

Pulse oximetry

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Pulse oximetry is one of the most commonly employed monitoring modalities in the critical care setting. This review describes the latest technological advances in the field of pulse oximetry. Accuracy of pulse oximeters and their limitations are critically examined. Finally, the existing data regarding the clinical applications and cost-effectiveness of pulse oximeters are discussed.

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Introduction

The human eye is poor at recognizing hypoxemia. Even under ideal conditions, skilled observers cannot consistently detect hypoxemia until the oxygen (O_2) saturation is below 80% [1]. The difficulty that physicians have in detecting hypoxemia was recently exemplified in a study of over 14000 patients being evaluated at the UCLA Emergency Department [2]. Patients were monitored by oximetry but recordings were given to physicians only after they completed their initial assessment. Changes in diagnostic testing and treatment were most likely at an O_2 saturation of 89%, and changes were actually less common at lower saturations, probably because the physicians were able to detect evidence of hypoxemia without requiring a pulse oximeter.

With the proliferation of pulse oximeters in different locations of the hospital throughout the 1980s, several investigators demonstrated that episodic hypoxemia is much more common than previously suspected with an incidence ranging from 20–82% [3–5] (Fig. 1). The significance of episodic desaturation on patient outcome is largely unknown [6]. In patients admitted to a general medical service, Bowton *et al.* [7] found that O_2 saturation <90% of at least 5 min duration occurred in 26% of the

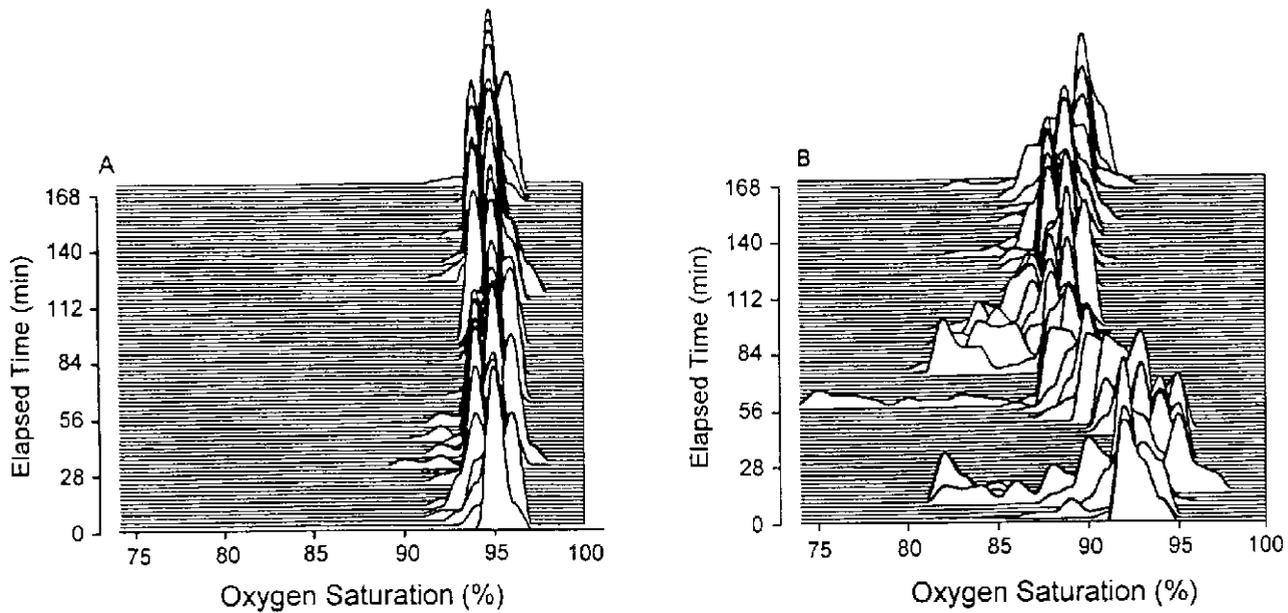
patients. On follow-up over the next 4–7 months, those patients experiencing hypoxemia during the first 24 h of hospitalization had more than a threefold higher mortality than patients who did not desaturate. Although episodic desaturation may simply be a marker of increased risk rather than the direct cause of decreased survival, an increased mortality rate was still observed in patients with episodic hypoxemia when the investigators corrected for severity of illness. Whether or not the early detection and treatment of episodic hypoxemia can affect patient outcome remains unknown.

