

Respiratory monitoring during pediatric sedation: pulse oximetry and capnography

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Abstract

A major concern in pediatric dentistry is maximizing risk management through optimal monitoring of respiratory function during sedation techniques. This article examines the problems inherent in respiratory monitoring in sedated pediatric dental patients, the traditional methods of respiratory monitoring, and new technologies which are useful in optimizing respiratory monitoring. The authors discuss transcutaneous oximetry and pulse oximetry as possible monitors of oxygenation, and capnography as a possible monitor for apnea, airway obstruction, and developing hypoventilation.

Risk management involves striving for maximum patient safety and should be a primary concern to all dentists and physicians practicing conscious or deep sedation. A major component of risk management for sedation or anesthesia involves physiologic monitoring. Monitoring may be defined as continuous observation of data from specific organ systems to evaluate the status of physiologic function. The purpose of monitoring is to permit prompt recognition of any deviation from normal, so corrective therapy can be instituted before morbidity ensues. Ideal monitors should be continuous or "real time", rapidly responsive, noninvasive, accurate, dependable, convenient, and affordable. The principal systems monitored during pediatric sedation are the central nervous, cardiovascular, and respiratory systems.

This discussion reviews monitoring of the respiratory system. There is compelling evidence that this is the most important system to monitor for pediatric patients. Furthermore, major scientific advances are being made in this area which should be understood by all who use sedation and/or anesthesia, especially those who treat pediatric patients.

Routine Respiratory Monitoring: The Problem

What should constitute routine respiratory monitoring for all pediatric patients undergoing conscious or deep sedation long has been a topic of debate. In 1985 the American Academy of Pediatrics and the American Academy of Pediatric Dentistry jointly adopted the *Guidelines for the Elective Use of Conscious Sedation, Deep Sedation, and General Anesthesia in Pediatric Patients* (1985). These guidelines require the use of a precordial stethoscope, visual assessment of the child's color, continuous monitoring of heart and respiratory rate, and the frequent assessment of head position to ensure a patent airway. Visual assessment of chest and abdominal movement to monitor for effective respiratory excursions is implied in the guidelines. These standard methods should be used routinely to assess the rate, depth, and adequacy of respiration.

While these time-tested methods are essential, each has serious practical limitations. Visual assessment of patients' respiratory excursions, color, and general appearance requires close and continuous attention. For pediatric dental sedation, the sedationist is usually also the operator. Airway assessment is very difficult because attention must be given to performance of detailed and sophisticated dental procedures. Even with constant attention, shallow respirations of a sedated child can be difficult to assess because of clothing, drapes, and restraining devices. Breath sounds may be difficult to hear with the precordial stethoscope, especially with the noise of the dental equipment. One is often left to assess respiratory function by the patient's color and vital signs. In children this is a physiologically dangerous method for respiratory monitoring, because these changes do not occur until late in the process of

respiratory compromise when it may be too late to prevent an emergency situation leading to morbidity.

Hypoxemia

Hypoxemia has been shown to be the leading cause of morbidity and mortality during anesthesia (Bendixen and Laver 1965). Hypoxemia is defined as a low partial pressure of oxygen in the blood and may be caused by such conditions as a failure of oxygen supply, pulmonary disease, cardiovascular collapse, hypoventilation, apnea (cessation of breathing), or airway obstruction. Hypoxemia develops readily during deep sedation techniques used for dentistry in young adults (Dionne et al. 1981). It also has been shown to be the leading cause of death in two studies that focused specifically on dental sedation and anesthesia in adults (Tomlin 1974; Al-Kishali et al. 1978).

Evidence is overwhelming that hypoxemia is also the major complication in the sedation of pediatric dental patients. Goodson and Moore (1983) reported several cases of life-threatening reactions after sedation for pediatric dental procedures. Although morbidity and mortality were induced by drug overdosage, close scrutiny of the cases reveals that the common factor that led to death or severe morbidity was respiratory failure leading to hypoxemia.

The development of hypoxemia in pediatric dental patients is almost certainly more subtle and insidious than most practitioners realize. Moore et al. (1984) reported that 25% of children sedated with 60 mg/kg chloral hydrate and 50% nitrous oxide/oxygen could not maintain a patent airway. Houpt et al. (1985) reported partial airway obstruction and transitory reductions in respiration in a study that compared several sedation regimens, including one with as little as 50 mg/kg chloral hydrate and 50% nitrous oxide/oxygen.

