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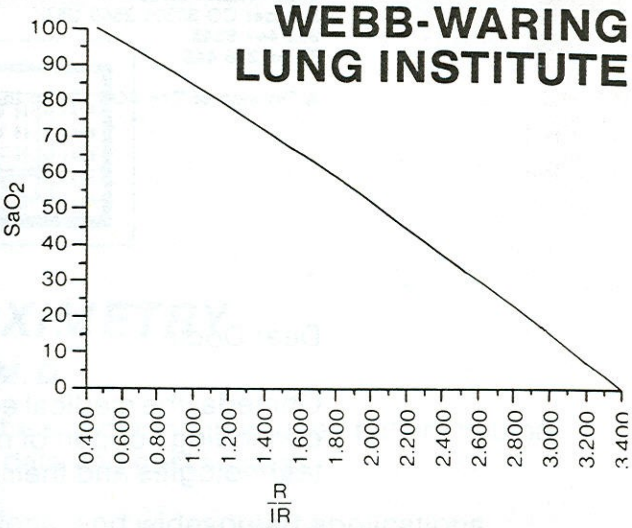
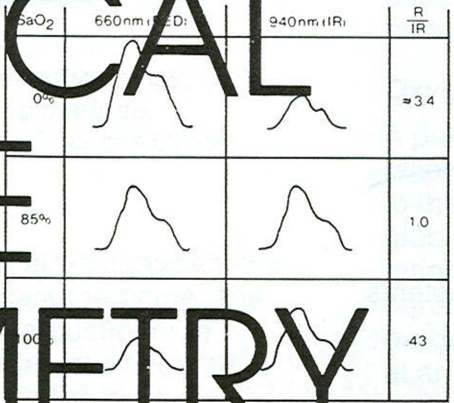
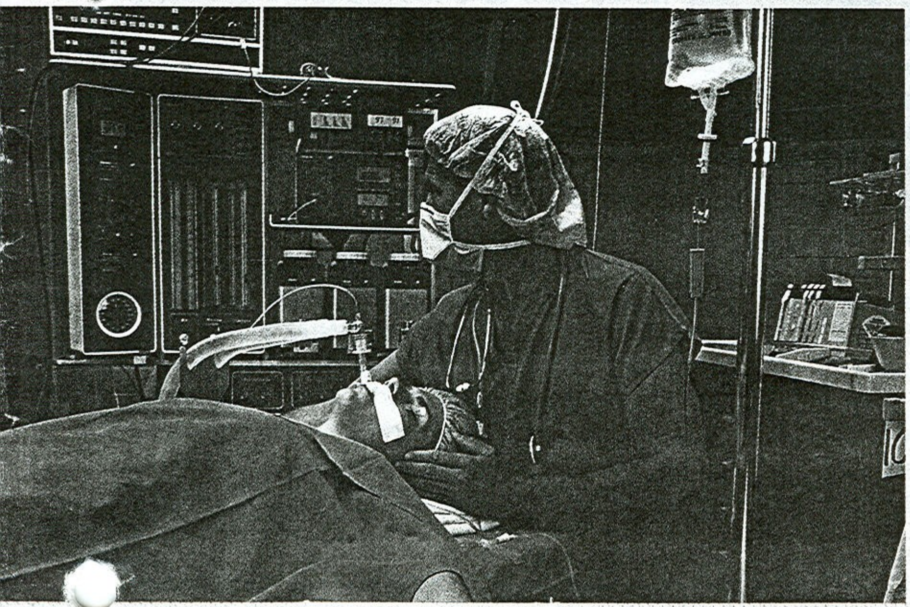


CLINICAL PULSE OXIMETRY





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Dear Doctor.

Ohmeda, the medical equipment division of BOC Health Care, is dedicated to the continuing support of medical education, particularly in the field of new medical technologies and their clinical applications.

Ohmeda and the Webb-Waring Lung Institute are pleased to bring you this handbook on pulse oximetry which explains the many clinical uses of this noninvasive oxygenation (SaO_2) monitor.

Ohmeda is dedicated to improving patient care and delivering equipment of value to the clinician in this cost conscious era of health care.

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Sincerely.

