Official Journal of the Asian Pacific Society of Respirology
Respirology

CLINICAL PRACTICE GUIDELINES

Clinical use of pulse oximetry: Official guidelines from the Thoracic Society of Australia and New Zealand

JEFFREY J. PRETTO,[1,2] TEANAU ROEBUCK,[3] LUTZ BECKERT[4,5] AND GARUN HAMILTON[6,7]

[1]*Department of Respiratory & Sleep Medicine, John Hunter Hospital,* [2]*School of Medicine & Public Health, University of Newcastle, Newcastle, New South Wales,* [3]*Alfred Sleep Disorders & Ventilatory Failure Service, The Alfred, Prahran,* [6]*Monash Lung and Sleep, Monash Medical Centre,* [7]*Monash Institute of Medical Research, Monash University, Clayton, Victoria, Australia,* [4]*Department of Respiratory Medicine, Canterbury District Health Board, and* [5]*Department of Medicine, University of Otago, Christchurch, New Zealand*

ABSTRACT

Pulse oximetry provides a simple, non-invasive approximation of arterial oxygenation in a wide variety of clinical settings including emergency and critical-care medicine, hospital-based and ambulatory care, perioperative monitoring, inpatient and outpatient settings, and for specific diagnostic applications. Pulse oximetry is of utility in perinatal, paediatric, adult and geriatric populations but may require use of age-specific sensors in these groups. It plays a role in the monitoring and treatment of respiratory dysfunction by detecting hypoxaemia and is effective in guiding oxygen therapy in both adult and paediatric populations. Pulse oximetry does not provide information about the adequacy of ventilation or about precise arterial oxygenation, particularly when arterial oxygen levels are very high or very low. Arterial blood gas analysis is the gold standard in these settings. Pulse oximetry may be inaccurate as a marker of oxygenation in the presence of dyshaemoglobinaemias such as carbon monoxide poisoning or methaemoglobinaemia where arterial oxygen saturation values will be overestimated. Technical considerations such as sensor position, signal averaging time and data sampling rates may influence clinical interpretation of pulse oximetry readings.

Key words: clinical medicine, guideline, hypoxemia, oxygen, pulse oximetry.

Abbreviations: ODI, oxygen desaturation index; OSA, obstructive sleep apnoea; SpO_2, pulse oximeter oxygen saturation.

Correspondence: Jeff Pretto, Department of Respiratory & Sleep Medicine, John Hunter Hospital, Hunter Region Mail Centre, Locked Bag 1, Newcastle, NSW 2310, Australia. Email: jeff.pretto@hnehealth.nsw.gov.au

Received 4 September 2013; accepted 18 September 2013 (Associate Editor: Chi Chiu Leung).

INTRODUCTION

Pulse oximetry has become a common practice in a variety of clinical situations and is now often part of standard patient observations. A good understanding of the principles of pulse oximetry and its clinical utility is important in enabling safe and effective use of it as a vital sign.[1,2] The aims of these guidelines are to document the clinical applications, principles of use, interpretation and limitations of pulse oximetry, to assist with incorporating pulse oximeter oxygen saturation (SpO_2) readings into the assessment of respiratory status and to inform clinicians which factors are important to consider when choosing and using an oximeter. Oximetry measurements should always be considered in the clinical context, and appropriate clinical judgement rather than complete reliance on oximetry readings should provide the basis of effective patient management. These guidelines aim to inform clinical staff of important considerations involved in pulse oximetry to enable optimum use and are to be used as an adjunct to other professional guidelines.[3,4] Although modern oximeters are capable of measuring more than SpO_2, these guidelines will focus solely on the measurement of haemoglobin oxygen saturation.

Assessing the availability of oxygen for delivery to the peripheral tissues is critical in the assessment and management of all patients at risk of respiratory dysfunction. Adequate oxygen content in arterial blood, satisfactory tissue perfusion, and effective tissue oxygen extraction and utilization are all essential components to ensuring normal organ function. Measurement of the oxygen content in arterial blood via blood gas analysis provides critical information about ventilation, pulmonary gas exchange and acid/base status; however, it is invasive, can only provide intermittent assessment and is not available in all settings. The majority of oxygen carried in arterial blood is reversibly bound to haemoglobin molecules. As such, the percentage of haemoglobin molecules in arterial blood that are bound with oxygen, referred to as the SaO_2, is a clinically relevant marker of oxygen

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology

doi: 10.1111/resp.12204

Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

Table 1 List of clinical applications for pulse oximetry and issues to consider relevant to each application

Use	Setting	Features/issues to consider
Spot SpO_2 Check	ED, primary care, outpatient observation (e.g. rehabilitation, oxygen clinic, pre-flight assessment and others)	• Set long averaging times to minimize motion artefact • Pulsatile waveform display useful for checking signal quality • Select most appropriate sensor/site (e.g. finger/earprobe)
Detection of nocturnal breathing disorders in the laboratory	Sleep laboratory	• Use oximeter in 'sleep' mode or with alarms disabled • Set averaging time to 3 s or less • Set data sampling and storage rate to a minimum of 10 Hz • Ability to output data in real time to capture on polysomnograph system
Detection of nocturnal breathing disorders in the home setting	Overnight domiciliary monitoring	• Use oximeter in 'sleep' mode or with alarms disabled • Set averaging time to 3 s or less • Set data sampling and storage rate to a minimum of 1 Hz • Adequate data storage capacity (minimum of 8 h) • Download/analysis software required for report generation
Critical monitoring (adult)	Intensive/high dependency care	• Consider ABG sampling to assess $PaCO_2$, pH and Hb status • Select oximeter with good motion artefact rejection • Consider using central sensor site • Set alarm levels appropriate for individual patient
Critical monitoring (paediatric)	Neonatal intensive/high-dependency care	• Select oximeter with good motion artefact rejection • Consider using central sensor site • Set alarm levels appropriate for individual patient
Screening or titration for supplemental oxygen	Outpatient clinic, domiciliary care, primary care	• Set long averaging times to minimize motion artefact
Detection of exercise desaturation	Exercise laboratory, pulmonary rehabilitation	• Consider using central sensor site • Select oximeter with good motion artefact rejection • Set averaging time at medium to long (balance between motion artefact sensitivity and rapid desaturation detection)
Non-critical monitoring	Hospital ward	• Set long averaging times to minimize motion artefact • Set alarm levels appropriate for individual patient
Perioperative monitoring of oxygenation	Operating theatre, recovery room	• Set alarm levels appropriate for individual patient