Recently, Mueller et al. (1985) evaluated oxygenation in sedated pediatric dental patients. Oxyhemoglobin saturations below physiologically acceptable levels were reported for a high percentage of children sedated with alphaprodine or with chloral hydrate plus 50% nitrous oxide/oxygen. This finding was significant because it demonstrated positively that children become hypoxemic even when supplemented with an enriched oxygen mixture. Furthermore, despite episodes of hypoxemia, there were no detectable changes in vital signs or mucosal color (Mueller et al. 1985). This finding is not surprising because the signs and symptoms of hypoxemia often do not become evident clinically until very low and dangerous levels of oxygen tension develop (Manninen and Knill 1979). Expert observers are unable to recognize hypoxemia consistently until the arterial oxygen tension (PaO₂) falls below 40 mm Hg (Comroe and Bethelmo 1947). The normal value for PaO₂ when breathing room air is 90-100 mm Hg.

In summary, hypoxemia is a serious problem in the sedation of pediatric dental patients and none of the time-honored methods of monitoring these patients is reliable as a warning of hypoxemia. We conclude that there is a critical need for more precise monitoring of the respiratory system during pediatric sedation. Specifically, monitoring should detect respiratory depression early, to prevent hypoxemia from occurring, rather than detecting physiologic changes that occur as a result of hypoxemia.

Respiratory Monitoring: The Questions

There are two principal questions to be answered by respiratory monitoring: (1) Is the patient breathing? (i.e., Is apnea or airway obstruction present?); and (2) Is ventilatory exchange adequate? (i.e., Are oxygen and carbon dioxide being exchanged adequately?). For continuous intraoperative monitoring during sedation, these two questions should be addressed separately.

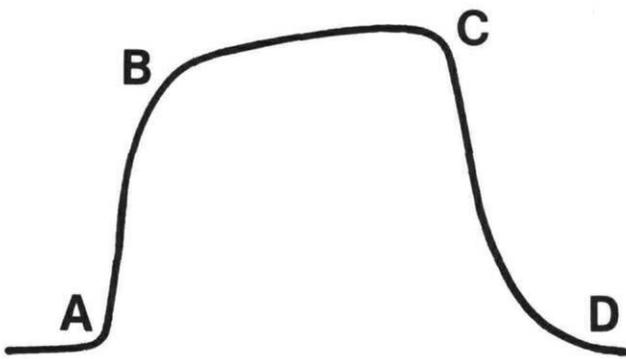
Monitoring Apnea or Airway Obstruction

Several monitoring devices have been suggested to assess whether or not the patient is breathing (exchanging air). These include capnography, rib cage/abdominal wall plethysmography, and nasal thermisters. Each will detect the presence or absence of normal air exchange more precisely than observation or auscultation alone. In studies on the detection of sleep apnea, Keener and Phillips (1985) found the use of capnography to be more reliable than the nasal thermister. Rib cage/abdominal respiratory inductive plethysmography measures a difference in electrical impedance between surface electrodes placed on the chest or abdominal wall during respiratory movements, generating a respiratory waveform. Because chest and abdominal wall movements continue and often become exaggerated during airway obstruction, this technique will not detect early obstruction reliably (Peabody et al. 1979).

The most promising technology for detection of these respiratory problems appears to be capnography which is the continuous analysis of the carbon dioxide content of respired gases. Capnography recently has risen to the forefront as a means of detecting apnea and airway obstruction. The simplest capnographs merely detect the presence of carbon dioxide as CO₂ is exhaled and therefore will indicate whether or not the patient is breathing. This type of unit is the least expensive, but provides the least information. The more commonly used capnographs are more sophisticated in that the carbon dioxide detected is also quantified. This proves to be a valuable source of additional data regarding ventilatory adequacy.

In capnography gas is suctioned continuously from the airway for analysis. A waveform (Fig 1 — next page) is produced that may be analyzed to detect the presence

NORMAL CAPNOGRAM



A: Exhalation begins

B-C: Plateau = outflow of alveolar gas

C: End-Tidal CO₂

FIG 1. Capnography produces a waveform by the continuous analysis of respired gas for CO₂. The presence of the waveform implies exhalation of gases from the lungs. The end-tidal CO₂ (point C) corresponds to alveolar gas which may correlate closely with the PaCO₂.