Principles of pulse oximetry

Pulse oximetry is based on two physical principles: (a) the presence of a pulsatile signal generated by arterial blood, which is relatively independent of non-pulsatile arterial blood, venous and capillary blood, and other tissues; and (b) the fact that oxyhemoglobin (O_2Hb) and reduced hemoglobin (Hb) have different absorption spectra [8]. Currently available oximeters use two light-emitting diodes (LEDs) that emit light at the 660 nm (red) and the 940 nm (infrared) wavelengths. These two wavelengths are used because O_2Hb and Hb have different absorption spectra at these particular wavelengths. In the red region, O_2Hb absorbs less light than Hb, while the reverse occurs

O_2 = oxygen; O_2Hb = oxyhemoglobin; Hb = hemoglobin; LED = light-emitting diode; S_aO_2 = oxygen saturation; S_pO_2 = arterial saturation; F_iO_2 = fractional inspired oxygen concentration; P_aO_2 = arterial oxygen tension; COHb = carboxyhemoglobin; MetHb = methemoglobin; ICU = intensive care unit; SET = signal extraction technology; ABG = arterial blood gas

Figure 1



Sequential distribution plots of oxygen saturation at intervals of 2 min over a 3-h period in a stable patient (A) and unstable patient (B). The

unstable patient shows episodic desaturations. Published with permission [3].

in the infrared region. The ratio of absorbencies at these two wavelengths is calibrated empirically against direct measurements of arterial blood oxygen saturation (S_aO_2) in volunteers, and the resulting calibration algorithm is stored in a digital microprocessor within the pulse oximeter. During subsequent use, the calibration curve is used to generate the pulse oximeter's estimate of arterial saturation (S_pO_2) [9,10] (Fig. 2). In addition to the digital readout of O_2 saturation, most pulse oximeters display a plethysmographic waveform which can help clinicians distinguish an artifactual signal from the true signal (Fig. 3).

Accuracy

The accuracy of commercially available oximeters differ widely, probably because of the different algorithms employed in signal processing [8]. These algorithms are limited by the range of saturations that can be safely obtained in volunteers, and also the accuracy of the measurement standard (CO-oximeter) [11]. Comparison of pulse oximetry with direct CO-oximeter measurements should be reported in terms of the mean difference between the two techniques (bias) and the standard deviation of the differences (precision).

In healthy volunteers, oximeters commonly have a mean difference (bias) of <2% and a standard deviation (precision) of <3% when S_aO_2 is 90% or above [12,13]. Comparable results have also been obtained in critically ill patients

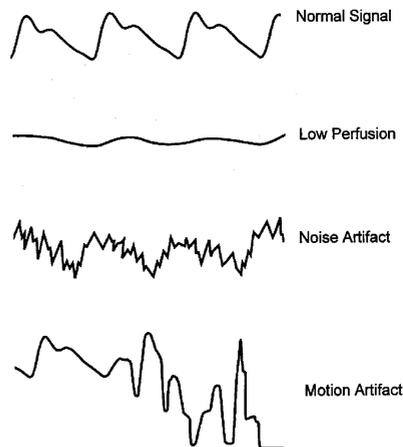
Figure 2

S_aO_2	660 nm (R)	940 nm (IR)	R/IR
0%			~3.4
85%			1.0
100%			0.43

Red (R) and infrared (IR) scaled alternating current (AC) signals at arterial oxygen saturation (S_aO_2) of 0%, 85% and 100%. The numeric value of the red-to-infrared (R/IR) ratio can be easily converted to S_aO_2 . Published with permission [10].