ABG, arterial blood gas; ED, emergency department; Hb, haemoglobin; $PaCO_2$, arterial carbon dioxide partial pressure; SpO_2, pulse oximeter oxygen saturation.

delivery to the tissues. Pulse oximetry provides a means for safe, simple, continuous and non-invasive estimation of SaO_2, referred to as SpO_2.

NORMAL VALUES FOR SpO_2

Normal values for SpO_2 are not clearly established due to variations in measurement technique, sensor site, device type, subject age, altitude and definitions of normality. However, the mean SaO_2 from co-oximeter measurement of arterial blood in normal adults breathing air at sea level ranges from 97.1% at 18 years of age to 95.4% at 70 years, with lower limits of normal being 96–94%, respectively.[5]

Paediatric normal values for SpO_2 have also not been clearly defined; however, normal sea level values of 97–99% have been reported for healthy infants and children, with slightly lower values (down to 93%) in neonates and young infants.[6]

The reduction in atmospheric pressure with altitude results in reduced inspired oxygen tension, with corresponding decreases in arterial oxygenation. In healthy adults, arterial oxygen partial pressure (PaO_2) is approximately 20 mm Hg lower at an altitude of 1400 m than at sea level, with a corresponding decrement of around 1.5% in SaO_2.[5] It is noteworthy that inspired oxygen pressures at cruising altitude in commercial jet aircraft are approximately three-quarters of that experienced at sea level. As a consequence, oxygen saturation is reduced during flight and healthy subjects can be expected to exhibit resting SpO_2 of around 92%.[7]

CLINICAL APPLICATIONS OF PULSE OXIMETRY

The availability of pulse oximetry has revolutionized monitoring of respiratory function, particularly given that multiple or continuous measurements can be obtained rapidly and non-invasively. Table 1 summarizes the use of pulse oximetry in different clinical situations. It is important to realize that hypoxaemia is not a surrogate for other respiratory signs. Hypoxaemia correlates poorly with respiratory and heart rates,[8] and tachypnoea may be a better predictor of respiratory compromise in some patients.[9] Nevertheless, hypoxaemia provides information about the adequacy of gas exchange or ventilation and is an

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology

Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

independent predictor of mortality in acute illness.[10,11] Pulse oximetry therefore provides additional and independent information to a comprehensive respiratory assessment.

In general, pulse oximetry plays a role in the monitoring and treatment of respiratory disease by detecting hypoxaemia, guiding the titration of supplemental oxygen and other therapies (such as weaning from supported ventilation) and reducing the need for blood gas analysis. Monitoring oxygen saturation during exercise is a standard component of pulmonary rehabilitation. Despite the widespread routine use of pulse oximetry, there is a limited systematically derived evidence supporting its clinical utility. The evidence for using pulse oximetry in specific clinical settings is summarized below; however, for a comprehensive review of the clinical use of supplemental oxygen therapy, please refer to accompanying Thoracic Society of Australia and New Zealand position statements.[3,4]

Adult applications

Pre-hospital settings

SpO_2 has been shown to accurately correlate with SaO_2 measured using arterial blood gases in pre-hospital care.[12] The transport of unstable patients to hospital makes pulse oximeters prone to data loss due to movement artefact and hypovolaemia, but this does not affect their clinical utility. A recent study reported that although SpO_2 reading failure during ambulance transfer was found to be worse in hypovolaemic patients, the overall failure rate using two modern oximeters was low even in the presence of peripheral vasoconstriction.[13] Using pulse oximetry to guide oxygen therapy is an important component of pre-hospital care which has been shown to improve clinical outcomes. A recent Australian study has demonstrated that using pulse oximetry to titrate low-dose oxygen therapy (targeting SpO_2 between 88 and 92%) has been shown to reduce mortality in chronic obstructive pulmonary disease.[14]

Critical care units/emergency department/perioperative care

Pulse oximetry is part of routine care in critical care settings; however, it does not provide precise assessment of true arterial saturation in the critically ill with a mean difference between SpO_2 and SaO_2 (bias) of 1.3% and limits of agreement ranging from −2 to +5%.[15] Despite this, it is useful in providing broad assessment of oxygenation and has been shown to be adequate in guiding clinical decision making, such as the diagnosis of acute lung injury/acute respiratory distress syndrome.[16]

In the emergency department, SpO_2 is effective at detecting hypoxaemia, as long as the carboxyhaemoglobin level is less than 2%.[17] Oxygen saturation measured in the emergency department has been shown to be an independent predictor of hospital mortality[11] and is therefore an important component of patient assessment. Although oxygen saturation monitoring is part of routine care in the perioperative period, whether this improves outcomes is unclear. A Cochrane review of five randomized controlled trials assessing perioperative SpO_2 monitoring showed that pulse oximetry improved the detection of hypoxaemia but did not alter the rate of complications such as mortality, intensive care unit admission or length of stay.[18]

General ward

Pulse oximetry commonly constitutes part of routine clinical care on medical and surgical wards; however, whether this results in improved outcomes on the general ward is unknown, primarily due to a lack of high-quality data in this area. One area of potential benefit is assistance in detecting the acutely deteriorating patient. An Australian study of medical emergency team calls found that nursing staff 'worry' was the single most common reason for medical emergency team calls (29% of all calls studied), and almost half of these were related to either respiratory distress or a low SpO_2 in patients whose vital signs otherwise did not meet medical emergency team criteria.[19]

Pulse oximetry is commonly used to guide supplemental oxygen therapy, which can be problematic given the common but incorrect assumption that SpO_2 provides a measure of adequacy of ventilation (which is best assessed using partial arterial carbon dioxide concentration measurement). There are currently no widely accepted guidelines in this country regarding the use of SpO_2 to guide oxygen therapy during inpatient stay with most institutions/health networks implementing locally developed protocols.

