Neonatal and Pediatric Pulse Oximetry

John W Salyer MBA RRT-NPS FAARC

The pulse oximeter has become a vital instrument in the care of infants and children with cardiopulmonary disease. Recent advances in pulse oximetry technology have improved some aspects of pulse oximeter performance. However, the reliability, accuracy, and clinical utility of pulse oximetry remain problematic in some types of patients under certain conditions. Improved signal processing technology has substantially improved the ability of certain oximeters to work reliably under conditions of poor perfusion and motion artifact. There is a growing body of evidence describing the effect of pulse oximeter utilization on processes and outcomes. This article describes the principles, limitations, current state of oximetry technology, and the impact of oximetry data and alarms on diagnosis and clinical decision-making. *Key words: pediatric, respiratory, pulmonary, pulse oximetry, motion artifact, false alarm, low perfusion, accuracy, pulse oximetry, precision, signal processing, dyshemoglobinemia, processes, outcomes.* [Respir Care 2003;48(4):386–396. © 2003 Daedalus Enterprises]

Introduction

Pulse oximetry has become ubiquitous and a great deal has been published about it. A MEDLINE (National Library of Medicine) search with the term "pulse oximetry" yields over 2,300 citations. This review describes the principles, limitations, and current state of oximetry technology, as well as what is known about the pulse oximeter's effect on processes and outcomes.

Pulse oximetry technology was widely introduced in the United States in the early 1980s.[1] The first application of pulse oximetry was in perioperative care, but it soon expanded into neonatal, pediatric, and adult intensive care units (ICUs).

Pulse oximetry was invented by Takuo Aoyagi, a biomedical engineer working for the Shimadzu Corporation in Kyoto, Japan, in the early 1970s.[2,3] He serendipitously discovered the spectrophotometric measurement principles of pulse oximetry while studying methods of measuring cardiac output. Considering the widespread belief in the value of continuously monitoring various aspects of patient's physiologic status, it is not surprising that the spread of pulse oximetry was rapid and extensive. By 1989 there were 29 manufacturers producing 45 different models of oximeter.[4]

John W Salyer MBA RRT-NPS FAARC is affiliated with the Department of Respiratory Care, Children's Hospital and Regional Medical Center, Seattle, Washington.

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Correspondence: John W Salyer MBA RRT-NPS FAARC, Mail Stop 3-D-6, Children's Hospital and Regional Medical Center, 4800 Sand Point Way NE, Seattle WA 98105. E-mail: john.salyer@seattlechildrens.org.

But has pulse oximetry completely delivered as promised? An important premise of the use of such monitors is that they are capable of early identification of changes in a patient's condition, allowing rapid response. However, few reports have tested the assumption that the oximetry significantly impacts patient outcomes or provides other benefits, and some of the studies that have been published are not altogether encouraging.

As many as 86% of ICU alarms (from all types of monitors) are false alarms and another 6% are true but clinically irrelevant.[5] Thus the potential benefit of continuous physiologic monitoring may be limited by the overwhelming prevalence of false alarms. Pulse oximetry is particularly prone to false alarms, especially in neonatal and pediatric applications, and many clinicians have become somewhat jaded about the urgency of responding to alarms. Clinician response to alarms is probably also affected by the wide variety of alarm sounds used, which can be hard to distinguish. Cropp et al found that experienced ICU nurses were able to identify as few as 38% of vital alarms.[6] The advance of monitoring capability may have outpaced the development of our wisdom in how best to apply it.

There have been some attempts to improve the integration of various alarms in the ICU setting. One such system integrates alarm algorithms for heart rate, systolic and diastolic blood pressure, and pulse oximetry. This technology seemed promising, resulting in a 10-fold increase in the likelihood that an alarm was clinically important. However, as judged by the ICU staff, the system failed to detect 18% of clinically important changes.[7]

Measurement Principles

Pulse oximetry estimates arterial oxygen saturation by measuring the absorption of light (of 2 wavelengths, approximately 660 nm and 940 nm) in human tissue beds. As light passes through human tissue, it is absorbed in various degrees by tissue, bone, blood vessels, fluids, skin, venous blood, and arterial blood, including various types of hemoglobin. The light absorption changes as the amount of blood in the tissue bed changes and as the relative amounts of oxygenated and deoxygenated hemoglobin change (Figure 1).[8] Measuring the changes in light absorption allows estimation of heart rate and arterial oxygen saturation. To measure accurately, the oximeter must distinguish between the background (or constant) absorption and the pulsatile changes in absorption caused by the changing blood volume with each heartbeat. The background absorption can change when there is a change in the shape or position of the tissues through which the light passes, which can cause false readings.