with good arterial perfusion [14,15]. Accuracy of pulse oximeters deteriorates when S_aO_2 falls to 80% or less. In healthy volunteers under hypoxic conditions, bias of pulse oximetry varies from -15.0 to 13.1 while the precision ranges from 1.0 to 16.0 [12,16-18]. In a study in critically ill patients, eight out of 13 oximeters had a bias $\geq \pm 5\%$

Figure 3



Common pulsatile signals on a pulse oximeter. (Top panel) Normal signal showing the sharp waveform with a clear dicrotic notch. (Second panel) Pulsatile signal during low perfusion showing a typical sine wave. (Third panel) Pulsatile signal with superimposed noise artifact giving a jagged appearance. (Lowest panel) Pulsatile signal during motion artifact showing an erratic waveform. Published with permission [8].

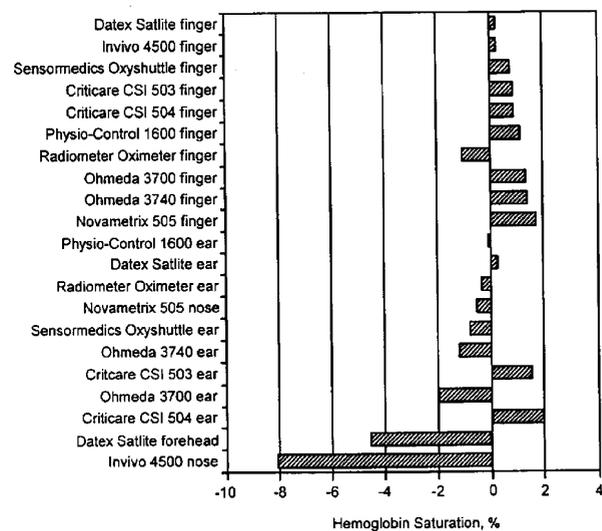
when S_aO_2 was $<80\%$ [14]. In a study of 54 ventilator-dependent patients, the accuracy of oximetry deteriorated significantly at low S_aO_2 values. Bias \pm precision was $1.7 \pm 1.2\%$ for S_aO_2 values $>90\%$, and it increased to $5.1 \pm 2.7\%$ when S_aO_2 was $\leq 90\%$ [19].

Different probes that are used with a pulse oximeter can also affect the accuracy of S_pO_2 measurements. In patients with poor peripheral perfusion as a consequence of cardiopulmonary bypass surgery, finger probes had lower precision and more readings within 3% of the reference (CO-oximeter) than the other probes. Overall rankings were significantly better for the finger probes than probes on other sites (Fig. 4) [20]. The response time of oximeter probes was assessed by Severinghaus and Naifeh [17] who induced 30–60 s hypoxic plateaus between an S_aO_2 of 40 and 70% in healthy volunteers. Oximeter probes placed on the ear generally had a much faster response to a sudden decrease in fractional inspired oxygen concentration (F_iO_2) than did the finger probes (10–20 versus 24–35 s, respectively). Employing hypobaric facility to induce hypoxia in normal volunteers, Young *et al.* [21] also observed that the response time of the finger probes were slower than the ear probes in response to either a decrease or increase in O_2 saturation.

Limitations

Oximeters have a number of limitations which may lead to inaccurate readings (Table 1). Pulse oximeters measure S_aO_2 that is physiologically related to arterial oxygen

Figure 4



Pulse oximeter probes placed on the finger, ear, nose or forehead ranked for accuracy in terms of bias under conditions of poor perfusion. Bias of pulse oximeters ranged from 0.2 to 1.7 for finger probes and 0.1 to 8.1 for other probes. Adapted with permission [20].

Table 1

Limitations of pulse oximetry

- Shape of oxygen dissociation curve
- Carboxyhemoglobin
- Methemoglobin
- Anemia
- Dyes
- Nail polish
- Ambient light
- False alarms
- Motion artifact
- Skin pigmentation
- Low perfusion state

tension (P_aO_2) according to the O_2Hb dissociation curve. Because the O_2Hb dissociation curve has a sigmoid shape, oximetry is relatively insensitive in detecting the development of hypoxemia in patients with high baseline levels of P_aO_2 [11,22].