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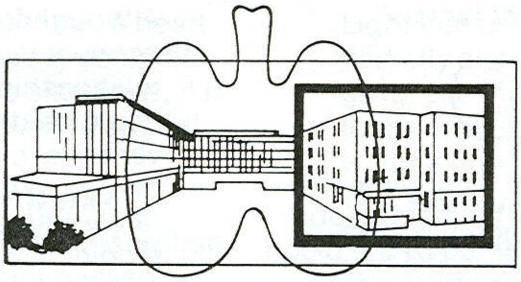
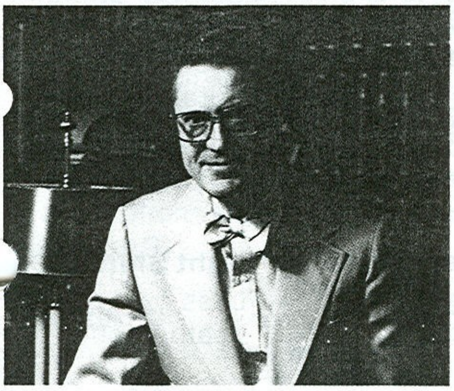


CLINICAL PULSE OXIMETRY

By Thomas L. Petty, M. D.



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An accurate assessment of arterial oxygenation is fundamental to critical care medicine. The rational use of oxygen, the adjustment of ventilators in a variety of different clinical situations, and monitoring during the period of weaning from any form of respiratory support requires knowledge of the adequacy of arterial oxygenation. The advent of arterial blood gas analysis on a practical basis two decades ago helped to revolutionize the field of critical care medicine. However, the invasiveness of these measurements, their time requirements and costs with repeated arterial blood gas samples are serious limitations. In addition, there are numerous critical situations where knowledge of oxygenation alone is adequate for clinical purposes. This is particularly true where the alveolar ventilation is apt to be constant. For example, when it is controlled with a mechanical ventilator and when the pH of arterial blood is also unlikely to change. Here a simple noninvasive assessment of arterial oxygenation by pulse oximetry would be clearly advantageous from the standpoint of reduced patient trauma, rapid data and cost savings.

Additional and widespread applications include the monitoring of oxygenation during sleep, exercise testing, ambulation and other activities of daily living in hospitalized patients. Pulse oximetry is also valuable in the emergency room, on the wards, in the operating room and even in the home. A review of the many advantages and applications of noninvasive pulse oximetry in a variety of clinical situations follows.

Oxygen Saturation

A pulse oximeter measures the oxygen saturation of arterial blood. Oxygen saturation refers to the amount of oxygen carried by hemoglobin. Expressed as a percent, oxygen saturation is the amount of oxygen carried compared to total capacity. A normal arterial oxygen saturation (SaO_2) at sea level is 95%, at an altitude of 5000 ft., 92%, and at 10,000 ft. approximately 88%.

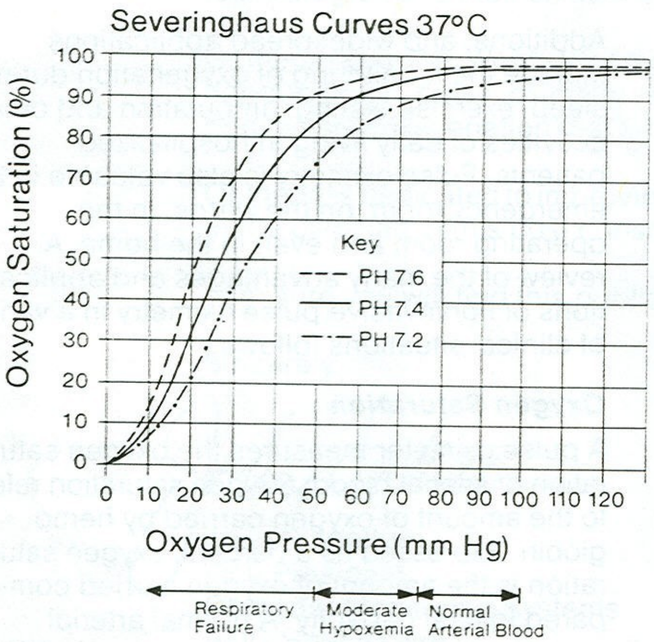
Oxygen saturation and oxygen tension (PaO_2) are related by the oxyhemoglobin dissociation curve (Figure 1). On the horizontal axis is oxygen tension, the pressure of oxygen dissolved in the blood and on the vertical axis is oxygenation saturation, the amount of oxygen carried by Hb. Oxygen tension is the function of the inspired oxygen tension, alveolar ventilation and gas transfer across the alveolar capillary membrane. At a given altitude, oxygen tension (PO_2) relates directly to the level of ventilation (alveolar) and the inspired oxygen concentration.