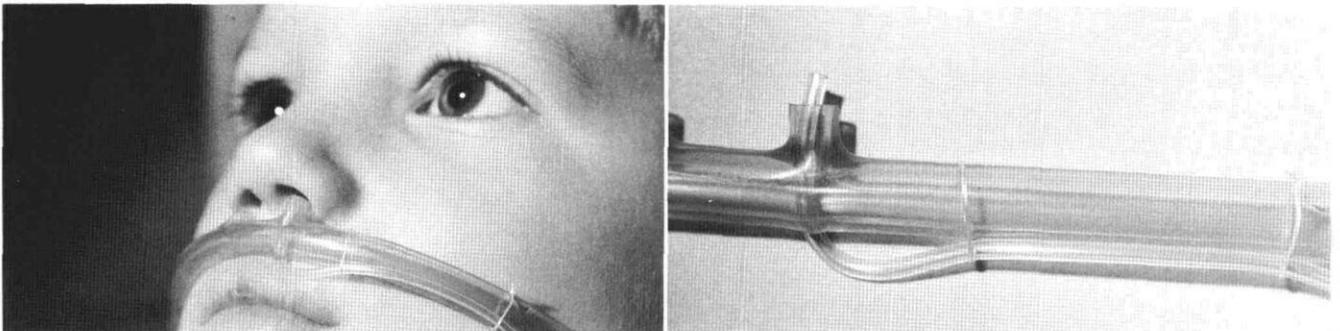
or absence of ventilation (i.e., apnea or airway obstruction) and the depth of respiration (hypo- or hyperventilation) by analysis of the end-tidal CO₂ (PetCO₂) which is the concentration of CO₂ measured at the terminal portion of the exhalation curve. It is displayed continuously by most capnographs. It represents gas coming from the alveoli and has been shown to correlate closely with the PaCO₂ (partial pressure of CO₂ in arterial blood) in intubated patients (Burton 1966). Gases may be sampled at the endotracheal tube connector in intubated patients or at the nares in nonintubated patients.

Anderson et al. (1987) evaluated capnography as a respiratory monitor during outpatient general anesthesia for oral surgery. In these nonintubated patients, respired gases were sampled via a modified nasal oxygen cannula placed at the nares. The plastic sampling

tube was inserted through a small needle puncture in the nasal cannula and threaded up the nasal prong so that the sampling tube lay just inside the nostril when the cannula was in place (Figs 2a, b—below). This study revealed that the capnograph provided a consistent waveform, representing the breath-to-breath ventilatory pattern. When apnea or airway obstruction occurred, the PetCO₂ dropped immediately to zero, allowing for immediate detection of these entities. Additionally, arterial blood samples were obtained for comparison of PaCO₂ with simultaneously recorded PetCO₂ values. The absolute value of the PetCO₂, measured via nasal prongs, was not reliable for reflecting the exact PaCO₂ at any given moment in all patients. The PetCO₂ values did provide a good "trend" indicator for the detection of developing hypoventilation as they rose. The accuracy of this monitor in predicting PaCO₂ in nonintubated, spontaneously breathing patients requires further study.

In summary, capnography provides two valuable parameters for continuous respiratory monitoring: (1) The continuously displayed CO₂ concentration provides a breath-to-breath representation of the presence or absence of air flow (i.e., functional respirations), and thus serves as an effective monitor for apnea and airway obstruction; and (2) the PetCO₂ value serves as a trend indicator of the depth or adequacy of respiration. It is important to note that these changes may be detected by capnography long before detectable changes in oxygenation, especially during oxygen supplementation.

A nasal nitrous oxide hood can be placed directly over the sampling tube-nasal prong assembly for use during the administration of nitrous oxide conscious sedation. Because CO₂ sampling occurs during exhalation, the flow of nitrous oxide and oxygen will not prevent CO₂ sampling. Several companies are introducing devices designed for sampling in nonintubated patients. Finally, capnography has been used with success in pediatric patients for the assessment of airflow in sleep studies to detect sleep apnea (Keener and Phillips 1985). Further study is needed to determine the usefulness of capnography for respiratory monitoring during



FIGS 2a and b. Respired gases are sampled for capnography by inserting the sampling tube through a nasal oxygen cannula and placed at the patient's nares.

pediatric sedation for dentistry.