Pulse oximeters employ only two wavelengths of light and, thus, can distinguish only two substances, Hb and O_2Hb . When carboxyhemoglobin (COHb) and methemoglobin (MetHb) are also present, four wavelengths are

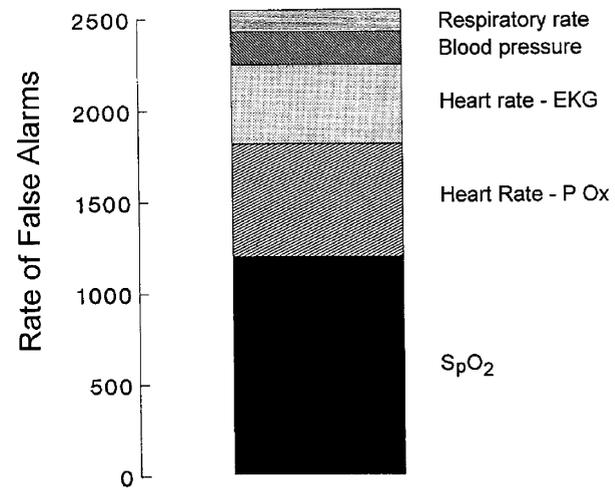
required to determine the 'fractional S_aO_2 ': i.e., $(O_2Hb \times 100) / (Hb + O_2Hb + COHb + MetHb)$. In the presence of elevated COHb levels, oximetry consistently overestimated the true S_aO_2 [23,24] by the amount of COHb present. Elevated MetHb levels also may cause inaccurate oximetry readings [25,26]. Anemia does not appear to affect the accuracy of pulse oximetry: in non-hypoxic patients with acute anemia (mean Hb, 5.2 ± 0.3 (SE) g/dl), pulse oximetry was accurate in measuring O_2 saturation with a bias of only 0.53% [27]. However, in patients with sickle cell anemia presenting with acute vaso-occlusive crisis [28], mean bias of pulse oximetry was 4.5% (in some patients it was as high as 8%), which was significantly greater than in a control group of patients without sickle cell anemia. Severe hyperbilirubinemia (mean bilirubin, 30.6mg/dl) does not effect the accuracy of pulse oximetry [29].

Intravenous dyes such as methylene blue, indocyanine green, and indigo carmine can cause falsely low S_pO_2 readings [30], an effect that persists for up to 20 min [31]. Nail polish, if blue, green or black, causes inaccurate S_pO_2 readings [32], whereas acrylic nails do not interfere with pulse oximetry readings [33]. Falsely low and high S_pO_2 readings occur with fluorescent and xenon arc surgical lamps [34].

Motion artifact continues to be a significant source of error and false alarms [35–38]. In a recent, prospective study in an intensive care unit (ICU) setting, S_pO_2 signals accounted for almost half of a total of 2525 false alarms [39] (Fig. 5). In 123 patients recovering from general or spinal-epidural anesthesia, 77% of pulse oximeter alarms were false in nature, which the investigators attributed to sensor displacement, motion artifact, and a decrease in skin perfusion [40]. In this study, the alarm threshold was set at an S_pO_2 of 90% and it is not clear if a minimum duration was specified. A recent study in 647 patients in the recovery room compared the influence of two pulse oximeter lower alarm limit settings (S_pO_2 90% = group 90 and S_pO_2 85% = group 85) on the incidence of hypoxemia [41]. Although the number of audible alarms was lower in group 85, hypoxic episodes (defined as $S_pO_2 \leq 90\%$ lasting > 1 min) were more common in group 90 than in group 85 (11 versus 6%, respectively). The investigators concluded that decreasing the alarm limit to reduce false alarms may lead to increase in more relevant episodes of hypoxemia.

