REVIEW ARTICLE
Julien F. Biebuyck, M.B., D.Phil., Editor

Anesthesiology
76:1018–1038, 1992

Recent Developments in Pulse Oximetry

John W. Severinghaus, M.D., Joseph F. Kelleher, M.D., M.A.†*

CONTENTS

Pulse oximeters now occupy most critical care arenas and virtually every operating room in the United States. They are manufactured by more than 35 firms, with 1989 annual world wide sales estimated at 65,000 units valued at $200 million.

In January 1989, two comprehensive reviews of pulse oximetry were published. One gave relative emphasis to theory of operation and other technical aspects,[1] while the other focused primarily on clinical issues.[2] Since the reviews of 1989 were completed, more than 500 additional publications have described methods, uses, problems, progress, and effects of pulse oximetry—135 of them in the 6-month period prior to the end date of this review (October 1, 1991). The past 3 yr have seen a variety of other reviews concerning some recent developments[3–12] as well as the history of pulse oximetry.[13,14]

The purpose of this article is to summarize the literature on pulse oximetry that has appeared since the major reviews of early 1989. Expressions such as "before 1988" and "since 1988," unless otherwise indicated, refer herein to the mid-1988 cutoff date for the references appearing in those reviews.

Methodological Developments

There is relatively little to report as to methodological advance in pulse oximetry since 1988. A potential exception is surface reflectance ("surface") oximetry, which has received significant recent experimental attention but does not appear ready for widespread clinical use. In 1988, a review of pulse oximetry[2] could dismiss the topic of reflectance oximetry by observing that it was "one desirable possibility for the future of pulse oximetry . . . in which measurements of reflected light would allow monitoring at nontransilluminable sites, such as the fetal presenting part during labor." With the possible exception of its use in labor, reflectance oximetry is still largely investigational. Some models now couple the oximeter to the ECG (see "Limitations of Pulse Oximetry: Motion

* Department of Anesthesia and Cardiovascular Research Institute, University of California, San Francisco, California.

† Anesthesia Service Medical Group, Inc., San Diego, California.
Received from the Department of Anesthesia and Cardiovascular Research Institute, University of California, San Francisco and the Anesthesia Service Medical Group, Inc., San Diego, California. Accepted for publication January 21, 1992.

This review contains portions of Severinghaus JW: Oximetry: Uses and limitations. ASA Refresher Courses in Anesthesiology 19:139–152, 1991.

Address reprint requests to Dr. Severinghaus: 1386HSE, UCSF, San Francisco, California 94143.

Key words: Blood: oxygen measurement; oxygen saturation. Complications: hypoxia; postoperative hypoxia; respiratory problems. Equipment: optical; oximeters. Monitoring: oximetry.

Artifact"). Probe design has been evolving toward reduced size and greater comfort. Two recent reviews discussed the technology of pulse oximetry,[15,16] although it must be noted that by and large this technology has not changed since 1988.

Equipment is now available to permit central nursing stations to monitor several patients remotely (Novametrix Inc). Pan and James[17] reported trials of a telemetric pulse oximetry network for use in monitoring of patients on a ward (after caesarean section). Their study was concerned primarily with false alarms (see "Limitations of Pulse Oximetry: False Alarms and False Nonalarms").

Uses of Pulse Oximetry

Clinical uses of pulse oximetry may be divided into the oximetric and the plethysmographic.[2] The oximetric applications are largely concerned with detecting and quantitating hypoxemia in various settings, but considerable attention and controversy have surrounded oximetry's use in avoiding neonatal hyperoxia as well.

In 1988, the detection of hypoxemia in perioperative and critical-care settings was an established use for the pulse oximeter; its utility as the sole monitor for neonatal hyperoxia was controversial at best; and a large number of plethysmographic uses had been suggested anecdotally, relatively few of which had been submitted to more rigorous examination.[1,2] All three of these generalizations still hold, despite worthwhile developments in each area.