There is controversy about exactly what the pulse oximeter measures. A conventional pulse oximeter measures the ratio of the absorption of 2 wavelengths of light, discriminates the changes that it assumes are a result of pulsatile changes and oxygenation changes, averages the readings over a short period of time, and then looks up the resulting absorption ratio in a table or calibration curve of corresponding arterial saturations. These calibration tables/curves are developed from experiments with volunteers, by comparing simultaneous light absorption readings and blood oxygen values measured via co-oximetry. In 1986 Severinghaus speculated that the oximeter is actually a desaturation meter (ie, desaturation = 100 – saturation)[9] and suggested that among the unsettled issues is whether oximetry should be used for intermittent sampling (spot checks) or continuous monitoring only, and what constitutes an appropriate application of oximetry (who ought to monitored). These issues have not been entirely settled.

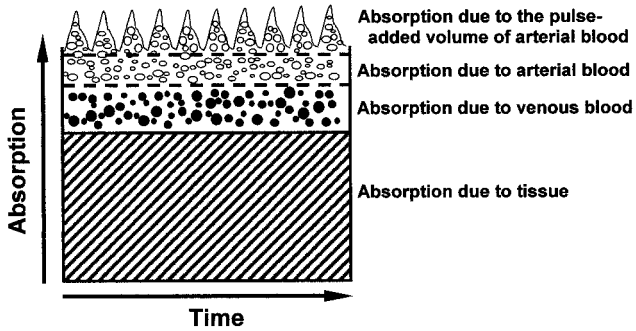

Fig. 1. Sources of absorption in a tissue bed during the use of pulse oximetry. When light is passed through tissue some of the light is absorbed by each constituent of the tissue, but the only variable light absorption is by arterial blood. (From Reference 8, with permission.)

In a 2002 editorial Severinghaus again listed some of the more pressing current issues in the use of oximetry. These include continued disagreement about definitions of the oximeter readings, controversy regarding alarms, regulatory issues, patent infringements, and the inability of researchers to demonstrate that oximetry affects patient outcomes.[10]

The controversy about exactly what oximeters measure is related to the definitions of *fractional* vs *functional* oxygen saturation.[10–12] In my opinion this is largely a theoretical concern that is invisible to many clinicians and has little impact on how oximeters are used clinically, except in the presence of dyshemoglobinemia.

These somewhat arcane debates aside, the readings from pulse oximeters are used clinically as a surrogate for arterial oxygen saturation and have had a substantial impact on how oxygenation is managed. Continuous monitoring of pulse oximetry is now a de facto standard of care for virtually all infants and children receiving mechanical ventilation or intensive care, and its use is increasing in the non-ICU population. Table 1 lists typical applications of continuous pulse oximetry.

Table 1. Typical Applications of Continuous Pulse Oximetry in Neonatal and Pediatric Populations

Indication	Comment
Intensive care and during mechanical ventilation	Now a standard of care for nearly all patients in neonatal and pediatric intensive care, especially those receiving mechanical ventilation[13,14]
Procedural sedation	A recommended standard of care for all patients undergoing procedural sedation[15,16]
Patient-controlled anesthesia	Used in many hospitals continuously on all patients who are receiving patient-controlled anesthesia
During oxygen administration	Now used in many hospitals continuously on all neonatal and pediatric patients receiving oxygen therapy, even in general care areas
Delivery room	Use in the delivery room has been difficult and controversial.[17–23] However, recent improvements in performance during low perfusion and motion have made such monitoring more feasible[24]
Perioperatively	Used universally on all patients during surgery, during the immediate postoperative period, and in many pediatric facilities for the first 12–24 hours after postanesthesia care
High-risk	Some in-house oximetry protocols include continuous monitoring of all patients <3 months of age with any respiratory symptoms, such as during bronchiolitis care[25–27]
Pediatric emergency care	Used as a screening tool for triage of pediatric patients and regarded by some as a "fifth vital sign"[28–33]

Accuracy of Oximeters

There are numerous studies of the accuracy and precision of oximeters in various populations.[34–51] The methods for describing accuracy differed in those studies, making an overall summary of accuracy challenging. There are considerable performance differences among the various brands of oximeter, which are probably due to differences in the signal processing software and calibration curves. Most manufacturers claim confidence limits in any given oximeter reading of ± 4% for readings above 70%.[52] Others have summarized oximetry accuracy as ± 2% above 70%.[53] During periods of desaturation below 70% the bias and precision is substantially less, being highly variable among brands, probably because of the limited amount of calibration data for these low saturation states.[36,39] This seems to me an unimportant limitation, since most patients who desaturate to such a low level are treated as aggressively as possible, regardless of whether the true saturation is 40% or 60%.

Certain pulse oximeters have been shown to operate under some fairly adverse conditions. Carter et al[51] studied the performance of pulse oximeters with 46 newborns and infants in the immediate postoperative period following cardiac surgery. These patients had skin temperatures ranging from 27.0 to 37.4° C and core-to-skin temperature differences of 0.1–10.1° C. These wide derangements in temperature might have been expected to affect oximeter function because of the associated changes in peripheral perfusion, but the authors found that the oximeters' performance was acceptably accurate and did not correlate to skin temperature or core-to-skin temperature difference.