Monitoring Adequacy of Ventilatory Exchange

The second basic question posed in respiratory monitoring involves the assessment of the adequacy of the ventilatory exchange that is occurring. Adequate alveolar ventilation is evaluated most precisely via arterial blood gas analysis. Blood gas analysis, though very accurate, is not practical for continuous respiratory monitoring because it is invasive, inconvenient, and expensive. It is also retrospective, i.e., the values obtained from the laboratory represent the state of arterial blood several minutes earlier.

Advances in noninvasive, continuous monitoring of the respiratory system have occurred in recent years. Hypoxemia is the leading cause of mortality and morbidity during dental sedation and anesthesia, and its signs and symptoms do not occur until late. Thus, a sensitive, continuous method of monitoring oxygenation is desirable. This parameter represents the "bottom line" in respiratory monitoring. Several monitors have been introduced for this purpose, including the transcutaneous oxygen monitor, ear oximeter, and pulse oximeter.

Transcutaneous Oxygen Monitor

The transcutaneous oxygen monitor can monitor PaO_2 continuously and noninvasively over the entire physiologic range of oxygenation. The instrument utilizes a heated polarographic electrode that is sealed to the patient's skin. The heat causes vasodilatation of cutaneous capillaries, producing a state of arterialization of blood flow. This causes the oxygen tension of the blood at the skin to increase to levels similar to arterial PaO_2 . Oxygen from the blood diffuses through the skin and reacts with the electrode, which measures the PO_2 .

The transcutaneous oxygen monitor has several clinical disadvantages. It is expensive and requires extensive calibration and a lengthy warm-up period. Also, arterialization of the skin may cause burns. Beech and Lytle (1982) evaluated the monitor during dental anesthesia and concluded that it was useful and accurate, though accuracy was determined by only 11 random blood samples.

Cassidy et al. (1986) used transcutaneous oxygen monitoring in children to assess the respiratory effects of nitrous oxide sedation. They reported that it seemed to offer a reliable modality of early detection of ventilation-related complications. They noted rapid responses in transcutaneous oxygen tension (PtcO_2) following changes in delivered oxygen concentration, but did not verify accuracy. They noted that stabilization of the electrode required 8-15 min following placement.

Knill et al. (1982) assessed the transcutaneous oxygen monitor during anesthesia and reported that stable

PtcO_2 values varied considerably. Trend detection was inconsistent and response time was extremely variable and slow, occasionally taking as long as 15 min to stabilize following changes in inspired oxygen concentration. They concluded that the transcutaneous oxygen monitor was an inadequate monitor of arterial oxygenation during anesthesia.

Anderson et al. (1987) evaluated the transcutaneous oxygen monitor during ultralight general anesthesia for dentistry. Although a high correlation was demonstrated between PaO_2 and PtcO_2 overall, a considerable lag time was demonstrated between changes in PaO_2 and accurate changes in PtcO_2 during any period when PaO_2 was changing rapidly. This same phenomenon was demonstrated by Kafer et al. (1981).

Accurate monitoring of respiratory status is critical during periods of apnea, airway obstruction, and severe respiratory depression. For this reason the transcutaneous oxygen monitor does not appear to be optimal for use during dental sedation. Still, the ability to monitor the PaO_2 remains an attractive concept and technological changes could make transcutaneous oxygen monitoring a better option in the future.

Pulse Oximetry

The most recent and promising development for respiratory monitoring is the pulse oximeter. It functions by placing a pulsating vascular bed between a 2-wavelength red and infrared light source and a photodiode detector (Fig 3). Light absorption varies with arterial pulsation, the wavelength of light used, and the oxyhemoglobin saturation. Using spectrophotometric analysis, the oximeter determines the ratio of oxygenated (red) hemoglobin to deoxygenated (blue) hemoglobin and displays oxyhemoglobin saturation (SaO_2). Artifacts that otherwise would be caused by tissue and venous blood are eliminated.