The time-honored, if not ideally rigorous, technique of "citation analysis" (used memorably in Keats's 1983 Rovenstine Lecture,[18] among other publications) helps to illustrate where current clinical interest in pulse oximetry is directed. It is clear from table 1 that pulse oximetry, having entrenched itself in the bank of operating-room monitors, is now under active scrutiny for the recovery room and for outpatient settings such as the endoscopy suite, the dentist's office, and the sleep laboratory. Table 2 lists recent active topics of investigation into performance or limitations of pulse oximetry, independent of clinical setting.

TABLE 1. Uses of Pulse Oximeters: Topical Analysis by Frequency of Publication from May 1988 to October 1991

Subject	Number of Papers
Endoscopy	26
Postoperative recovery	22
Neonatal intensive care unit	21
Oral surgery and dentistry	14
Airway management	13
Sleep studies	13
Hypotension, poor perfusion	12
Premedication	11
Pediatric anesthesia	10
Transport	10
Emergency	9
Chronic obstructive pulmonary disease, lung disease	8
Adequacy of circulatory tests	8
Anesthesia, adult	8

Topics reported in three to seven papers include croup; infection; fetal monitoring; magnetic resonance imaging; exercise; epidural morphine; altitude studies; mechanical ventilation; caesarean section; intensive care units; hypothermia; embolism; one-lung anesthesia; positioning problems; heart surgery; and anemia. Other uses discussed in one or two papers include home monitoring of sudden infant death syndrome patients; weaning from a ventilator; hypoxemia during labor; seizures; asthma; induction of anesthesia with jet ventilation; obesity and apnea; hemodialysis; pneumothorax; pulmonary edema; aspiration; malignant hyperthermia; efficacy of cardiopulmonary resuscitation; effect of sickle cell disease; application in ear, nose, and throat practice; and home O_2 therapy control.

TABLE 2. Performance and Limitations of Pulse Oximetry: Topical Analysis by Frequency of Publication from May 1988 to October 1991

Subject	Number of Papers
Effects of methemoglobin, carboxyhemoglobin	19
Tests of accuracy	18
Sites for probes	13
Failure with hypoperfusion	12
Standards and legal issues	7
Motion artifact	6
Skin pigments	6
Uses in animals	6
Models for *in vitro* testing	5
Palmar circulation (Allen's test)	5

Other publications described oximetry in burn patients; comparisons with transcutaneous P_{O_2}; use in tissue revascularization and transplantation; effect on use of arterial blood gas analysis; reports of finger burns by probes; blood pressure measurement; and cost–benefit ratio estimations.

The Detection of Hypoxemia

The high prevalence of clinically unsuspected hypoxemia is perhaps the most famous disclosure that pulse oximetry has made. The incidence of hypoxemia was studied intraoperatively in a single-blind study of 296 adult anesthetics by Moller *et al.*[19] In 53%, mild hypoxemia (86–90%) was seen. Severe hypoxemia, with hemoglobin (Hb) oxygen saturation measured by pulse oximetry (Sp_{O_2}) as < 81%, was recorded in 20% of the patients; 70% of these severe episodes were not detected by the anesthetist. McKay and Noble[20] found that 6% of a series of nearly 5,000 anesthetics involved critical incidents, of which 29 involved Sp_{O_2} readings < 75%. Coté *et al.*,[21] in a single-blind study of 402 pediatric cases, separately examined the effect of withholding oximeter and/or capnograph data from the anesthesia team. They identified 59 major

desaturation events (Sp_{O_2} < 85% for > 30 s) in 43 patients and 130 minor desaturations (< 95% for > 60 s). Of the major events, 41 (≃ 70%) were first diagnosed by oximetry, 13 by the anesthesiologist and 5 by the capnograph. Blinding the oximeter data increased the number of patients experiencing major desaturation events from 12 to 31 ($P = 0.003$). Infants ≤ 6 months of age had the highest incidence of major desaturation events. Blinding the capnograph data altered neither the frequency of desaturation events nor the incidence of major capnograph events but did increase the number of patients with minor capnograph events ($P = 0.0026$). The authors concluded: "1) The pulse oximeter is far superior to either the capnograph or clinical judgment in providing the earliest warning of desaturation events. 2) Capnography can provide an early warning to potentially life-threatening problems, but such problems often result in desaturation . . . ."[21]