Impediments to gas transfer are ventilation perfusion mismatchings, diffusion defects and anatomic shunt. These three factors can be lumped together as "shunt factor."

$$\left(PO_2 \propto \frac{\dot{V}_E}{\text{Shunt Factor}} \times FO_2\right)$$

On the vertical axis is oxygen saturation, the amount of oxygen carried by the hemoglobin. The total amount of oxygen carried by the blood thus becomes a function of oxygen tension, oxygen saturation and hemoglobin. The delivery of oxygen to the tissues then is the product of the amount of oxygen carried by the blood and the cardiac output.

FIGURE 1



Oxygen Tension and Oxygen Saturation Relationships

Figure 1 presents the standard relationship between oxygen tension and arterial oxygen saturation, the familiar "s-shaped" oxyhemoglobin dissociation curve. It shows the shift in the position of the curve caused by changes in the pH of arterial blood. Other factors alter the PaO_2-SaO_2 relationship. These include body temperature, naturally occuring abnormal hemoglobins which have different affinities for oxygen, fetal hemoglobin, hemoglobin alterations (due to toxins) such as carboxyhemoglobin, methemoglobin and sulfhemoglobin caused by drugs. Disease states such as sickle cell anemia, hyperthyroidism and hypothyroidism can also alter the relationship.

Although formulas have been developed to account for these altered tension-saturation relationships, it is doubtful that any formula could be developed to deal with the large variety of clinical situations. Thus caution is offered to those who would attempt to accurately extrapolate oxygen tension from an empirically determined oxygen saturation measurement. But the reverse is equally true. Oxygen tension numbers tell us less about oxygen amount, i.e. saturation, than commonly believed unless we consider the complex relationships of tension in relation to saturation. As a general guide, Table 1 lists the factors which shift the oxyhemoglobin dissociation curve to the left (higher saturation for a given oxygen tension) or to the right (lower saturation for a given oxygen tension).

TABLE 1

Left Shifted Curve (More oxygen saturation)	**Right Shifted Curve** (Less oxygen saturation)
Alkalemia (increase in pH)	Acidemia (decrease in pH)
Hypothermia	Hyperthermia
Hypometabolism	Hypermetabolism
Fetal Hemoglobin	Certain Abnormal Hemoglobins
Certain Abnormal Hemoglobins	Some Chronic Hypoxemic States
Residence at High Altitude	Hypercapnia

Thus the oxygen saturation numbers, like oxygen tension numbers should be used as guidelines to help the clinician judge the adequacy of arterial oxygenation. Blood gases in general should be interpreted in the context of the patient and the multiple variables which can alter the cardiorespiratory systems ability to achieve adequate oxygenation of not only the arterial blood, but also of the body's tissues. These variables include blood pressure, the apparent perfusion of tissues as judged by the temperature of the extremities, urine flow and of course, by the patient's mentation.

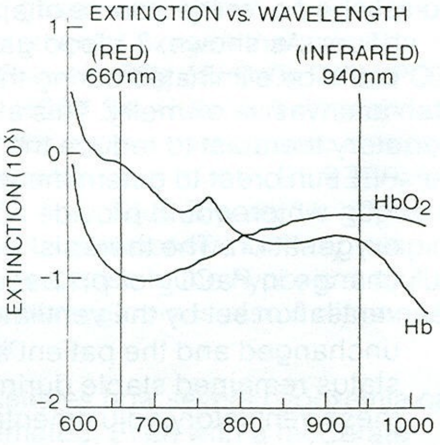
What Then is Adequate Arterial Oxygen Saturation?

For most patients, a saturation of 90-95% would be considered adequate. There may be clinical situations, such as a stroke, a heart attack, or severe angina, where greater than 95% SaO_2 is desired. In these situations, it is probably reasonable to achieve full arterial saturation.

How Does a Pulse Oximeter Work?