Normal values for pulse oximetry are generally assumed to be the same as normal values for arterial oxygen saturation. However, the effect of altitude and normal, intra-individual variations in saturation readings must be taken into account. The effect of altitude on "normal" pulse oximetry readings in infants and children has been studied.[54–58] Thilo et al studied the effect of altitude on pulse oximetry readings from infants and children.[57] Among healthy infants, 1–3 months of age, at an altitude of 1,610 m (in Denver, Colorado), mean pulse-oximetry-measured blood oxygen saturation (S_{pO_2}) was 92–93%, and the lower end of the reference range was 86% during quiet sleep.[57] Niermeyer et al studied serial S_{pO_2} measured from birth to 4 months with healthy infants born at high altitude (3,100 m). The mean S_{pO_2} ranged from 80.6 ± 5.3% to 91.1 ± 1.7% during the 4-month period.[55]

Limitations of Oximetry

Pulse oximetry has several well known limitations, including the effects of ambient light, skin pigmentation, dyshemoglobinemia, low peripheral perfusion states, and motion artifact. These affect bias, precision, applicability of the instrument, and clinician confidence in the readings. In the early days of pulse oximetry in the neonatal ICU, it was not uncommon to hear oximeters referred to by some of the more skeptical as "random number generators." This was generally due to the well known problem of motion artifact in neonates. Though that skeptical view is a bit extreme, it demonstrates how the limitations of oximeters have affected how they have been viewed by some clinicians.

Ambient light can affect oximeter operation,[59–63] but this problem can be overcome by simply wrapping the oximeter probe in opaque material. Skin pigmentation also affects pulse oximeter performance.[64–66] As skin pigmentation darkens, oximeter performance deteriorates. This could be because the empirical calibration data was derived from predominantly white volunteers.

Dyshemoglobinemia also compromises pulse oximetry readings, because pulse oximeters are unable to distinguish between oxygenated hemoglobin and the various

Table 2. Pulse Oximetry Readings, Actual Arterial Saturation, and Methemoglobin Levels in a 12-Month-Old Male Infant Suffering from Phenazopyridine Hydrochloride Ingestion

Time	P_{aO_2} (mm Hg)	S_{pO_2} (%)	S_{aO_2} (%)	MetHb (g/dL)
Admission	155	63	43.7	54.8
4 h	102	81	66.1	30.2
16 h	110	89	82.2	15.2
24 h	100	95	93.1	5.8

P_{aO_2} = arterial partial pressure of oxygen measured from arterial blood gas sample
S_{pO_2} = oxygen saturation measured via pulse oximetry
S_{aO_2} arterial oxygen saturation measured from arterial blood sample
MetHb = methemoglobin
S_{aO_2} and MetHg levels were obtained from whole blood samples via co-oximetry.
(Adapted from Reference 69.)

dysfunctional hemoglobins, such as methemoglobin and carboxyhemoglobin,[67–73] which are unable to bind with and carry oxygen. Dyshemoglobinemia is apparent when there are large differences between *functional* and *fractional* oxygen saturation.

$$\text{Functional Saturation} \quad \frac{HbO_2}{HbO_2 + HHb} \tag{1}$$

$$\text{Fractional Saturation} \quad \frac{HbO_2}{\text{TotalHb}} \tag{2}$$

in which HbO_2 is oxygenated hemoglobin, HHb is deoxygenated (reduced) hemoglobin, and TotalHb includes all the hemoglobin types: HbO_2, HHb, metHb (methemoglobin), and COHb (carboxyhemoglobin).

Functional saturation concerns only the hemoglobin that can transport oxygen. With dyshemoglobinemia it is possible to have a substantial reduction in the blood's oxygen carrying capacity and yet have normal functional saturation. Thus, normal functional saturation does not ensure adequate oxygen carrying capacity, so a functional saturation reading could mislead someone who did not know the difference between functional and fractional saturation. Some manufacturers report that their oximeters closely estimate functional saturation. However, dyshemoglobinemia can compromise both functional and fractional pulse oximetry readings.[11] Co-oximetry can provide accurate fractional saturation readings, so care must be taken when comparing pulse oximetry readings to co-oximetry readings during dyshemoglobinemia. Carbon monoxide poisoning, which causes carboxyhemoglobinemia, is not uncommon in emergency rooms.[72] Methemoglobinemia has been reported in series of infants and children.[69,70] Table 2 illustrates the magnitude of pulse oximetry measurement error that can be introduced by methemoglobinemia. One of the first clinical clues of dyshemoglobinemia is the presence of normal or near-normal pulse oximetry readings in the presence of cyanosis. If that circumstance, or if patient history leads a practitioner to suspect dyshemoglobinemia, an arterial blood sample should be obtained and analyzed via co-oximetry.[73] Co-oximeters use measurement principles similar to pulse oximeters, but typically use more than just 2 wavelengths of light and thus are better able to distinguish the various types of hemoglobin.