In a less-controlled study of 91 pediatric anesthesia cases, Schulz *et al.*[22] found hypoxic episodes (Sp_{O_2} < 95%) in 52% and major desaturations (Sp_{O_2} < 85%) in 54% of newborn infants. They reported that "desaturation was more likely to occur in intubated children than in those with a mask ($p < 0.05$)" (reflecting problems with the processes of intubation and extubation).

These last 3 yr have seen the investigative focus turn from the operating room and intensive care unit, where unanticipated hypoxemia is relatively rare, to the postanesthesia recovery period, clearly demonstrating the high incidence of hypoxemia due to the effects of anesthetic, sedative, relaxant, and especially opioid drugs.[23–36] In Copenhagen, a single-blind study[32] of 202 adults in the recovery room following elective operations, found decreases to Sp_{O_2} < 91% in 55% of all patients at some time before discharge, despite administration of nasal oxygen in more than half of these hypoxic episodes, and to Sp_{O_2} < 80% in 13%. Patients who had undergone regional anesthesia had a lower risk of hypoxemia. A randomized study by Lampe *et al.*[31] of 141 patients for carotid endarterectomy or hip replacement noted postoperative Sp_{O_2} < 90% in 63% and <86% in 21%; they monitored that portion of the postoperative period included in "a 24-hour period beginning just after induction of anesthesia." Use of oxygen during the first postoperative night reduced the incidence of hypoxemia from 29% to 0%.

During recovery from anesthesia studied in Sydney, Australia[34] with routine use of nasal oxygen as judged appropriate by nurses, 80% of patients' saturations decreased to < 90% Sp_{O_2} and 26% decreased to < 80% Sp_{O_2} during the first 15 min of recovery. Sixty-four percent decreased to < 90% even while the patients received nasal oxygen. On the other hand, in Boston, Morris *et al.*[23] showed that only 14% of inpatients developed at least transient hypoxemia during recovery, and only 1% of outpatients became hypoxic in the recovery room. The amounts of premedication and injected sedatives and opioids were not significantly different between inpatients and outpatients.

Canet *et al.*[36] not only demonstrated postoperative hypoxemia in 44% of more than 200 patients and showed that 35% oxygen prevented hypoxemia, but also reviewed other evidence that supported the routine administration of oxygen and the concomitant use of pulse oximetry.

The incidence of hypoxemia has been investigated in various outpatient or "office" procedures accompanied by sedation without professional anesthesia assistance. The greatest attention has centered on bronchoscopy and endoscopy. Schnapf[37] demonstrated > 5% desaturation in 80% of 36 children aged 6–142 months during fiberoptic bronchoscopy in a pediatric special care unit or pulmonary laboratory, with higher incidence in the youngest patients.

Pulse oximetry has shown potentially dangerous desaturation to be present in 45% of patients undergoing endoscopy under sedation.[38] A prospective study by Moore *et al.*[39] in surgical intensive care disclosed hypoxic episodes in 21% of patients in the surgical intensive care unit, mostly during mechanical ventilation. In a recent review with 63 references, Bell[40] suggests that during gastrointestinal endoscopy, hypoxic problems are common, with 60% of deaths during endoscopy attributed to cardiopulmonary complications. Al-Hadeedi and Leaper[41] observe that the 1:5,000 mortality during upper gastrointestinal endoscopy—itself "several fold" lower than that for endoscopic retrograde cholangiopancreatography—still "does not compare favorably with the much lower perioperative mortality directly attributed to anesthesia." In 132 patients undergoing endoscopic retrograde cholangiopancreatography under sedation, they found that Sp_{O_2} decreased from 95.7 ± 2.4% (mean ± standard deviation) to 88.9 ± 6.4%. The largest decreases occurred after positioning of the endoscope (rather than after administration of the sedative or completion of the procedure). In 57 patients between the ages of 6 weeks and 36 months undergoing 60 flexible upper intestinal endoscopies with parenteral sedation only, 7 patients showed oxygen desaturation to < 90% after sedation but before insertion of the endoscope without overt clinical evidence of complications.[42] The British Society of Gastroenterology recommended and approved guidelines for use of pulse oximetry as a standard during all procedures and also suggested that oxygen be administered.[43]