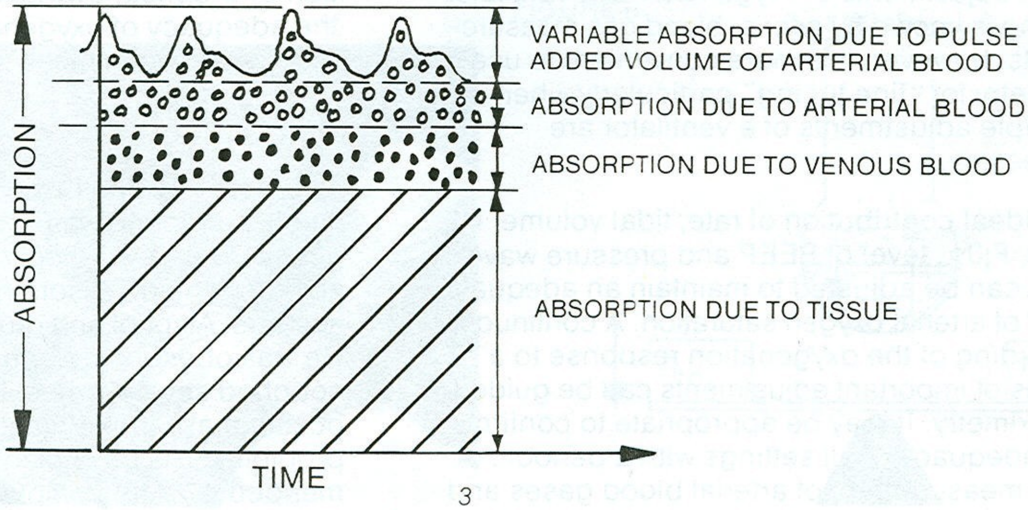
The pulse oximeter measures the absorption of selected wavelengths of light passed through a living tissue sample. Oxygenated-hemoglobin (HbO_2) and reduced hemoglobin (Hb) absorb light to varying degrees as a function of incident light (see Figure 2). As a result of this known relationship the quantity of HbO_2 and Hb can be calculated. The central problem in translating oximetry theory into an effective medical device, however, is to differentiate between the absorption due to oxygenated and reduced hemoglobin and the absorptions due to all other constituents. (Figure 3).

FIGURE 2



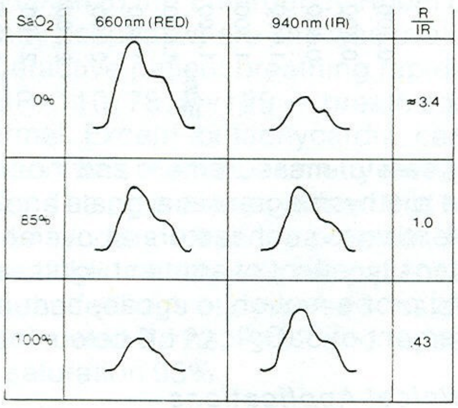
Oxygenated hemoglobin (HbO_2) and reduced hemoglobin (Hb) exhibit markedly different absorption (extinction) characteristics to red light @660nm and infrared light @940nm.

FIGURE 3



Light transmitted through a tissue site is partially absorbed by each constituent. For a given site the absorption is constant, except for the absorption from the added blood volume due to arterial pulsations. (Figure 3). This varying absorption is translated into a plethysmographic waveform at both the red and infrared wavelengths. This relationship between the amplitude of these plethysmographic waveforms can be directly related to arterial oxygen saturation. (Figure 4).

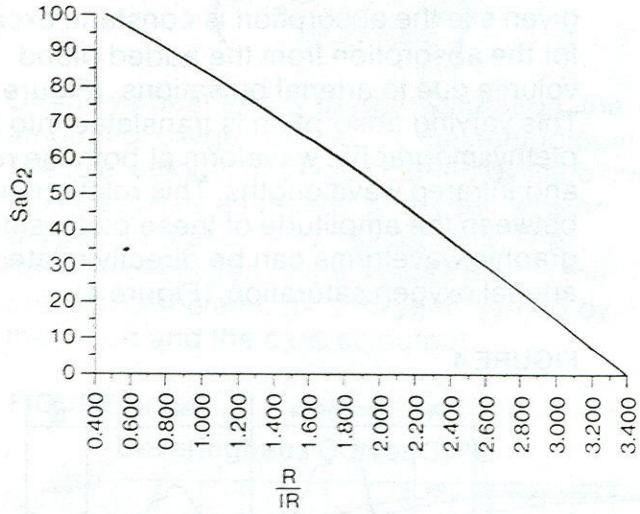
FIGURE 4



RELATIVE PLETHYSMOGRAPHIC SIGNAL AMPLITUDES ASSUMING THE TRANSMISSION INTENSITIES ARE EQUAL.