Motion Artifact, Poor Perfusion, and Oximeter Alarms

The utility of pulse oximetry alarms and the performance of pulse oximeters are closely linked. Oximeter performance is profoundly affected by low peripheral perfusion states[74–80] and patient motion.[81–83] The use of alarms during continuous monitoring has different objectives in different populations. The low-saturation alarm limit setting depends on several factors and can be controversial. In general, the higher the low alarm is set, the greater the likelihood of alarming during true hypoxemia, but also the greater the likelihood of false alarms caused by a false low reading or no reading at all. Low peripheral perfusion and motion artifact are the 2 most common causes of inaccurate S_{pO_2} readings.

Low peripheral perfusion and motion of the tissue bed compromise oximeter performance, partly because of the extremely low signal-to-noise ratio inherent to pulse oximetry. False alarms continue to be an important problem in ICUs.[5,7,84]

Two studies of neonates and children found that (1) 44–63% of all critical care alarms were caused by pulse oximeters, (2) 94% of oximeter alarms were considered clinically unimportant, and (3) 71% were false alarms.[85,86] Because oximeter alarms are false most of the time, clinicians will tend either to ignore alarms or spend a lot of time determining whether alarms are false. The high incidence of false oximetry alarms may cause clinicians to have an unjustified skepticism about the reliability of other types of alarms.

New pulse oximeter designs have been claimed to improve performance during low perfusion states and patient motion. One of the more promising is signal extraction technology (SET) (Masimo Corporation, Mission Viejo, California), which uses "signal processing algorithms that detect and ignore sources of S_{pO_2} and pulse rate interference."[87,88]

Poets et al studied pulse oximetry alarm frequency. They compared Masimo SET to a conventional pulse oximeter with 17 nonsedated preterm infants.[89] The median frequency of alarms per hour was 4.0 (range 2.6–15.0) with the conventional pulse oximeter and 0.3 (range 0.0–1.9)

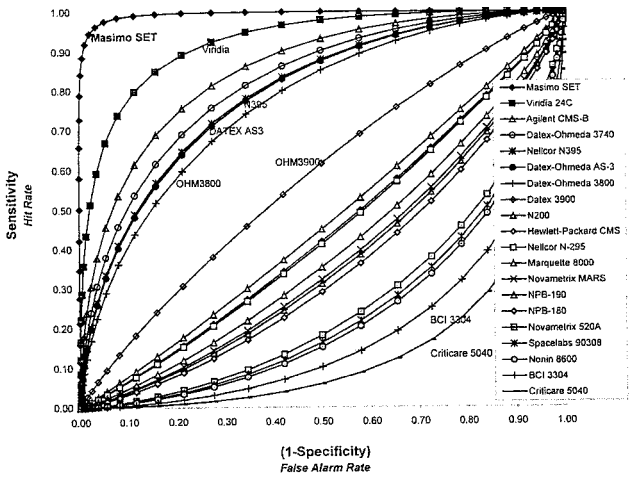

Fig. 2. Pulse oximeter receiver operator characteristic curves (including drop-outs) for 20 pulse oximeters tested during machine-generated motion. The curves plot sensitivity (the probability of the monitor identifying true hypoxemia) against false alarm rates. The specificity is defined as the probability of the oximeter identifying periods of normoxemia, so 1 minus specificity is the false alarm rate. The best-performing oximeters are found in the upper left hand corner of the graph. (From Reference 91, with permission.)

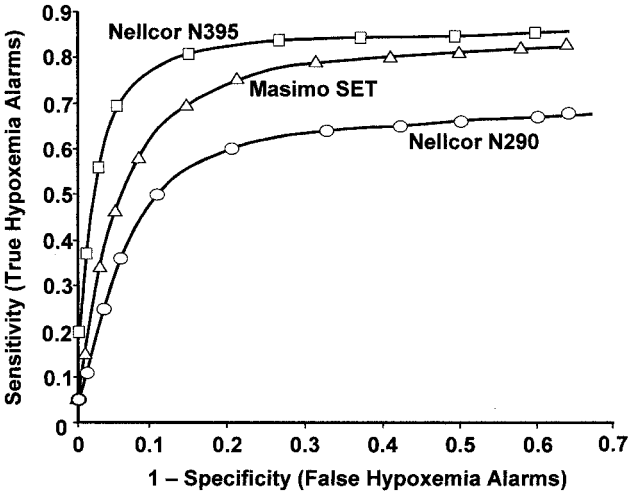

Fig. 3. Receiver operator characteristics for 3 oximeters tested during voluntary motion. The curves plot sensitivity (the probability of the monitor identifying true hypoxemia) against false alarm rates. The specificity is defined as the probability of the oximeter identifying periods of normoxemia, so 1 minus specificity is the false alarm rate. The best-performing oximeters are found in the upper left hand corner of the graph. (From Reference 98, with permission.)