Sedation and anesthesia are commonly used without professional anesthesia assistance in oral surgery and dentistry. In view of the potentially high incidence of hypoxia, pulse oximetry has been strongly recommended,[44] although Wilson[45] suggested that 87–90% of desaturation episodes in his study of 22 sedated children were due to motion artifacts.

Marjot and Valentine[46] found an 80% incidence of hypoxemia ("persistent desaturation to S_aO_2 less than 90%") following premedication with lorazepam, morphine, and droperidol for cardiac surgery, accompanied in 33% by ECG changes, previously unsuspected and easily corrected by oxygen administration. Hypoxemia ($Sa_{O_2} < 90\%$) was documented in 10 of 15 women in labor, 7 of whom had received opioids.[47]

Oximetry has also been used to demonstrate that periodic breathing in premature and newborn infants is unrelated to the occurrence of apneic spells.[48] Oximetry may reduce the need for intensive care in low-risk groups. In 30 patients during emergency field rescue operations, Sp_{O_2} was compared with arterial blood oxyhemoglobin (O_2Hb) and found to correlate with $r = 0.898$ and bias ($Sp_{O_2} - O_2Hb$) of -0.3 ± 2.4.[49]

Airway management problems aided by oximetry include evaluation of the performance of experimental rescue devices such as the "glossopalatinal tube,"[50] detection of obstructed[51] or misplaced[52–54] endotracheal tubes, assessment of readiness for removal of tracheostomy,[55] foreign body removal,[56] and effectiveness of use of helium.[57] Oximetry is especially useful in managing one-lung anesthesia.[58]

Use of oximetry and end-tidal P_{CO_2} instead of arterial blood gas in assessing a patient's ability to be separated from mechanical ventilation was studied in 60 patients by Withington *et al.*[59] After assessing noninvasive method reliability in 20 subjects, they demonstrated the success of the method in the next 40. Pulse oximetry has been used in optimizing continuous positive airway pressure and positive end-expiratory pressure[60] and, for quantitative purposes, pulse oximetry has been a documented help in a variety of procedures, such as determination of the needed oxygen flow rate or concentration in ventilator-dependent patients.[61]

When epidural morphine came into general use for pain relief, there was concern about possible unobserved apnea on wards. Choi *et al.*[62] demonstrated in 20 post–caesarean section women that half of the patients experience desaturation to < 85% over the 15-h monitoring period, whether they were given morphine parenterally or epidurally, but the desaturation occurred within 3 h with parenteral morphine and at 13.7 ± 5.9 h with epidural morphine.

In a study in general hospital (non–critical-care) units, Bowton *et al.*[63] found that 75% of patients monitored for 36 h had at least one episode of desaturation to < 90% and 58% had at least one episode of desaturation to < 85%. Few of these episodes were documented, and even the availability of monitoring had little effect on care.