For example, when the plethysmographic amplitudes at 660 nm and 940 nm are equal, the SaO_2 is approximately 85%. Figure 5 shows the relationship between the ratio of the plethysmographic amplitudes $\frac{[R]}{[IR]}$ and SaO_2.

FIGURE 5



By careful measurement and monitoring of the plethysmographic signals and careful attention to such factors as overall transmitted intensity, effect of ambient lights, and patient and probe motion, clinically accurate measurement of SaO_2 can be determined.

Clinical Applications

Pulse Oximetry in the ICU

All physicians, nurses and respiratory therapists have become accustomed to relying on frequent "monitoring" of blood gases in critically ill patients receiving oxygen or mechanical ventilation. Knowledge of the state of oxygenation (PaO_2 or SaO_2), CO_2 elimination ($PaCO_2$) and acid base status of the blood (pH and bicarbonate) are fundamental measurements as is the hemoglobin concentration.

Once adjustments of oxygen flow or a ventilator setting is known by arterial blood gas measurements, however, it is more convenient to use oximetry for "fine tuning" particularly when multiple adjustments of a ventilator are necessary.

The ideal contribution of rate, tidal volume, I/E ratio, F_IO_2, level of PEEP and pressure wave form can be adjusted to maintain an adequate level of arterial oxygen saturation. A continuous recording of the oxygenation response to a series of important adjustments can be guided by oximetry. It may be appropriate to confirm the adequacy of all settings with a periodic or final measurement of arterial blood gases and pH, once the idealized settings of a ventilator are determined. An example of how this str egy can assist in ventilation adjustments is cited in Table 2.

TABLE 2 – USE OF OXIMETRY IN VENTILATION ADJUSTMENTS IN PATIENTS WITH ARDS

Sequence of Blood Gas Responses to various Ventilator Settings

Ventilator Settings	F_1O_2	0.6	1.0	0.8	0.6	0.5	0.45
	TV	800	800	800	800	800	800
	R	18	18	18	18	18	18
	PEEP	0	5	10	10	10	10
Blood Gas Response	SaO_2	80%	98%	99%*	96%*	94%*	96%
	PaO_2	41	110	—	—	—	75
	pH	7.48	7.47	—	—	—	7.45

*Determined by Pulse Oximetry

Comment:

These ventilator adjustments were accomplished over the course of approximately 3 hours. As shown, 3 blood gas determinations could be eliminated during this period by using noninvasive oximetry. This allowed the respiratory therapist to reduce the F_IO_2 and adjust PEEP in order to determine the lowest possible F_IO_2 which would provide adequate arterial oxygenation. The therapist did not expect any change in $PaCO_2$ or pH because the minute ventilation set by the ventilator remained unchanged and the patient's hemodynamic status remained stable during the period of these ventilatory adjustments.

Pulse Oximetry in the Emergency Room

Noninvasive oximetry can be extremely useful for emergency room personnel in the eval tion of dyspnea, cyanosis and in assessin the adequacy of oxygenation by nasal prongs or masks. Two clinical examples follow.

Case #1

A 62 year old man involved in a minor automobile accident, was brought to the Emergency Room by the police because he appeared mildly disoriented and vague in his answers. Alcohol and drug abuse were denied. He was obese and during examination coughed several times. He reported that he occasionally took Primatine Mist for breathing problems. His physician once had recommended stopping smoking because of the possibility of emphysema. Physical exam revealed R=18, BP=155/88, P=80. A slight duskiness of the face was present, but no clearcut cyanosis of the nail beds was observed. Chest examination revealed slightly reduced breath sounds. Cardiac examination was normal. Edema and clubbing were absent.

Application of a pulse oximeter revealed a SaO_2 of 72%. Oxygen by nasal prongs at 2 L increased the SaO_2 to 90%. Pulmonary function tests, done in the ER revealed FVC 2.45 L (70%), FEV_1 1.2 L. (45%). Chest x-ray was normal except for a slightly enlarged pulmonary outflow tract and enlarged right and left pulmonary arteries. The patient was admitted for further evaluation of COPD.