with the Masimo SET ($p < 0.0001$). Though the study was not designed to determine the incidence of true alarms, the authors pointed out that the cardiac monitor revealed a median of only 0.6 alarms per hour (range 0.1–1.6), which might suggest the number of true periods of cardiovascular compromise per hour. Thus, they reported that the Masimo SET produced 93% fewer alarms during frequent body movement. Miyasaka reported a 90% lower false alarm rate with Masimo SET, but they did not tell which brand of conventional pulse oximeter they tested.[90]

A number of studies have suggested that Masimo SET is superior during conditions of low perfusion and/or motion in laboratory experiments using adult volunteers.[91–97] In most of those studies motion was simulated by placing the hand being studied on a motion-generating table, while having the subject tap and rub the fingers, each of which was attached to one of the various oximeters being tested. Control values for S_{pO_2} are typically obtained from fingers of the opposite hand, which remains motionless during the experiment. Low perfusion is often simulated by lowering the room temperature to 16–18° C, and both conditions are tested during hypoxemia by having subjects breath subambient concentrations of oxygen. There are then various methods of comparing the agreement of the oximeters being tested with the control values from the opposite hand. In addition, calculations are typically made of the amount of time readings are unavailable (ie, drop-out rates). There is controversy regarding this research methodology.[98,99] The criticisms center on the type of motion created in the laboratory setting. It has been suggested that these mechanical motion simulators produce motion artifact that is too "homogenous" and thus is not representative of real patient motion in the clinical environment. Critics suggest that nonmechanical and therefore "irregular" and voluntary motions are more representative of the clinical environment.

One of the more intriguing aspects of this debate is the very different research findings produced by the proponents of 2 different research models, and incidentally proponents of the 2 most prominent players in this pulse oximetry debate: Nellcor and Masimo. Barker et al[91,92,95,97] have consistently produced work using mechanical motion simulators, producing findings like those illustrated in Figure 2. However, Jopling et al[98] have produced somewhat different findings, illustrated in Figure 3. As we try to sort out these divergent findings, we are aided by a growing body of literature comparing the performance of these 2 brands of pulse oximeter. The Masimo SET device has been found to perform better than conventional oximeters or newer-generation oximeters in a number of studies with infants and children.[100–112] Hay et al[109] studied oximetry with 26 nonsedated neonatal ICU infants who were on supplemental oxygen or mechanical ventilation. They compared the performance of the Masimo SET to the Nellcor N-200, the Nellcor N-395, the Novametrix Mars, and the Philips Viridia 24 C. Compared to the Nellcor N-200, the Masimo had 92% less total alarm time and better identification of bradycardia. Compared to the newer-generation pulse oximeters, false desaturations, drop-out rates, and false bradycardias were lowest with Masimo SET.

In a study with neonates Bohnhorst et al[105] found better clinical performance with Masimo SET than with either the Nellcor N-200 or N-3000, with regard to detection of low saturation and bradycardia in 17 spontaneously breathing preterm infants (mean birthweight 673 g, range 520–1,575 g). Malviya et al[113] reported that Masimo SET reduced the incidence and duration of false alarms and identified true alarm conditions more frequently than did the Nellcor N-200 among 75 children age 4.9 ± 2.7 years studied in a post-anesthesia care unit. The Masimo SET has also been studied during apnea testing and polysomnography. In studies comparing Masimo SET with Nellcor N-200 and Nellcor N-395 the Masimo SET had better desaturation detection.[114–117]

There are some studies in which the Masimo SET was not found to perform better than other technologies. Barcelona et al[118] studied the drop-out rates during pediatric anesthesia application of 4 oximeters: Nellcor N-200, Nellcor N-290, Nellcor N-395, and Masimo SET. They concluded that all these oximeters worked equally well during pediatric general anesthesia, but that the drop-out rate with the Masimo SET was higher during motion and hypoxemia, but this occurred in a very small percentage of patients (3.1%). The report states that the Nellcor N-290 provided more information than the other oximeters, but the study did not make clear whether that greater quantity of data was representative of the patient's true condition.

The Barcelona et al findings differ considerably from those of Lichtenthal and Barker,[119] who reported that the Masimo SET had a drop-out rate of 2% with light-skinned patients and 7% with dark-skinned patients during cardiopulmonary bypass. The drop-out rates of the Nellcor N-200 and N-395 ranged from 24 to 42%. Of course, the performance of pulse oximeters could reasonably be expected to differ considerably during general pediatric anesthesia versus during cardiopulmonary bypass. However, the difference in performance under these 2 conditions was large and important.

There are other reports that present divergent views of the comparative performance of newer-generation pulse oximeters, but the overwhelming majority of that research is in the abstract stage only, and thus we must take care not to overinterpret those early findings. Nevertheless, at this point there is a substantial body of evidence indicating the superiority of the Masimo SET.