The use of oximetry in emergency care situations was reviewed.[64] Patients transported by ambulance, helicopter, and aircraft are increasingly monitored by pulse oximetry because the vibration makes most other methods of ventilatory and circulatory monitoring ineffective.[65] Short *et al.* compared seven oximeters during helicopter transport, and reported three to be subject to vibration interference or otherwise unacceptable.[66]

Pulse oximetry is used (in connection with periodic arterial blood gas determination) to help adjust the flow rates and periods of use of home oxygen therapy of patients with chronic obstructive pulmonary disease, *e.g.* in response to increased needs with exercise and rapid–eye-movement sleep. A review of this field by Tiep (110 references) suggests that the involvement of physician and oxygen supplier may have increased in the effort to tailor oxygen supply to demand and to reduce possible excessive oxygenation (and respiratory depression).[67]

In summary, pulse oximetry is now well-established—both inside and outside the operating room and intensive care unit— as a useful and sensitive detector of hypoxemia. Its acceptance as a supplement to clinical detection for hypoxia is clearly apparent. Equally apparent, however, is the role of motion artifact in limiting its specificity, especially in certain populations (see "Limitations of Pulse Oximetry: Motion Artifact"). Furthermore, outcome studies are generally lacking for the above-mentioned applications, leaving open the question of whether pulse oximetry reduces morbidity and mortality (see "Does Pulse Oximetry Increase Patient Safety?").

Monitoring Circulation

The pulse oximeter's plethysmographic capability has been proposed as a monitor of circulatory adequacy. By 1988, a number of anecdotal applications of this type had been reported.[2] This list is now longer (below), but an earlier caution[2] still holds true: the pulsatile perfusion required to generate a pulse signal on a given pulse oximeter in not *a priori* either necessary or sufficient to guarantee adequacy of circulation for a given application. Machine characteristics, intersubject variability, and intrasubject variability all are involved. Only controlled studies can resolve these issues; by and large, these have not been done for plethysmographic applications of the pulse oximeter.

The best-studied use of this type is Allen's test. In 1988 there was no consensus among those who had investigated pulse oximeter plethysmography as a measure of palmar collateral circulation.[2] Several others have now tried and recommended it without controlled testing.[68,69] Levinsohn *et al.*,[70] taking digital cuff sphygmomanometry as the "gold standard," showed laser Doppler to be equally accurate and easier to use, and found the classic ("subjective") Allen's test to be sensitive but not very specific ("a good screening test"). But they found pulse oximetry to indicate false adequacy of collateral circulation in two of three hands with abnormal digital systolic pressure.

In contrast, Pillow and Herrick[71] found that laser Doppler agreed with pulse oximetry in 109 of 109 patients with respect to both ulnar collateral flow (100 sufficient, 9 insufficient) and radial collateral flow (108 sufficient, 1 insufficient). They were unable to account for the contrary results of Glavin and Jones,[72] who rejected pulse oximetry for this test 2 yr earlier, in 1989, except to speculate that the thumb may be a more sensitive site than the index finger for monitoring ulnar collateral flow. Despite the further study, this issue appears no more settled than it was three yr ago.

Systolic blood pressure may be accurately determined by reappearance of the pulsatile waveform during cuff deflation in instruments that display the waveform (tested with Ohmeda 3700)[73,74] or, perhaps more accurately, by waveform disappearance during slow cuff inflation.[75–77] Comparison of pulse amplitudes on the finger and the toe demonstrated toe vasodilation due to sympathetic blockade with spinal anesthesia.[78] The waveform response to a Valsalva maneuver can detect patients with autonomic dysfunction or blockade.[79]

Other new reported uses include determining ductus arteriosus patency,[80] assessing the level of ischemia in peripheral vascular disease (in which it is claimed to be more sensitive than either transcutaneous P_{O_2} [tcP_{O_2}] or Doppler flowmetry[81]), assuring patency of major arterial grafts,[82] testing viability of the bowel,[83,84] indicating artery compression in shoulder arthroscopy[85] or fracture manipulation,[86] determining limb vascularity,[87] assessing circulatory adequacy of the arm when an unconscious patient is placed in the lateral or prone position or with arms elevated or hyperabducted for surgery,[88] and monitoring circulation of reimplanted digits or grafts.[89] In general, these are anecdotal uses, not verified by controlled studies.