Sleep unit/exercise unit/outpatient setting

Pulse oximetry plays a central role in the diagnosis of sleep-related breathing disorders, particularly obstructive sleep apnoea (OSA), contributing a crucial component of overnight polysomnography. OSA commonly exhibits characteristic repetitive oxygen desaturation followed by resaturation throughout the night, and as such, pulse oximetry is increasingly being used as a tool for screening for OSA in the domiciliary setting. Home overnight pulse oximetry recordings can be analysed to calculate the oxygen desaturation index (ODI) which represents the number of desaturation events per hour of recording. The ODI performs reasonably well in detecting moderate to severe OSA;[20] however, it performs less well in ruling out OSA as the accuracy of the ODI is dependent upon various factors such as the cutoff threshold used for diagnosis, the population studied, body mass index (ODI accuracy falls when body mass index is less than 25)[21] and other technical factors (see *Technical Considerations*). In the primary care setting, domiciliary overnight oximetry and ODI have been shown to be of value when used as part of a dedicated clinical pathway for the diagnosis and management of OSA.[22,23]

Documentation of oxygen desaturation during exercise is most simply accomplished using pulse oximetry, which is routinely done in the exercise laboratory during diagnostic testing and in the physical therapy setting during exercise training (particularly as part of pulmonary rehabilitation programmes). Although degree of desaturation during

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology
Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

exercise has been shown to be highly variable in interstitial pulmonary fibrosis,[24] it is still of utility in predicting mortality in this disease.[25] The evidence base for the clinical utility of exercise pulse oximetry in chronic obstructive pulmonary disease and other diseases is not as clearly established.

Because of the inability for PaO_2 to be accurately estimated from SpO_2 (see *Interpretation Issues*), the role of 'spot' pulse oximetry readings for assessing suitability for long-term supplemental oxygen therapy[4] is limited to determination of whether more invasive blood gas sampling is warranted.[26] However, 24-h pulse oximetry monitoring may have a role in assessing long-term oxygen therapy requirements because a single arterial blood gas sample has a relatively poor sensitivity in detecting significant 24-h hypoxaemia in chronic obstructive pulmonary disease.[27]

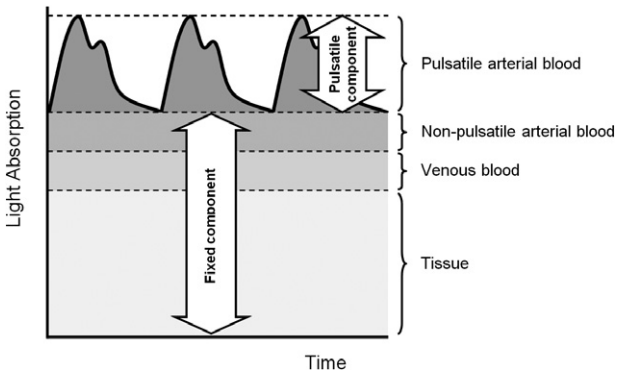

Figure 1 Diagrammatic representation of the components contributing to the absorption profile of the oximeter probe light as it travels through the tissue.

Paediatric applications

In utero

It is possible to measure fetal pulse oximetry during labour using a probe attached to the baby, inserted via the vagina of the mother. Whether this additional monitoring improves outcomes compared with cardiotocography and clinical assessment has been assessed in a number of studies. A Cochrane review analysed four trials and did not show an overall reduction in caesarean section rates or improvement in maternal or fetal outcomes.[28] However, there was a decrease in caesarean section when fetal pulse oximetry was used in the setting of a non-reassuring cardiotocography,[20,28] which supports the use of fetal pulse oximetry in this situation.

Neonates

The early neonatal period for extremely premature babies (particularly <28 weeks gestation) puts them at risk not only from hypoxaemia but also from hyperoxia due to a susceptibility to the adverse effects of oxidative stress. Hypoxaemia increases the risk of neuro-developmental abnormalities and retinopathy of prematurity, but hyperoxia increases the risk of bronchopulmonary dysplasia and also retinopathy of prematurity.[29,30] The optimal target oxygen saturation for preterm infants during the early neonatal period and beyond 36 weeks gestation is controversial,[3,29] and readers are referred to the accompanying Thoracic Society of Australia and New Zealand position statement on oxygen therapy in infants with chronic neonatal lung disease for a detailed discussion of this area.[3] Some data exist comparing different oxygen saturation targets,[31] but interpretation is complicated by the need to consider relative proportions of adult and fetal haemoglobin (which have different oxygen carrying capacities), and the unpredictable correlation between SpO_2 readings and blood oxygen content. Castillo *et al.* have provided some degree of guidance in this area by demonstrating that neonatal SpO_2 levels of 85–93% are associated with PaO_2 levels between 40 and 80 mm Hg for 87% of the time, reflecting what is generally felt to be a safe level of blood oxygen content.[32]

Pulse oximetry has also been suggested to enable improved detection of congenital heart defects in newborn infants when performed prior to maternity ward discharge.[33] Ewer *et al.* found that SpO_2 readings of less than 95% in either the infant's right arm or one foot (or a difference of more than 2% between limbs) triggered referral for echocardiography and increased the detection of significant congenital heart defects compared with antenatal ultrasonography and clinical examination alone.[33]

HOW THE PULSE OXIMETER WORKS

The principle of operation of the pulse oximeter is based on the different light absorption characteristics of haemoglobin at different wavelengths. The absorption spectra of oxygenated haemoglobin and deoxygenated haemoglobin are sufficiently different such that the distinction can be made with photometric techniques. Although this principle had been used to determine haemoglobin saturation *in vitro* for many decades, it was not until optical and microprocessor technology had developed sufficiently that accurate readings *in vivo* could be obtained under a broad range of conditions.