Another aspect of oximeter performance to consider with the neonatal population is the unique need among neonatal ICU patients to prevent prolonged hyperoxemia, to minimize the risk of retinopathy of prematurity. Various studies have suggested different pulse oximetry upper alarm limits to avoid hyperoxemia.[120–123] Bohnhorst et al tested 3 newer-generation pulse oximeters' ability to identify periods of hyperoxemia.[124] The Agilent Viridia, Masimo SET, and Nellcor N-3000 were tested with 56 infants. By defining hyperoxemia as $P_{aO_2} > 80$ mm Hg they were able to get sensitivities in the 93–95% range by setting the upper alarm limit at 95%. In other words, with the upper alarm limit set at 95%, the oximeters had a 93–95% probability of alarming in the presence of $P_{aO_2} > 80$ mm Hg. Unfortunately, this high sensitivity was associated with low specificity, which ranged from 26 to 45%, meaning that there was a 55–74% probability that the high alarm would be false. They concluded that pulse oximetry should not be the sole means of monitoring oxygenation in the neonatal ICU—a recommendation with which I agree.

Processes, Outcomes, and Pulse Oximetry

The term "processes" refers to the conduct of diagnostic and therapeutic interventions. The advent of pulse oximetry substantially changed the processes of care for infants and children with cardiopulmonary disease. Some of these changes have been to the benefit of our patients, but some may not be. Whether pulse oximetry has had significant impacts on outcomes is hard to determine and has yet to be substantially demonstrated in the literature.[125] We need to determine whether the use of pulse oximetry increases survival, speeds recovery, reduces complications, eases pain or suffering, or reduces the cost of care.

In terms of processes, pulse oximetry has been shown to reduce the number of arterial blood gas samples taken in various populations.[126–131] However, sometimes this reduction has been as modest as 10%,[128] and pulse oximetry may not always reduce arterial blood gas sampling and analysis. Using standardized protocols for reducing blood gas sampling and analysis along with pulse oximetry will help to ensure the most efficient use of blood gas analyses.[132]

In an excellent study Durbin and Rostow demonstrated that, compared to a conventional pulse oximeter (Ohmeda 3740), the Masimo SET was associated with lower oximeter failure rates, fewer arterial blood gas samples, and shorter oxygen weaning time with adult cardiovascular surgery patients.[133] Bedside clinicians had access to the readings from one type of oximeter or another during the study, while data from both oximeter types were obtained and recorded during the postoperative period of weaning from oxygen and/or mechanical ventilation. This important research is one of the first such studies to compare the impact of different pulse oximetry technologies on patient processes *and* outcomes.

There are special issues regarding the impact of continuous pulse oximetry on processes of care in the general medical-surgical pediatric in-patient population. The use of continuous oximetry with this population can result in excessive alarms (mostly false) that often go unnoticed or ignored by clinical staff. Attendant parents sometimes become disgruntled that no one is responding to their child's oximeter alarm. Plus, the poor performance of pulse oxime-

ters during motion can create special problems for pediatric medical-surgical patients. Some clinicians speculate that hospitalization is sometimes prolonged because of pulse oximetry readings. Some children will appear ready to be discharged, with no physical findings of respiratory difficulty or oxygenation problems, but have marginally low S_{pO_2} readings, which can result in delaying discharge. These S_{pO_2} readings could indeed be spurious, but sometimes it is difficult for clinicians to determine this, especially with an infant or toddler in whom vascular access for blood gas analysis is not readily available.

The widespread use of continuous pulse oximetry has revealed the presence in various patient populations of subclinical, usually self-correcting hypoxemia that is generally occult to the clinician.[134–139] The incidence of this clinically unapparent hypoxemia ranges from 20 to 82%, with some of the variation probably due to differing definitions of the magnitude and duration of qualifying episodes of desaturation.[12] One of the more pressing questions regarding this phenomenon is, does it matter whether these hitherto unknown periods of hypoxemia are treated?

Rosenberg et al[134] identified clinically occult desaturations in sleeping, otherwise healthy, elderly patients before and after hip replacement surgery. They found episodic desaturation to $<$ 80% in 18% of patients before surgery and 59% on the second postoperative night. They found that these desaturations were associated with changes in these patients' electrocardiograms, including ST segment depression, tachycardia, and increased frequency of premature ventricular contractions. However, no postoperative cardiac complications requiring treatment or adverse outcomes were found in any of these patients. From that study one is tempted to speculate that episodic hypoxemia appears to be normal in some patients and that it does not appear to be associated with adverse outcomes, although the sample size was admittedly small. Also, it might be argued that the study was designed to identify markers of poor outcomes, as opposed to the outcomes themselves.

In a follow-up study[135] Rosenberg et al randomized a similar sample of patients to have or not have a simple oxygen mask while sleeping on the second postoperative night. They found no significant differences in the number of hypoxemic episodes between the groups with and without the oxygen mask! Thus, the authors concluded that oxygen therapy in this population did not, ". . . influence the basic mechanism leading to episodic hypoxemia." Again, no difference in overall mortality or morbidity was found between the patients who did and did not receive oxygen. I interpret these data to suggest that not only does it not matter whether such desaturations are monitored, it doesn't seem to matter if they are treated. However, there are divergent opinions about this.