Role in Preventing Retinopathy of Prematurity

In premature infants, the administration of supplemental oxygen is associated with retinopathy of prematurity (ROP).[90,91] The duration, concentration, and pattern of oxygen toxicity all are implicated—as are gestational age, hypercapnia (possibly *via* a vasodilatory increase in oxygen delivery to the retinal vasculature[92]), the state of the ductus arteriosus (open[93] or closed[94]), light,[95] and literally dozens of other factors, which may or may not be confounding.[91] Indeed, premature infants can develop ROP despite persistent hypoxemia.[96]

Empirical recommendations for arterial oxygen saturation (Sa_{O_2}) in infants at risk for ROP generally fall into the 90%–95% range.[2,97] The pulse oximeter has obvious application here, but its main use is in preventing hypoxemia, not hyperoxia. It is generally agreed that pulse oximetry is not adequate for evaluating hyperoxia in this setting—not only because its inherent inaccuracy of 2–3% looms so large in the region of the Hb–oxygen dissociation curve above Sa_{O_2} 90%, but also, and more fundamentally, because there is no consensus on an acceptable safe upper limit for Sa_{O_2}.

A recent "consensus report" on neonatal pulse oximetry,[98] definitive enough in its other recommendations, was able to recommend "further research" only after "long and complex" discussion of a safe upper limit. The current uncertainty about this issue is illustrated by the various definitions of hyperoxia used in recent investigations into neonatal pulse oximetry; they include $P_{O_2} > 80$ mmHg,[99] $P_{O_2} > 90$ mmHg,[100] and $P_{O_2} > 100$ mmHg.[98]

Hay *et al.*[101] noted that when an Ohmeda 3800 displayed $Sp_{O_2} = 92 \pm 3\%$ in neonates, the Pa_{O_2} was between 40 and 100 mmHg 100% of the time—but they added that, while keeping $Sp_{O_2} = 92 \pm 3\%$ "seems prudent and safe, . . . this conclusion is arbitrary and not tested."

Bucher *et al.*[100] recently concluded that the Nellcor N-100 and the Ohmeda Biox 3700 are highly (95%) sensitive for hyperoxic episodes ($P_{O_2} > 90$ mmHg) but have only mediocre specificity (38% and 52%, respectively); this 95% sensitivity was achieved by choosing an Sp_{O_2} upper limit of 96% for the Nellcor N-100 but of only 89% for the Ohmeda Biox 3700. Findings like these suggest that caution is required in interpreting blanket recommendations on safe upper limits, such as Hay's "consensus" of Sp_{O_2} 94–95%,[98] that do not make reference to a specific pulse oximeter brand and model.

On the other hand, Reynolds and Yu,[99] also using the Ohmeda Biox 3700 and studying 175 readings in 12 neonates with pulmonary compromise, recommended an Sp_{O_2} upper limit of 90% to avoid $P_{O_2} > 80$ mmHg. If nothing else, the incongruity between this result and that of Bucher *et al.*[100] underscores that the prevention of ROP may involve more than just control of Sa_{O_2} or Pa_{O_2}. Indeed, the recent slowdown in published investigations into a safe upper limit of Sa_{O_2} for neonates—in contrast to a veritable spate of such studies *circa* 1987—may signal a conceptual retrenching as the multifactorial nature of ROP is acknowledged in practice.

What is certain is that pulse oximetry cannot currently be recommended as the sole monitor of oxygenation for the neonate at risk for ROP. The prevention of ROP is probably best accomplished by either intermittent arterial blood gas analysis or continuous tcP_{O_2} monitoring, with pulse oximetry as a supplementary modality.

As Sa_{O_2} decreases, because of the steepening dissociation curve, oximetry becomes progressively more dependable than tcP_{O_2} measurement in assessing, controlling, and maintaining some defined level of oxygenation. In an infant with mostly fetal Hb, a 5-mmHg change in P_{O_2} at 70 mmHg ($\simeq$ 97% Sa_{O_2}) is equivalent to only about

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS
Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS
Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS
Sync your system to PACER to automate legal marketing.