Modern pulse oximeters utilize light-emitting diodes to generate wavelengths of red and near infrared light which are specifically selected to allow the greatest distinction between oxygenated and deoxygenated haemoglobin. The pulse oximeter incorporates these light-emitting diodes into a probe together with a photo diode which detects the light transmitted or reflected through the tissue. Figure 1 illustrates the pattern of light absorbance detected as the oximeter light passes through the living tissue. Most of the absorbance is caused by the tissue and venous blood (which is relatively constant and comprises the fixed component of the absorbance) with a small proportion attributable to the pulsatile component caused by inflow of arterial blood. The pulse oximeter calculates the ratio of the pulsatile component with the non-pulsatile component. This ratio is calculated separately for each of the two wavelengths

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology

Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

(by having the light-emitting diodes alternately turning off and on), and it is the ratio of these two ratios which is empirically related to arterial oxygen saturation. In this way, the oximeter is able to correct for the underlying light absorption of the tissue and venous blood and effectively 'focus' on the arterial blood and thereby display arterial oxygen saturation. This reading is relatively independent of the intensity of the light, the thickness of the tissue and the degree of skin pigmentation.

Most commonly used clinical oximeters are transmittance types where the light emitter and detector face each other, and the linear photo transmission through the tissue is assessed. These are suitable for use on the finger, toe or earlobe in adults, and also on the foot in neonates. Reflectance oximeter probes use an emitter adjacent to the detector and rely on the signal being reflected or backscattered through the tissue. These probes are used on the forehead, and they have been shown to provide a more accurate SpO_2 measurement due to lesser sensitivity to poor peripheral perfusion,[34] reduced cardiac index,[35] cold temperatures and movement artefact.[36] Being located more centrally, they also respond more quickly to rapid changes in saturation than peripheral sensors.[37]

Further technological developments have led to miniaturization, reduced sensitivity to movement artefact, increased memory storage and, more recently, the development of sensors capable of measuring parameters such as total haemoglobin, carboxyhaemoglobin and methaemoglobin. The clinical utility of these later devices has yet to be demonstrated; however, it is likely that further development and evaluation will broaden the clinical applicability in the future.

FACTORS AFFECTING PULSE OXIMETRY MEASUREMENTS

With its simplicity of use and high accessibility in the clinical setting, pulse oximetry is subject to incorrect use and interpretation.[38] The following provides a list of factors known to affect pulse oximetry readings, with some recommendations about dealing with these factors.

Clinical factors

Low perfusion

Because oximetry is dependent upon the pulsatile component of the light absorption from arterial blood entering the tissue, poor perfusion results in a reduction of this component of the signal and thus reduces the signal-to-noise ratio, thereby potentially reducing SpO_2 accuracy. Modern oximeters have signal strength indicators to give the user feedback about the quality of the signal. Where poor perfusion or low-quality signal messages are displayed, saturation readings are unlikely to be accurate, and the oximeter probe should be moved to an alternative site to obtain the best possible signal. Application of vasodilator cream to the earlobe can improve perfusion and improve signal quality, or the use of a reflectance sensor on the forehead has been shown to be less susceptible to perfusion problems[34] and results in fewer malfunctions during emergency transport.[36]

Dyshaemoglobinaemias

Carboxyhaemoglobin (from carbon monoxide inhalation) has similar light absorption characteristics to oxyhaemoglobin and can therefore give an erroneously high reading for SpO_2. In the respiratory assessment of patients where carbon monoxide poisoning is suspected (or possible), SpO_2 values should always be confirmed by arterial blood gas sampling and co-oximetry analysis. Methaemoglobin also exhibits similar absorption characteristics. Methaemoglobinaemia (congenital or acquired through antibiotic use or nitrate contamination of water) has been shown to significantly affect SpO_2 in animal models[39] and also following patent blue dye injection;[40] however, it is an uncommon clinical problem. In general, arterial blood sampling with analysis by co-oximetry should be used to validate concomitant SpO_2 readings to assess pulse oximeter accuracy when dyshaemoglobinaemias are suspected or possible.

Low oxygen saturation

Arterial oxygen saturation is calculated using an internal algorithm programmed into the oximeter relating saturation to the ratio of the signals described above. This algorithm was derived from experimental data obtained by subjecting normal subjects to hypoxic conditions and contemporaneously measuring SpO_2 and SaO_2. As from an ethical and safety perspective it is not feasible to reduce oxygen saturation in volunteers to very low levels, these algorithms are usually applicable only for oxygen saturations down to approximately 70%. The accuracy of pulse oximeter readings is also dependent upon the precision of the wavelengths emitted by the light-emitting diodes. This becomes more important at lower SpO_2 values because of the shape of the oxyhaemoglobin absorbance–wavelength relationship. As a consequence, the accuracy of pulse oximeters below SpO_2 values of less than 70% is effectively indeterminate, although this is unlikely to affect patient management.