Various methods have been employed to reject motion artifact but have met with little success [8,42,43]. An innovative technological approach, termed Masimo signal extraction technology (SET™; Masimo Corporation, Mission Viejo, California, USA), was recently introduced to extract the true signal from artifact due to noise and low perfusion [44]. This technique incorporates new algorithms for processing the pulse oximeter's red and infrared light signals that enable the noise component, which is common to the two wavelengths, to be measured and sub-

Figure 5

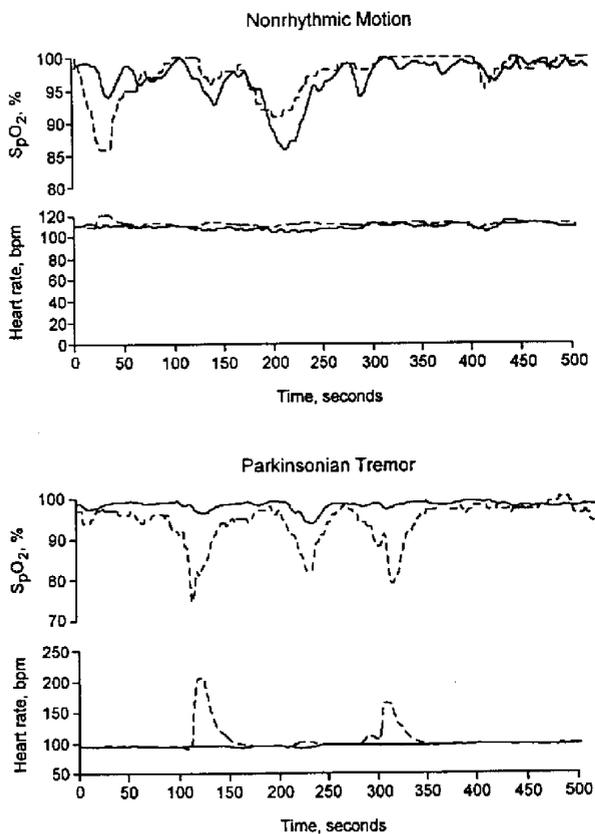


Number of false alarms for devices used to monitor respiratory rate, mean systemic blood pressure from an arterial catheter, heart rate from an electrocardiogram (EKG), heart rate measured by pulse oximetry (P Ox) and O_2 saturation measured by a pulse oximetry (S_pO_2). Forty-five per cent of all false alarms were due to the S_pO_2 signal. Data from [39].

tracted. When tested in healthy volunteers during standardized motion, Masimo SET™ exhibited much lower error rates (defined as percentage of time that the oximeter error exceeded 5%, 7%, and 10%) and dropout rates (defined as the percentage of time that the oximeter provided no S_pO_2 data) than did the Nellcor N-200 and Nellcor N-3000 oximeters (Nellcor Puritan Bennett, Pleasanton, California, USA) for all test conditions [45]. The lowest performance index (defined as the percentage of time that the oximeter's value was within 7% of the control S_pO_2 value) was 97% for Masimo SET™ compared with 47% for the N-3000 and 68% for the N-200. In 50 postoperative patients, Dumas *et al.* [46] observed that a pulse oximeter's alarm frequency was decreased twofold with a Masimo SET™ system versus a conventional oximeter (Nellcor N-200). Improved performance was particularly striking during conditions of gross (non-rhythmic) motion and tremor, when a 22-fold reduction in signal loss over time was observed (Fig. 6).

Inaccurate oximetry readings have been observed in pigmented patients, but not by all investigators [8]. In 33 healthy black subjects during normoxia and hypoxia, the correlation between S_pO_2 and S_aO_2 was inferior with a Biox IIA oximeter (Ohmeda, Boulder, Colorado, USA) ($r=0.80$) than with the older Hewlett-Packard (Waltham, Massachusetts, USA) (non-pulse) oximeter ($r=0.94$) [47]. In critically ill patients [19], bias \pm precision was greater in black patients, $3.3 \pm 2.7\%$, than in white patients, $2.2 \pm 1.8\%$; also,

Figure 6



Artificial pulse oximetry signals during nonrhythmic motion (i.e., gross arm motion; top panel) and during Parkinsonian tremor (lower panel). Solid line denotes Masimo signal extraction technology (SET™), aimed at minimizing spurious pulse oximetry readings due to motion artifact; dashed line denotes conventional pulse oximetry. Spurious changes in S_pO_2 were less with Masimo SET™ than with conventional pulse oximetry. Published with permission [46].

a bias $>4\%$ occurred more frequently in black patients (27%) than in white patients (11%).

