dramatic health benefits were seen in those who went from not exercising at all to exercising a little bit. The data also show that there is an indirect relationship between the amount of exercise and the risk of heart disease. Compared to sedentary people, those who engaged in 150 minutes of moderate-intensity exercise each week had a 14% reduced risk of heart disease. Those who exercised 300 minutes/week had a 20% risk reduction, and a 25% risk reduction if they exercised 750 minutes/week. Women, for unknown reasons, derive a greater benefit from exercise than men. Bursts of activity followed by long periods of inactivity, however, were not beneficial. This suggests that for better health, one needs to keep moving. Although researchers have not been able to quantify the exact health benefit to 75 minutes of weekly moderate-intensity exercise, the American College of Sports Medicine recently revised its guidelines. Although the guidelines still recommend that adults engage in at least 150 minutes of moderate-intensity exercise each week to achieve weight reduction and help maximize the health benefits of exercise, just a little exercise, such as 75 minutes/week, is likely to be beneficial. The data are fairly clear. To borrow a marketing phrase from Nike: just do it.*

Noted by WVR, MD

Pulse Oximetry in Pediatric Practice

Sotirios Fouzas, Kostas N. Priftis and Michael B. Anthracopoulos

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