Other patient factors: skin colouring, digital clubbing, nail polish

At normal oxygen levels, skin colour does not affect SpO_2 accuracy;[41,42] however, at low oxygen saturations (particularly below 90%), very dark skin may potentially lead to SpO_2 overestimating the true SaO_2 by a small amount (around 2%).[43] Jaundice (hyperbilirubinaemia) is not known to affect SpO_2 readings.[44] Finger oximeter sensors have been shown to produce erroneously low SpO_2 readings in the presence of digital clubbing,[45] with the magnitude of the error larger (up to 8%) at lower SpO_2 values. Other sensor types (earlobe or forehead reflectance) are recommended in the presence of clubbing.

The effects of nail polish and of acrylic nails on pulse oximeter readings have been well studied with somewhat variable results, but most studies report

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology
Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

statistically significant decreases in SpO_2 readings with nail polish, particularly with darker colours (brown, blue or black).[46,47] These changes are not usually clinically important;[48,49] however, either removing the nail polish or turning the finger probe sideways so that the light does not pass through the fingernail may improve accuracy.[46]

Interpretation issues

From an interpretation perspective, it is helpful to be aware of what the SpO_2 value is not measuring. SpO_2 values may appear normal despite substantial abnormalities of alveolar ventilation (indicated by arterial CO_2 tension) or acid-base status (indicated by pH), particularly if the patient is on supplemental oxygen therapy. This has the potential to falsely reassure clinicians, unless these factors are part of the patient assessment. In the setting of anaemia, oxyhaemoglobin saturation (and therefore SpO_2) may be normal, but oxygen content may be reduced, potentially resulting in reduced tissue oxygen delivery. Similarly, a low cardiac output can impair tissue oxygen delivery despite normal oxygen saturation. Assessment in this case is complicated by the fact that low cardiac output states may impair peripheral tissue perfusion enough to lead to low SpO_2 readings due to low signal quality. Furthermore, SpO_2 simply indicates the proportion of haemoglobin that is saturated—it does not provide information about what molecule is causing this saturation (oxygen or carbon monoxide). The key in overcoming these interpretation problems is to be aware that SpO_2 does not necessarily reflect tissue oxygen delivery and provides no information as to the underlying pathophysiological process. Clinical decision making based on pulse oximetry readings must always take these factors into consideration.

Over the 70–100% SpO_2 range, manufacturers' stated accuracy of pulse oximeters is typically within plus and minus two to three units compared with the gold standard SaO_2 measured by co-oximetry of arterial blood. The nature of the oxygen–haemoglobin dissociation curve shows that this corresponds with a large variation in PaO_2. Furthermore, an assessment of over 800 pulse oximeters in clinical use found that more than one-fifth exhibited incorrect light-emitting diode emission spectra such that SpO_2 inaccuracy of over 4% would result.[50] These factors, coupled with the nature of the oxygen–haemoglobin dissociation curve and its positional dependence upon factors such as pH, partial arterial carbon dioxide concentration and temperature, clearly illustrate why spot SpO_2 readings, despite their clinical utility, cannot be used to accurately estimate PaO_2.

The understanding of the principles behind oximetry and the significance of SpO_2 readings clearly has an impact on interpretation of measurements, which in turn may also affect the provision of quality healthcare. The magnitude of this problem was highlighted in a meta-analysis of 14 questionnaire-based studies and revealed generally poor understanding of pulse oximetry by medical and nursing clinicians.[38] This indicates a clear need for improved training in pulse oximetry, which is also generally acknowledged by the clinicians themselves.[38]

Technical considerations

It is worth noting that the technology involved in pulse oximetry is constantly evolving with ongoing developments in both sensor technology and software analysis. The following summary is derived from published clinical analyses of oximetry technology and therefore is likely to lag the current state of the art in this area.

Oximeter calibration

Although calibration and validation of other respiratory devices are part of standard practice, this is not the case for pulse oximeters. The finding that over 30% of oximeters used in clinical practice were found not to be working to manufacturers' accuracy specifications[50] suggests that systematic assessment of oximeter accuracy is required. We recommend that oximeters in clinical use, particularly those with reusable sensors, should be assessed at least every 2 years for measurement accuracy using dedicated, validated technology. Given the paucity of data available, we would encourage further research into long-term accuracy of pulse oximeters and in the assessment of oximeter ability to respond to dynamic changes in SpO_2.

Movement artefact

Artefact in the saturation signal due to patient and/or sensor movement can contribute to two separate issues in clinical oximetry measurement: inaccuracy in SpO_2, and false alarms and data dropouts. Motion-induced SpO_2 inaccuracy is thought to result from the movement of venous blood and other normally non-pulsatile fluids (such as tissue fluid in oedematous patients) being misinterpreted as being attributable to an arterial pulse.[51] This can be particularly problematic during patient transport or during clinical exercise testing.

False alarms from pulse oximeters used in the acute care are common with as little as 7% of alarms found to be clinically significant in the paediatric setting.[52] Motion artefact during SpO_2 monitoring has been found to be particularly frequent (contributing up to 91% of monitoring time in infants[53]), and a large proportion of false alarms are attributable to this artefact.[51] These false alarms adversely affect the provision of healthcare by requiring repeated and needless checks of the patient and/or monitor, resulting in mistrust of alarms and even their turning off.[51]

Use of less moveable monitoring sites (such as earlobe or forehead) can reduce the impact of movement artefact; however, the use of oximeters with 'motion tolerant' capabilities are recommended, particularly in settings of potential high movement. These devices incorporate specific algorithms designed to reduce oximeter sensitivity to motion artefact and have generally been found to provide improved SpO_2 accuracy during movement and to also reduce the rate of false alarms.[51,54]

Sensitivity to ambient light

Indoor light sources emit wavelengths in the range utilized by pulse oximeters and have been described

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology

Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

as contributing a further source of error in SpO_2 measurements.[55] However, in a well-controlled study investigating the influences of five different light sources, no statistical changes in SpO_2 were detected indicating little likely clinical relevance.[56]

Oximeter response time and sensor position

In adults, ear probes have been shown to respond more rapidly to transient changes in SpO_2 than peripheral (finger/toe) sensors.[57,58] It is recommended that consideration and documentation of sensor site should be made in settings where transient changes in saturation may be expected (such as in sleep and exercise laboratories or in hyperbaric/hypobaric settings).