Low perfusion states, such as low cardiac output, vasoconstriction and hypothermia, may impair peripheral perfusion and may make it difficult for a sensor to distinguish a true signal from background noise. In cardiac surgery patients experiencing hypothermia and poor perfusion, only two of 20 oximeters (Criticare CSI 503, Criticare Systems, Inc., Milwaukee, Wisconsin, USA; Datex Satlite, Datex Instrumentarium Corp., Helsinki, Finland) provided measurements within $\pm 4\%$ of the CO-oximeter value [48]. Measurements of S_pO_2 with a Biox 3700 oximeter had a bias $>\pm 4\%$ in 37% of patients receiving vasoactive therapy [49].

An under-recognized and worrisome problem with pulse oximetry is that many users have a limited understanding

of how it functions and the implications of its measurements. In a recent survey [50], 30% of physicians and 93% of nurses thought that the oximeter measured P_aO_2 . Some clinicians also have a limited knowledge of the O_2 -dissociation curve, and they do not recognize that S_pO_2 values in the high 80s represent seriously low values of P_aO_2 . In the above survey, some doctors and nurses were not especially worried about patients with S_pO_2 values as low as 80% (equivalent to $P_aO_2 \leq 45$ torr).

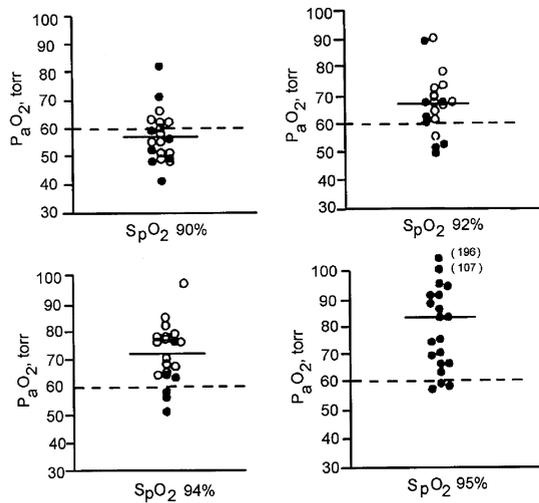
Clinical applications

Cullen *et al.* [51] demonstrated that the introduction of pulse oximetry to areas where anesthesia was administered decreased the overall rate of unanticipated admissions to the ICU. Moller *et al.* [52] conducted the first prospective, randomized study of pulse oximetry on the outcome of anesthesia care in 20802 surgical patients. A 19-fold increase in the detection of hypoxemia (defined as an $S_pO_2 < 90\%$) was noted in the oximeter group than in the control group. Myocardial ischemia was more common in the control group versus the oximetry group (26 and 12 patients, respectively); however, pulse oximetry did not decrease the rate of postoperative complications or mortality. In general care units of a university hospital, Bowton *et al.* [53] reported that 75% of patients had at least one episode of desaturation with $S_pO_2 < 90\%$, and 58% had at least one episode with $S_pO_2 < 85\%$. Despite these events, few nurses, and even fewer physicians, made mention of these hypoxemic episodes in their clinical notes. Moreover, the decrease in S_pO_2 values rarely resulted in a change in respiratory care orders.

Pulse oximetry can assist with titration of F_iO_2 in ventilator-dependent patients, although the appropriate S_pO_2 target depends on a patient's pigmentation [19]. In white patients, an S_pO_2 target value of 92% predicts a satisfactory level of oxygenation whereas, in black patients, this target may result in significant hypoxemia. While a higher target S_pO_2 value (95%) avoids hypoxemia in black patients, some will have P_aO_2 values as high as 198 torr (Fig. 7) and, if receiving a high F_iO_2 to achieve the S_pO_2 target of 95%, O_2 toxicity may result.