Bowton et al reported a study of general medical-surgical patients monitored with a pulse oximeter that recorded all desaturations.[136] Oximeter records were compared with the medical record. Desaturations in the oximetry record were noted in the nursing notes 33% of the time and in the doctors' progress notes 7% of the time. For patients who desaturated to $<$ 85%, respiratory therapy notes indicated a change in therapy in only 20% of episodes. Thus, having continuous pulse oximetry data from these patients, presumably to identify and treat otherwise occult hypoxemia, did not seem to achieve the desired outcome.

Bowton et al[138] later studied the frequency and adverse effects of hypoxemia in 100 general medical patients in a tertiary academic medical center. Using continuous pulse oximetry with computer acquisition of data, they found that 26% of patients had desaturations to $<$ 90% for $>$ 5 min. During the following 4–7 months, 32% of patients suffering episodic hypoxemia died, whereas only 10% without hypoxemia died. Even after adjusting for severity of illness, this difference was statistically significant; the relative risk of death was 3.3 (95% confidence interval 1.41–8.2). However, the design of the study does not permit the establishment of a causal link between episodic hypoxemia and mortality, which the authors readily admitted. Despite their findings they did not recommend general use of continuous pulse oximetry in that population.

Bierman et al published a report of a randomized trial of continuous pulse oximetry in the ICU.[137] Postoperative cardiac surgical patients (n = 35) were monitored continuously with pulse oximetry. They were randomized to have their oximetry values available to the bedside staff or to be monitored in a remote location and reported to the bedside personnel only after 5–10 min of hypoxemia, in order to allow the bedside staff to detect and react to hypoxemia episodes based on clinical assessment alone. Episodic hypoxemia undetected by the clinical staff was found in 47% of the remotely-monitored patients. Duration of ventilation, duration of oxygenation, and number of ventilator changes were not different between the 2 groups. The study confirmed that pulse oximetry helps to detect episodic hypoxemia, but the design did not allow for testing whether treating these episodes had any impact on outcomes.

Alario et al reported on the use of pulse oximetry in a pediatric emergency room population.[140] Pulse oximetry readings were taken before and after treatment for wheezing with 74 patients (ages 1–36 mo) presenting with acute wheezing. S_{pO_2} was compared to clinical response to treatment (eg, respiratory rate and a standardized respiratory distress score). The post-treatment S_{pO_2} readings revealed considerable individual variability. They concluded, "After therapy, young children can appear clinically improved but measured oxygen saturation may be variable and not correlated with traditional clinical assessment. In fact, in assessing the response to therapy for an individual patient, the S_{pO_2} may be misleading."

In another study pulse oximetry was found to be insufficiently sensitive to rule out the presence of pneumonia in children < 2 years of age who presented with respiratory complaints to an emergency room.[141] Some studies have reported that S_{pO_2} is a good predictor of outcomes in pediatric emergency room patients,[28–30] whereas others have not.[31,32]

Mower et al studied the use of S_{pO_2} as a "fifth vital sign" in a pediatric emergency room population.[33] S_{pO_2} measurements were made on all presenting children but were revealed to clinicians only when the patients were ready to discharge or admit. They then determined the changes in treatment that resulted after the disclosure of S_{pO_2}. Diagnoses were added or changed in 8% of patients, and 2% of patients scheduled for discharge were admitted. Physicians ordered 39 new therapies for 33 (11%) of the patients.

On the Horizon

Reflectance oximetry, which measures the amount of light reflected back from a tissue (as opposed to light that passes through) has existed since the early 1990s but has not gained wide acceptance. The reflectance principle might be less susceptible to the problems of motion artifact and poor peripheral perfusion, but testing with infants and children has not yet been reported. The only reflectance oximeters presently available are for patients ≥ 10 kg. It is unclear at this point whether the newer models of reflectance oximeter are any better than earlier releases.

Another new but largely untested development is a newly released oximeter that the manufacturer claims has superior performance because it has the computer technology and empirical calibration curves inside the probe instead of inside the oximeter. The suggested improved performance is ostensibly related to improvements in accuracy and precision. I have yet to encounter any suggestion from the manufacturer that this will improve performance during motion artifact or poor perfusion.

Further research is needed on the use of continuous pulse oximetry with noncritical-care infants and children. The use of this technology is growing considerably with these populations, but is unclear whether it offers any benefits to these patients.

Summary

Substantial advances have been made in pulse oximetry technology, and pulse oximetry data influence treatment decisions and processes of care in certain situations, but it is unclear whether patient outcomes would be any different without pulse oximetry. Clinicians must bear in mind that dyshemoglobinemia (for example, from carbon monoxide poisoning) causes inaccurately high S_{pO_2} readings, and motion and low peripheral perfusion often cause inaccurately low S_{pO_2} readings. Research is needed to determine whether pulse oximetry improves patient outcomes or processes of care; it may be that pulse oximetry is unnecessary and unhelpful (and therefore an inappropriate use of health care resources) in some settings.