Comment:

Since pulse oximetry revealed a low SaO_2, arterial blood gases were drawn on admission, prior to supplemental oxygen therapy. The patient's ABGs were PO_2 43, SaO_2 71%, PCO_2 55, pH 7.39, HCO_3 34, Hgb 18.5. These data indicate that the patient had chronic compensated CO_2 retention due to the "Blue Bloater" type of COPD. The "Blue Bloater" is known to have a relatively unresponsive or "lazy" respiratory center in response to the hypoxic stimulus. The elevated hemoglobin is also a response to hypoxemia.

This case illustrates how severe hypoxemia can be underestimated. Even with a moderate degree of polycythemia, the examining physician was not impressed by cyanosis. Cyanosis is a notoriously unreliable sign of the state of arterial oxygenation in many patients, particularly where anemia is present.

The first clearcut evidence of COPD in this case was initiated by an Emergency Room measurement of oxygen saturation by non-invasive oximetry which led to a complete workup and treatment for moderately advanced COPD.

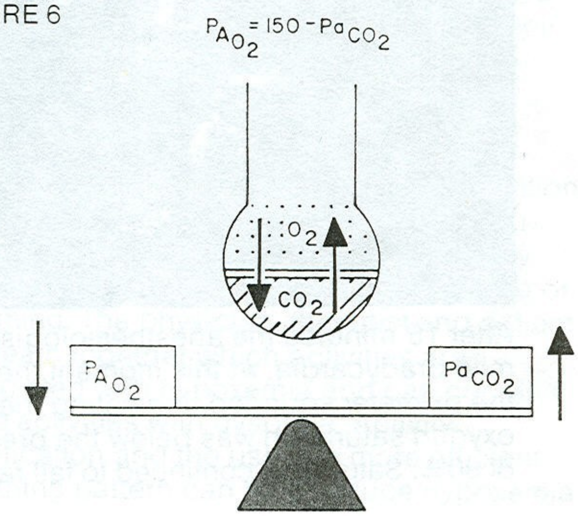
Case #2

A 27 year old woman had been recently divorced. She suffered insomnia, anxiety with depression and periods of sudden shortness of breath. Because of these symptoms she was taken to the Emergency Room of the community hospital where she was evaluated as a hyperactive patient breathing rapidly — R=32, BP=110/78, P=129 — breath sounds were normal. Except for tachycardia, cardiac examination was normal. Oximetry revealed SaO_2 99%. The physician surmised that hyperventilation syndrome was the problem. After the nurse talked calmly with the patient for 30 minutes, the feelings of dyspnea subsided. A recheck showed R=22, P=92 and repeat oxygen saturation 95%.

Comment:

A high oxygen saturation in the absence of supplemental oxygen therapy is almost always due to hyperventilation. This was confirmed in this case by a reduction in oxygen saturation to within the normal range as the patient's symptoms subsided. This example also emphasizes the reciprocal relationship between oxygen and carbon dioxide as depicted in Figure 6. Thus, the physician could surmise that this patient suffered from acute hyper-

FIGURE 6

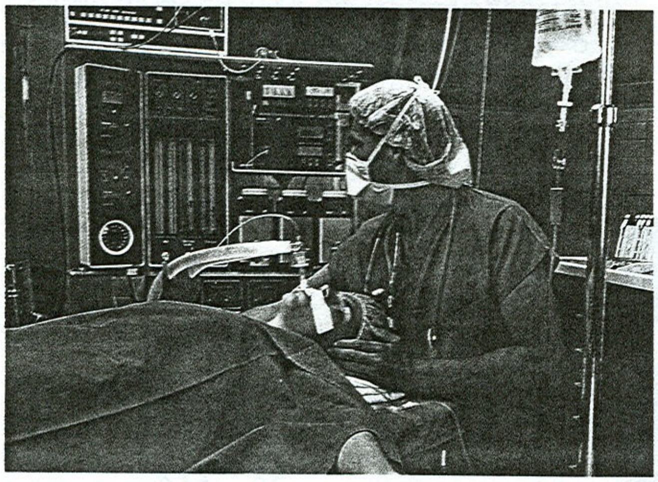


ventilation syndrome and hypocarbia without actually measuring the arterial PCO_2.