Pulse oximetry has been shown to be accurate during steady state conditions in young healthy volunteers (Yelderman and New 1983), intensive care patients (Kim 1984), and during general anesthesia (Brodsky et al. 1985). The usefulness of pulse oximetry has been reported for dental extractions under general anesthesia (Beeby and Thurlow 1986) and for pediatric dental sedation (Mueller et al. 1985; Moody et al. 1986). These studies suggest that the pulse oximeter is a useful monitor and that it is more sensitive for detecting hypoxemia than visual assessment and vital sign changes.

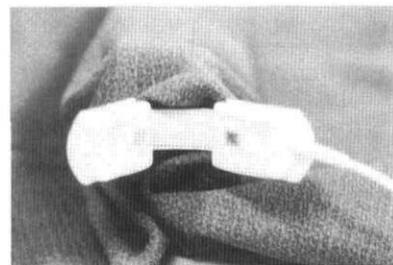


FIG 3. Pulse oximeter probe with light source and photodiode detector.

Accuracy was not assessed in these studies.

Anderson et al. (1988) evaluated the accuracy of pulse oximetry during ultralight general anesthesia for young, healthy adults undergoing third molar extractions. Patients were not intubated and presented a unique monitoring challenge because periods of hyper- and hypoventilation occurred commonly as boluses of intravenous anesthetic agents were given. Apnea, airway obstruction, and laryngospasm may easily occur during ultralight general anesthesia, and patients often move, vocalize, and shiver. Oxyhemoglobin saturations obtained using 4 brands of pulse oximeters were compared with arterial saturations measured in vitro from 122 arterial blood samples to determine accuracy. Despite the rigorous conditions imposed by this technique, 3 of 4 pulse oximeters were accurate in predicting arterial hemoglobin saturation over the range evaluated (70-100%).

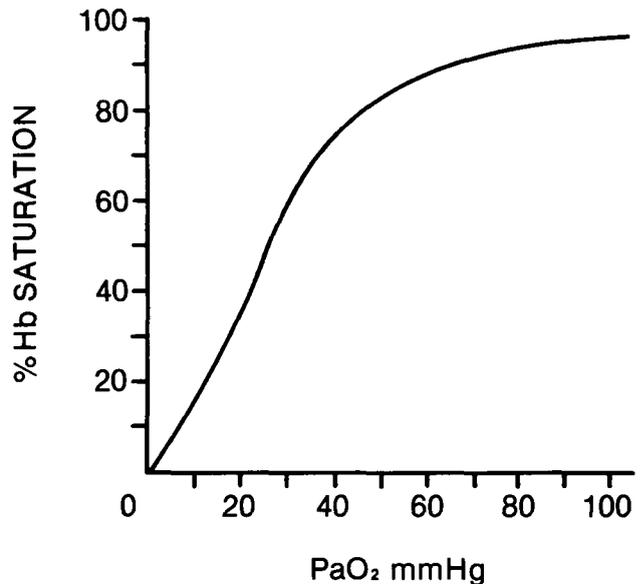
The fourth pulse oximeter tended to significantly underestimate SaO₂. Kagle et al. (1987) reported the same degree of inaccuracy in an evaluation of this oximeter. As a result, the software of the oximeter was modified by the manufacturer, resulting in a significant improvement in accuracy.

In summary, the pulse oximeter is very accurate and rapidly responsive. It is extremely convenient because it requires no calibration, warm-up time, or tissue preparation. Multiple probes are available for different sites such as the ear, finger, toe, and nose.

Pulse oximetry does have potential shortcomings. Any reduction in vascular pulsations in the area being monitored by the oximeter probe will decrease the instrument's ability to function. Such conditions could result from hypothermia, hypotension, vasoconstrictors, or direct vascular compression. Also, the oximeter may misinterpret movement of the probe as a pulse, producing motion artifact. Motion artifact may be a problem in uncooperative pediatric patients who are moving or struggling, or with involuntary motion such as shivering. Beeby and Thurlow (1986) reported that pulse oximetry was not useful in 4 of their 30 patients undergoing dental treatment due to motion artifact. Currently, attempts are being made to eliminate this problem by incorporating ECG analysis in the oximeter to determine the time interval during which the oximeter should detect arterial pulsations. This technology may eliminate much of the motion artifact problem in pediatric dental patients in the future.