Signal averaging time

The oxygen saturation value shown on the oximeter display represents the average of repeated SpO_2 readings over a specific window of time. In clinical pulse oximeters, this averaging time is often user adjustable over a range (typically from 2 to 16 s) to suit the clinical application. Although longer averaging times aid in 'smoothing out' motion-generated or other artefact, this also has the effect of reducing the sensitivity and capability of the oximeter in detecting more transient changes in oxygenation, such as those commonly seen during the apnoea/hyperpnoea events of OSA. This smoothing of more transient events using higher averaging times can have a marked effect on the dip rates, ODI and apnoea/hypopnoea index commonly used in evaluation of sleep disordered breathing.[59] As such, polysomnography guidelines specify that oximeter averaging times should be set at a maximum of 3 s for this application.[60,61]

Data storage and display

Pulse oximeters designed for extended monitoring provide a storage facility for later recall and/or download of SpO_2 data. The two primary concerns about oximeter storage include the number of SpO_2 readings stored per time unit (sampling rate) and the total amount of memory available. These two factors are interrelated to define the maximum period of time for which data can be recorded—higher sampling rates dictate shorter recording time for a given internal memory and vice versa. Similarly to signal averaging time (see above), sampling rate can have a marked influence on the oximeter's ability to replay SpO_2 variations over time and on calculated SpO_2 dip rates. Although a minimum sample rate of 10 per second is recommended to allow faithful reproduction of SpO_2 dynamics during polysomnography,[61] sampling rates down to one per second may be sufficient to allow relatively reliable documentation of SpO_2 patterns over extended periods. In addition, oximeters may play back summarized data, such as minimum SpO_2 values per 30-s epoch, instead of actual data. These factors can alter the patterns of replayed SpO_2 data, and consideration must be given in deciding whether the playback mode is suitable for the clinical application.

The oximeter memory capacity is of importance when recording over extended time periods, such as with domiciliary overnight oximetry. Recording capability for a minimum of 8 h is recommended for this application. Most modern recording oximeters provide longer duration recordings (up to 48 h). It is recommended that oximeter memory is erased after download to prevent incorrect linking with the subsequent patient. Ensuring that correct oximeter time/date setting is entered enables accurate time stamping of data.

Alarm settings

Oximeters designed for monitoring purposes incorporate high and low SpO_2 alarms which can usually be custom-set to suit the particular patient/application. When used for detection of sleep-related breathing disorders, it is recommended that alarms are turned off or disabled to avoid interfering with sleep. However, such oximeters should have alarms reinstated should they be used for usual clinical purposes. False alarms (see Movement Artefact) can be minimized with appropriate alarm settings; however, setting individualized SpO_2 limits was not found to improve clinical outcomes in the neonatal intensive care setting.[62]

OTHER CONSIDERATIONS

Infection control

No special safety measures are required; however, a universal precautions approach is recommended. Only oximeter probes designed for multiple patient use should be used as such, and cleaning and/or disinfection between patient applications should be carried out in accordance with manufacturer recommendations. This should also include the sensor lead and other parts coming in contact with potentially transmissible organisms. Given that failure to perform appropriate hand hygiene is considered the leading cause of healthcare-associated infection,[63] staff handwashing between patient contacts is strongly recommended.

Patient purchase of pulse oximeters

Small fingertip pulse oximeters designed and priced for non-clinical applications and aimed at the consumer (patient) market are now widely accessible via the internet. The utility of these devices in the management of respiratory and/or chronic disease patients is yet to be evaluated, and coupled with the general lack of device specifications, regulatory approval or clinical evaluation, their use in an unsupervised environment cannot be recommended at this time.

Acknowledgements

The authors are grateful for the assistance of the Australasian College for Emergency Medicine, the Australian and New Zealand College of Anaesthetists, and the Clinical Care and

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology
Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

Resources subcommittee of the Thoracic Society of Australia and New Zealand in the development of this document.