The potential usefulness of pulse oximetry as a screening tool that could supplement or supplant respiratory rate as a 'pulmonary vital sign' was investigated [54]. Paired measurements of respiratory rate (counted while auscultating breath sounds for 1 min) and S_pO_2 were obtained in over 12000 adult patients in the triage area of an Emergency Department [54]. The relationship between S_pO_2 and respiratory rate revealed correlation coefficients of 0.378 to -0.454 with a weighted mean of -0.160 , in other words, a weak inverse relationship between S_pO_2 and respiratory rate. Overall, only 33% of patients with an S_pO_2 below 90% exhibited an increase in respiratory rate (defined as any rate in the upper five percentile by age). The study con-

Figure 7



Arterial oxygen tension (P_{aO_2}) values at pulse oximetry O_2 saturation (S_pO_2) value of 90, 92, 94, and 95%. The inspired O_2 concentration (F_iO_2) was adjusted until the desired steady-state S_pO_2 value was achieved. The solid horizontal line represents the mean P_{aO_2} value obtained for each S_pO_2 target. The closed and open circles represent values obtained in black and white patients, respectively. In white patients, an S_pO_2 target of 92% resulted in a satisfactory level of oxygenation, whereas a higher S_pO_2 target, 95%, was required in black patients. Published with permission [19].

firmed previous observations [55,56] that respiratory rate alone is not accurate in detecting hypoxemia.

The usefulness of pulse oximetry as a means of screening for respiratory failure defined as $P_{aO_2} < 60$ mmHg and $P_{aCO_2} > 45$ mmHg in patients with severe asthma was examined [57]. Respiratory failure occurred in six patients out of 82 (7.3%) with an $S_aO_2 > 90\%$ versus only three out of 72 (4.2%) patients with an $S_aO_2 > 92\%$ ($P < 0.005$). The investigators concluded that an $S_pO_2 > 92\%$ suggests that respiratory failure is unlikely and therefore arterial blood gas measurements are unnecessary when evaluating patients with acute severe asthma. Interestingly, this threshold value of 92% is the same target value that predicted reliably a satisfactory level of oxygenation during titration of F_iO_2 in ventilator-dependent patients [19].

Cost-effectiveness

Bierman *et al.* [4] reported that fewer arterial blood gas (ABG) samples were obtained in cardiac surgery patients if S_pO_2 data were available to the caregivers. Interestingly, the availability of oximetry data had no effect on the duration of ICU stay, duration of mechanical ventilation, or the need for supplemental O_2 . In an emergency department, a recent report showed that the number of unjustified ABGs (as determined by independent experts) over a 2-month

period decreased from 29% when pulse oximetry was unavailable to 12% when oximetry was available; the number of justified ABGs did not change [58].

Solsona *et al.* [59] measured the number of blood gas measurements in 417 patients admitted to a medical-surgical ICU during a 12-month period in which only two pulse oximeters were available (i.e., control period). They then studied 306 patients admitted over a 9-month period when 12 pulse oximeters were available for the same number of beds (i.e., intervention period). Less frequent use of mechanical ventilation and a slightly lower number of arterial blood samples were observed when pulse oximetry was fully available. Inman *et al.* [60] examined the effect of implementing pulse oximetry without any specific algorithm for its appropriate use. They studied 148 patients before the implementation of oximetry in their ICU and 141 patients after its implementation. The number of ABG samples decreased from 7.2 to 6.4 per patient per day, a reduction of only 10.3% compared with average reductions of 39% in the previous studies [4,61]. This suggests that, without explicit guidelines, the pulse oximeter was used in addition to, rather than instead of, ABG samples.

Conclusion

Pulse oximetry is probably one of the most important advances in respiratory monitoring. Over the last 15 years, numerous studies have focused on the technical aspects of pulse oximeters and found that these instruments have a reasonable degree of accuracy. This degree of accuracy, coupled with the ease of operation of most instruments, has led to the widespread use of pulse oximetry for monitoring patients in the ICU. Perhaps the major challenge facing pulse oximetry is whether this technology can be incorporated effectively into diagnostic and management algorithms that can improve the efficiency of clinical management in the intensive care unit.

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