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Discussion

Hansell: I think one of the things that you're finding, and it's something I certainly see in our practice, especially with our postoperative cardiac patients, is that all the monitoring devices that we have in no way take the place of skilled personnel at the bedside who are actually evaluating the patients, looking at them, looking at perfusion, evaluating if the extremities are cold or warm. Even with all the Masimo SET oximeter does, and as impressive as that looks, I don't think that we have reduced the importance of the most critical monitor in the intensive care unit, and that is the respiratory therapist or nurse at the bedside.

Salyer: Thanks for bringing that up. House officers and nurses tended to have some knowledge deficit with regards to oximetry, but most of the published data about what nurses and doctors know about oximetry is from the early 1990s, and so we hope that's better by now. I totally agree with you that the biggest problem with applying monitors in general in the critical care unit is the training of respiratory therapists, nurses, and doctors in how to interpret and react to monitor readings.

I'll give you a little anecdote. We had a patient postoperative ventricular septal defect repair. The therapist did not set a high enough airway pressure. She applied an end-tidal carbon dioxide monitor and it read approximately 90 mm Hg. She couldn't believe it. She left the bedside and went to find the house officer, and they conferred, and decided to get a blood gas analysis and so there was a 20-minute delay. The blood sample values were pH 6.95 and P_{aCO_2} 105 mm Hg. I said to her later, "You know, if the end-tidal carbon dioxide is in error, the overwhelming majority of the time it under-reports the actual P_{aCO_2}, and so probably the patient is even worse than the device indicates." She, in fact, had just attended my wonderful lecture on this subject the week before! So it's a big training issue. I totally agree with you. I hope the manufacturers begin to help us more, with more training materials and more training support.

Donn: I think for neonatologists our bigger problem is that pulse oximetry is used as a surrogate for arterial oxygen tension, and when we're dealing with small premature babies and we get up to 98–99%, the reliability of knowing what the true P_{aO_2} is becomes an important problem with respect to oxygen toxicity and some of the other problems we deal with. I think it's mostly an education issue, but it's also compounded by the fact that alarm adjustments are always made to try to minimize the number of false alarms at the upper end. That creates a substantial problem for us clinically.

Salyer: Yes, that's what I found out when I studied the Ohmeda oximeter. If I set the alarm limits to have an 80–90% chance of identifying periods of hyperoxemia, the clinicians were not going to put up with it because the alarm sounded too frequently. The alarms were going to be disabled or readjusted. But that oximeter was a product from 8–10 years ago, and I think the technology has improved greatly.

Wagener: Why was oximetry ever started in the newborn intensive care unit? This device was developed to measure *hypoxia* and has *no* value in measuring hyperoxia. With a premature infant you need to know if the child is hyperoxic, so I don't understand why oximeters are used.

Salyer: I agree.

Giordano:* I would like to point out that, for the first time, at least in my memory, the Joint Commission on Accreditation of Health Care Organizations issued a Sentinel Event bulletin in February 2002 regarding alarms, and that's because of failure to apply alarms properly.[1] So this is a growing problem, especially with the staffing shortages occurring virtually across the board. I think that in some cases we're asking too much from the alarm, asking it to be a proxy for the trained eye of a person who understands what he's seeing.

* Sam P Giordano MBA RRT FAARC, Executive Director, American Association for Respiratory Care, Dallas, Texas

REFERENCE

1. Sentinel Event Alert. Preventing ventilator-related deaths and injuries. Issue 25, Feb 26, 2002. Available at http://www.jcaho.org/about+us/news+letters/sentinel+event+alert/sea_25.htm (accessed Nov 20, 2002).

Wagener: You pointed out that approximately 30% of alarms are noted by nursing staff and substantially fewer by physician staff. As we use monitors more, particularly oximeters, it seems the value of alarms becomes less and less. Pretty soon the alarm is completely disregarded because there are so many false alarms.

Salyer: I completely agree. In the general medical pediatric population being monitored with continuous pulse oximetry, if you walk through the bronchiolitis ward in bronchiolitis season you hear a cacophony of alarms, and they're routinely ignored. Parents are understandably upset because the device is alarming and no one is coming into the room to care for their child, and they don't understand. It creates a lot of tension in them. I'm a little more hopeful about it now, because I think the newer technology might give you more confidence by creating fewer false alarms. But this is a hard culture to change, to get clinicians a little more focused on reacting to alarms properly.

Myers: I'm looking for the monitor companies, especially pulse oximeter companies, to come out with something similar to what the ventilator companies are coming out with, and that's different alarm pitches for dif-

ferent failures. I think the ventilator companies are on the cutting edge here because they have 3 different levels of alarm. Again, that may be tuning people out to go into the room when they hear something that's a lower level alarm, but it is a start.

Salyer: Yes, that might help. However, an even larger problem is that alarms are simply turned off. You could have all sorts of different alarm tones, but if the alarm is disabled, it doesn't matter what you have the tone set at.

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