REFERENCES

1 Mower WR, Myers G, Nicklin EL *et al*. Pulse oximetry as a fifth vital sign in emergency geriatric assessment. *Acad. Emerg. Med.* 1998; **5**: 858–65.
2 Mower WR, Sachs C, Nicklin EL *et al*. Pulse oximetry as a fifth pediatric vital sign. *Pediatrics* 1997; **99**: 681–6.
3 Fitzgerald DA, Massie RJH, Nixon G *et al*. Infants with chronic neonatal lung disease: recommendations for the use of home oxygen therapy. *A Position Statement from the Thoracic Society of Australia and New Zealand*. 2007.
4 McDonald CF, Crockett AJ, Young IH. Adult domiciliary oxygen therapy. Position statement of the Thoracic Society of Australia and New Zealand. *Med. J. Aust.* 2005; **182**: 621–6.
5 Crapo RO, Jensen RL, Hegewald M *et al*. Arterial blood gas reference values for sea level and an altitude of 1,400 meters. *Am. J. Respir. Crit. Care Med.* 1999; **160**: 1525–31.
6 Fouzas S, Priftis KN, Anthracopoulos MB. Pulse oximetry in pediatric practice. *Pediatrics* 2011; **128**: 740–52.
7 Kelly PT, Swanney MP, Frampton C *et al*. Normobaric hypoxia inhalation test vs. response to airline flight in healthy passengers. *Aviat. Space Environ. Med.* 2006; **77**: 1143–7.
8 Thrush DN, Downs JB, Hodges M *et al*. Does significant arterial hypoxemia alter vital signs? *J. Clin. Anesth.* 1997; **9**: 355–7.
9 Subbe CP, Slater A, Menon D *et al*. Validation of physiological scoring systems in the accident and emergency department. *Emerg. Med. J.* 2006; **23**: 841–5.
10 Goodacre S, Wilson R, Shephard N *et al*. Derivation and validation of a risk adjustment model for predicting seven day mortality in emergency medical admissions: mixed prospective and retrospective cohort study. *BMJ* 2012; **344**: e2904.
11 Goodacre S, Turner J, Nicholl J. Prediction of mortality among emergency medical admissions. *Emerg. Med. J.* 2006; **23**: 372–5.
12 Aughey K, Hess D, Eitel D *et al*. An evaluation of pulse oximetry in prehospital care. *Ann. Emerg. Med.* 1991; **20**: 887–91.
13 Weber U, Tomschik E, Resch I *et al*. Comparison of two new generation pulse oximeters during emergency ambulance transportation. *Eur. J. Anaesthesiol.* 2011; **28**: 92–6.
14 Austin MA, Wills KE, Blizzard L *et al*. Effect of high flow oxygen on mortality in chronic obstructive pulmonary disease patients in prehospital setting: randomised controlled trial. *BMJ* 2010; **341**: c5462.
15 Perkins GD, McAuley DF, Giles S *et al*. Do changes in pulse oximeter oxygen saturation predict equivalent changes in arterial oxygen saturation? *Crit. Care* 2003; **7**: R67.
16 Rice TW, Wheeler AP, Bernard GR *et al*. Comparison of the SpO2/FIO2 ratio and the PaO2/FIO2 ratio in patients with acute lung injury or ARDS. *Chest* 2007; **132**: 410–7.
17 Lee WW, Mayberry K, Crapo R *et al*. The accuracy of pulse oximetry in the emergency department. *Am. J. Emerg. Med.* 2000; **18**: 427–31.
18 Pedersen T, Hovhannisyan K, Moller A. Pulse oximetry for perioperative monitoring. *Cochrane Database Syst. Rev.* 2010; (4): CD002013.
19 Santiano N, Young L, Hillman K *et al*. Analysis of medical emergency team calls comparing subjective to 'objective' call criteria. *Resuscitation* 2009; **80**: 44–9.
20 Flemons WW, Littner MR, Rowley JA *et al*. Home diagnosis of sleep apnea: a systematic review of the literature. *Chest* 2003; **124**: 1543–79.
21 Ling IT, James AL, Hillman DR. Interrelationships between body mass, oxygen desaturation, and apnea-hypopnea indices in a sleep clinic population. *Sleep* 2012; **35**: 89–96.
22 Antic NA, Buchan C, Esterman A *et al*. A randomized controlled trial of nurse-led care for symptomatic moderate-severe obstructive sleep apnea. *Am. J. Respir. Crit. Care Med.* 2009; **179**: 501–8.
23 Chai-Coetzer CL, Antic NA, Rowland LS *et al*. A simplified model of screening questionnaire and home monitoring for obstructive sleep apnoea in primary care. *Thorax* 2011; **66**: 213–9.
24 Eaton T, Young P, Milne D *et al*. Six-minute walk, maximal exercise tests: reproducibility in fibrotic interstitial pneumonia. *Am. J. Respir. Crit. Care Med.* 2005; **171**: 1150–7.
25 Flaherty KR, Andrei AC, Murray S *et al*. Idiopathic pulmonary fibrosis: prognostic value of changes in physiology and six-minute-walk test. *Am. J. Respir. Crit. Care Med.* 2006; **174**: 803–9.
26 Roberts CM, Franklin J, O'Neill A *et al*. Screening patients in general practice with COPD for long-term domiciliary oxygen requirement using pulse oximetry. *Respir. Med.* 1998; **92**: 1265–8.
27 Trauer JM, Gielen C, Trauer T *et al*. Inability of single resting arterial blood gas to predict significant hypoxaemia in chronic obstructive pulmonary disease. *Int. Med. J.* 2012; **42**: 387–94.
28 East CE, Begg L, Colditz PB. Fetal pulse oximetry for fetal assessment in labour. *Cochrane Database Syst. Rev.* 2007; (2): CD004075.
29 Finer N, Leone T. Oxygen saturation monitoring for the preterm infant: the evidence basis for current practice. *Pediatr. Res.* 2009; **65**: 375–80.
30 Deuber C, Terhaar M. Hyperoxia in very preterm infants: a systematic review of the literature. *J. Perinat. Neonatal Nurs.* 2011; **25**: 268–74.
31 Askie LM, Henderson-Smart DJ, Irwig L *et al*. Oxygen-saturation targets and outcomes in extremely preterm infants. *N. Engl. J. Med.* 2003; **349**: 959–67.
32 Castillo A, Sola A, Baquero H *et al*. Pulse oxygen saturation levels and arterial oxygen tension values in newborns receiving oxygen therapy in the neonatal intensive care unit: is 85% to 93% an acceptable range? *Pediatrics* 2008; **121**: 882–9.
33 Ewer AK, Middleton LJ, Furmston AT *et al*. Pulse oximetry screening for congenital heart defects in newborn infants (PulseOx): a test accuracy study. *Lancet* 2011; **378**: 785–94.
34 Schallom L, Sona C, McSweeney M *et al*. Comparison of forehead and digit oximetry in surgical/trauma patients at risk for decreased peripheral perfusion. *Heart Lung* 2007; **36**: 188–94.
35 Fernandez M, Burns K, Calhoun B *et al*. Evaluation of a new pulse oximeter sensor. *Am. J. Crit. Care* 2007; **16**: 146–52.
36 Nuhr M, Hoerauf K, Joldzo A *et al*. Forehead SpO2 monitoring compared to finger SpO2 recording in emergency transport. *Anaesthesia* 2004; **59**: 390–3.
37 Choi SJ, Ahn HJ, Yang MK *et al*. Comparison of desaturation and resaturation response times between transmission and reflectance pulse oximeters. *Acta Anaesthesiol. Scand.* 2010; **54**: 212–7.
38 Elliott M, Tate R, Page K. Do clinicians know how to use pulse oximetry? A literature review and clinical implications. *Aust. Crit. Care* 2006; **19**: 139–44.
39 Barker SJ, Tremper KK, Hyatt J. Effects of methemoglobinemia on pulse oximetry and mixed venous oximetry. *Anesthesiology* 1989; **70**: 112–7.
40 Lai HC, Hsu HM, Cherng CH *et al*. Interference of patent blue dye with pulse oximetry readings, methemoglobin measurements, and blue urine in sentinel lymph node mapping: a case report and review of the literature. *Acta Anaesth. Taiwan.* 2011; **49**: 162–4.
41 Bothma PA, Joynt GM, Lipman J *et al*. Accuracy of pulse oximetry in pigmented patients. *S. Afr. Med. J.* 1996; **86**: 594–6.
42 Adler JN, Hughes LA, Vivilecchia R *et al*. Effect of skin pigmentation on pulse oximetry accuracy in the emergency department. *Acad. Emerg. Med.* 1998; **5**: 965–70.
43 Feiner JR, Severinghaus JW, Bickler PE. Dark skin decreases the accuracy of pulse oximeters at low oxygen saturation: the effects of oximeter probe type and gender. *Anesth. Analg.* 2007; **105**: S18–23, tables of contents.
44 Veyckemans F, Baele P, Guillaume JE *et al*. Hyperbilirubinemia does not interfere with hemoglobin saturation measured by pulse oximetry. *Anesthesiology* 1989; **70**: 118–22.
45 Van Ginderdeuren F, Van Cauwelaert K, Malfroot A. Influence of digital clubbing on oxygen saturation measurements by pulse-oximetry in cystic fibrosis patients. *J. Cyst. Fibros.* 2006; **5**: 125–8.