The primary disadvantage of pulse oximetry is that it measures oxyhemoglobin saturation rather than PaO₂. Oxygen is carried in the blood in 2 forms, that dissolved in the plasma and that bound to hemoglobin. The portion dissolved in the plasma is reflected by the PaO₂ value and represents only a small fraction of the total oxygen content. The majority of oxygen is carried

in combination with hemoglobin and is reflected as hemoglobin saturation (SaO₂). Each hemoglobin molecule is capable of carrying 4 oxygen molecules. The combination of oxygen and hemoglobin results in a change in the shape of the hemoglobin molecule and thus a change in its affinity for oxygen. Because of these changes, the PaO₂ and the SaO₂ are not linearly related, but rather are related by the oxyhemoglobin dissociation curve (Fig. 4).



OXY-HEMOGLOBIN DISSOCIATION CURVE

FIG 4. The oxyhemoglobin dissociation curve reveals the nonlinear relationship between PaO₂ (partial pressure of oxygen in blood) and oxyhemoglobin saturation (SaO₂).

The "S" shape of the oxyhemoglobin dissociation curve is important for physiologic uptake and delivery of oxygen in the body. In the lungs, hemoglobin is rapidly and almost totally saturated over a wide range of PaO₂ (flat portion of the curve), while at the tissues a large amount of oxygen is unloaded as desaturation occurs over a relatively small drop in PaO₂ on the steep portion of the curve. An understanding of the relationship between PaO₂ and the SaO₂ is essential for those using pulse oximetry clinically. Pulse oximetry is limited in that changes in oxygenation are not detected until the PaO₂ falls to the point where oxyhemoglobin desaturation occurs, that is, the 70-80 mm Hg range, where the steep portion of the oxyhemoglobin dissociation curve is rapidly approached. When one is breathing room air, the normal PaO₂ is in the 90-100 mm Hg range, which corresponds to an SaO₂ of 96-100%. Because a PaO₂ of 60 mm Hg corresponds to an SaO₂ of approximately 90%, the PaO₂ must fall from approximately 100

mm Hg to 60 mm Hg for the saturation to fall from 96 to 90% (Table 1).

Often patients undergoing dental sedation or general anesthesia are receiving supplemental oxygen (with or without nitrous oxide), thus the PaO₂ may range from 150 to above 600 mm Hg. The PaO₂ must fall drastically before any change will be detected in the SaO₂. Barker et al. (1986) graphically demonstrated that large decreases in oxygenation may occur without any change being detected by pulse oximetry. The PaO₂ fell to less than 70 mm Hg before significant desaturation occurred in pulse oximetry. The pulse oximeter will not warn of downward trends in PaO₂ over the wide range of oxygen tensions above this level (Fig 5). In brief, when oxyhemoglobin desaturation begins to occur, serious

TABLE 1. Relationship Between PaO₂ and SaO₂*

PaO ₂ (mm Hg)	SaO ₂ (%)
500	100
400	100
300	100
200	100
150	100
120	100
100	99
95	98
90	97
80	96
70	94
65	93
60	91
55	89
50	85
45	80
40	75
35	65

* At pH 7.40, temperature 37°C, PCO₂ 40.