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology

Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584

46 Chan MM, Chan ED. What is the effect of fingernail polish on pulse oximetry? *Chest* 2003; **123**: 2163–4.
47 Sutcu Cicek H, Gumus S, Deniz O *et al*. Effect of nail polish and henna on oxygen saturation determined by pulse oximetry in healthy young adult females. *Emerg. Med. J.* 2011; **28**: 783–5.
48 Hinkelbein J, Genzwuerker HV. Fingernail polish does not influence pulse oximetry to a clinically relevant dimension. *Intensive Crit. Care Nurs.* 2008; **24**: 4–5.
49 Rodden AM, Spicer L, Diaz VA *et al*. Does fingernail polish affect pulse oximeter readings? *Intensive Crit. Care Nurs.* 2007; **23**: 51–5.
50 Milner QJ, Mathews GR. An assessment of the accuracy of pulse oximeters. *Anaesthesia* 2012; **67**: 396–401.
51 Petterson MT, Begnoche VL, Graybeal JM. The effect of motion on pulse oximetry and its clinical significance. *Anesth. Analg.* 2007; **105**: S78–84.
52 Lawless ST. Crying wolf: false alarms in a pediatric intensive care unit. *Crit. Care Med.* 1994; **22**: 981–5.
53 Fletcher J, Page M, Jeffery HE. Sleep states and neonatal pulse oximetry. *Sleep* 1998; **21**: 305–10.
54 Brouillette RT, Lavergne J, Leimanis A *et al*. Differences in pulse oximetry technology can affect detection of sleep-disorderd breathing in children. *Anesth. Analg.* 2002; **94**: S47–53.
55 Amar D, Neidzwski J, Wald A *et al*. Fluorescent light interferes with pulse oximetry. *J. Clin. Monit.* 1989; **5**: 135–6.
56 Fluck RR, Jr, Schroeder C, Frani G *et al*. Does ambient light affect the accuracy of pulse oximetry? *Respir. Care* 2003; **48**: 677–80.
57 Hamber EA, Bailey PL, James SW *et al*. Delays in the detection of hypoxemia due to site of pulse oximetry probe placement. *J. Clin. Anesth.* 1999; **11**: 113–8.
58 Young D, Jewkes C, Spittal M *et al*. Response-time of pulse oximeters assessed using acute decompression. *Anesth. Analg.* 1992; **74**: 189–95.
59 Farre R, Montserrat JM, Ballester E *et al*. Importance of the pulse oximeter averaging time when measuring oxygen desaturation in sleep apnea. *Sleep* 1998; **21**: 386–90.
60 Iber C, Ancoli-Israel S, Chesson A *et al*. *The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications*. American Academy of Sleep Medicine, Westchester, IL, 2007.
61 Thornton A, Ruehland W, Duce B *et al*. ASTA/ASA commentary on AASM manual for the scoring of sleep and associated events. Australasian Sleep Technologists Association, Australasian Sleep Association, Version1.7, December 2010.
62 Gupta R, Yoxall CW, Subhedar N *et al*. Individualised pulse oximetry limits in neonatal intensive care. *Arch. Dis. Child. Fetal Neonatal Ed.* 1999; **81**: F194–6.
63 *WHO Guidelines on Hand Hygiene in Health Care*. World Health Organization, Geneva, 2009.

© 2013 The Authors
Respirology © 2013 Asian Pacific Society of Respirology
Omni MedSci Ex. 2052
WHOOP, Inc. v. Omni MedSci - IPR2025-01584