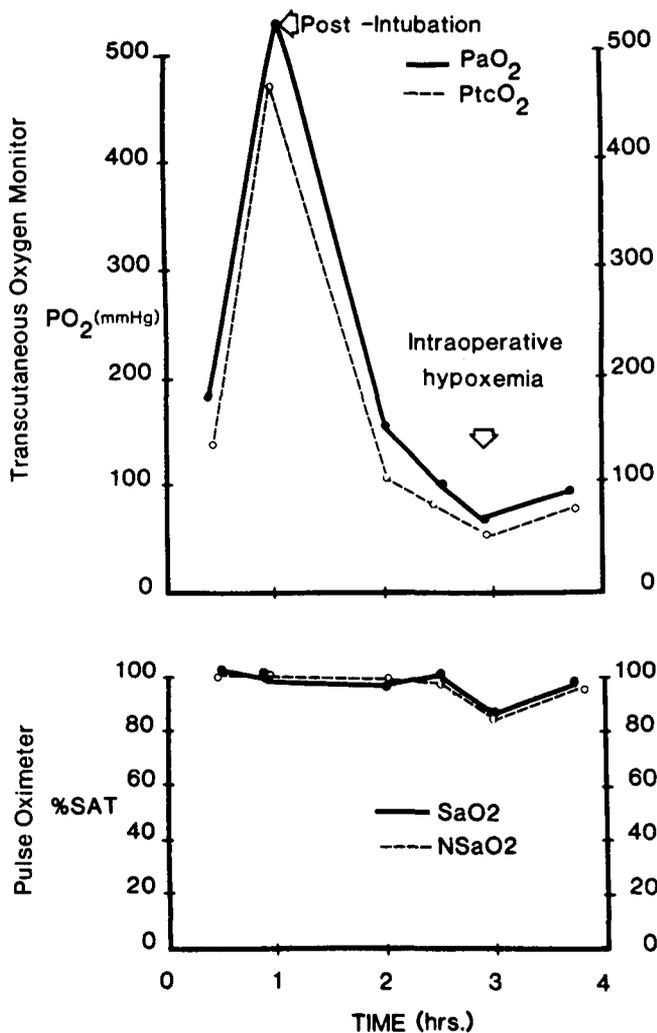


FIG 5. These data are from a 28-year-old female undergoing a general anesthetic. Note the wide range of transcutaneous oxygen tension (PtcO₂) and PaO₂ values. Although the PtcO₂ and PaO₂ decreased markedly, from 460 to 86 mm Hg, the SaO₂ showed no significant change. Only when the PtcO₂ decreased further to 47 mm Hg did the SaO₂ fall to 84%, a significant change.

respiratory depression may be present. Furthermore, more rapid desaturation may be imminent as the steep portion of the curve is approached. Therefore, during pediatric sedation, even a small change in saturation (e.g., 99 to 96%) must be noted quickly and evaluated before further desaturation occurs.

In summary, those using pulse oximetry must realize that though the SaO₂ scale ranges from zero to 100, even a small decrease in saturation requires close attention and prompt treatment. This is critical in children because their high basal oxygen consumption and smaller size produces less oxygen reserve. This results in more rapid and profound desaturations than in young, healthy adults.

Because the danger zone for severe hypoxemia is below 90%, it may be argued that the pulse oximeter will detect hypoxemia prior to any evidence of signs and symptoms. Thus, the pulse oximeter is a valuable monitor, especially considering its other advantages. Despite the initially high cost, the pulse oximeter is rapidly becoming a routine respiratory monitor during anesthesia. The cost is currently falling as more companies introduce pulse oximeters. Four pulse oximeters presently available on the market are illustrated in Figure 6 (next page).

Summary

Accurate, continuous and noninvasive respiratory monitoring represents a critical need when pediatric sedation is performed. In adult dental patients, the combination of pulse oximetry and capnography appears to be the most ideal monitoring system available for the respiratory system during sedation or general anesthesia. These monitors, combined with a precordial stethoscope and observation, serve to answer the two primary questions of "Is the patient breathing?" and "Is gas exchange adequate?"



FIG 6. Four available pulse oximeters.

Risk management in the sedation of pediatric dental patients is of primary importance if dentists are to retain the privilege of using sedation techniques. Strong consideration should be given to the routine use of the pulse oximeter during pediatric sedation. Further evaluation is necessary to determine whether capnography also will prove to be a respiratory monitor that is useful in the quest to assure safety for sedated child patients.

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Public: dentists are honest and ethical

When asked to rate the honesty and ethical standards of various professions, dentists ranked second only to pharmacists.

The July SRI Gallup poll showed that dentistry had grown in the public's esteem since the poll was last taken in 1983. Then, dentists ranked fourth — behind clergymen, pharmacists, and physicians. Doug Harris, the American Dental Association's director of marketing services, said, "It's the esteem in which dentistry is held by the public that is the profession's best marketing tool. And, it's important to the marketing of any practice that dentists fulfill the image that the public has of them."

Of the 734 respondents to the 1987 poll, 64% rated the ethical standards of dentists either "very high" or "high." This was an increase of 13% over the 1983 poll, when only 51% of the respondents rated dentists in these categories.