These are only two examples of the use of oximetry in the ER. Pulse oximetry would also be useful for the initial ER evaluation of asthma, airway obstruction, pneumonia, congestive heart failure, chest trauma, and chest pain from either a pneumothorax, major pulmonary embolism or an acute myocardial infarction. In these various clinical states, simple, non-invasive pulse oximetry could be the first major step in alerting nurses, physicians and respiratory therapists to the need for oxygen therapy and arterial blood gas analysis. Alternatively the presence of normal oxygen saturation could avoid the unnecessary drawing of blood gases while other explanations of the presenting symptoms were being sought.

Pulse Oximetry in the Operating Room

A 42 year old woman, mother of 5, was admitted for elective abdominal hysterectomy because of dysfunctional uterine bleeding and anemia. She had been in excellent health and pre-op evaluation revealed a normal physical examination. EKG, FVC, FEV_1 and urinalysis were normal. As a precaution, during the conduct of anesthesia, a finger probe was attached to her index finger and continuous monitoring of oxygen saturation was commenced before the induction of anesthesia.



After 15 minutes the anesthesiologist noted a mild bradycardia. At this moment the alarm on the oximeter sounded, indicating that the oxygen saturation was below the pre-set limit of 90%. Saturation continued to fall rapidly into the range of 75%. The anesthesiologist immediately disconnected the anesthesia ventilator and manually ventilated the patient w[illegible] 100% oxygen. Oxygen saturation rapidly elevated to 99% within one minute and the pulse stabilized at 80 bpm. Blood pressure remained normal. The surgery was continued uneventfully with a replacement anesthesia machine and the other device sent to maintenance to determine the cause of malfunction. The hysterectomy was completed without further incident.

Comment:

Each year, anesthesia related tragedies occur due to mechanical failure, errors in anesthetic management, as well as intraoperative cardiorespiratory events. In many of these cases, the result was hypoxemia that went undetected, which led to cardiac arrest, brain damage[illegible] death. In most instances, early recognition of the hypoxemia would have prevented the mishap. This suggests that the routine monitoring of arterial oxygenation would provide an early warning of impending complications and thus reduce the incidence of anesthetic mishap.
(Rubsamen & Keenan)

Pulse Oximetry in the Wards

There are numerous situations where pulse oximetry can be extremely useful and can replace the frequent use of arterial blood gases in the normal care of patients. Two examples follow:

Case #1

A 78 year old woman was admitted to the hospital with lobar pneumonia. After two days of penicillin therapy and supplemental oxygen in the ICU, her recovery was proceeding nicely and she was transferred to the medical ward for further observations. On the 4th hospital day, she complained of headache and nasal stuffiness and wanted the nasal prongs removed so that she could sleep. A respiratory therapist brought a portable oximeter to the bedside at the request of the nurse in charge that evening. On oxygen at 2 L, SaO_2 was 97%. The attending physician who had continued the order for nasal oxygen was called and agreed that the oxygen could be discontinued for 30 minutes to be followed by repeat oximetry. This revealed an oxygen saturation of 91%. It was then ordered that oxygen therapy be discontinued, with the knowledge that adequate oxygenation was now achieved by breathing room air.

Comment:

In this case, the decision to discontinue supplemental oxygen was based on the arterial oxygen saturation measurement by a pulse oximeter. Here the use of noninvasive oximetry avoided arterial puncture, and patient discomfort.

Case #2

A 54 year old man had been admitted for a massive pulmonary embolus 8 days earlier. After stabilization and initiation of heparin therapy in the ICU, he was transferred to the Medical Ward for further anticoagulation and observation. He refused to continue to wear his nasal prongs for continuous oxygen administration, even though a hypoxic condition had initially been established by arterial blood gas analysis. Upon hospitalization, at first he required 5 L/min for adequate oxygenation. As a quick check, the physician ordered bedside oximetry which revealed SaO_2 of 90% while the patient was resting in bed, breathing room air. The physician, therefore, agreed that oxygen could be discontinued. Later that same day the patient reported a lightheaded feeling and dyspnea while ambulating slowly in the hall. The physician had the respiratory therapist use a portable oximeter for monitoring oxygen saturation during ambulation in the hall. Oxygen saturation fell to 80% with only very slow walking. The patient then agreed to continue with the use of supplemental oxygen during slow ambulation, dressing and bathing. Three days later and just before discharge, it was determined that oxygen saturation was maintained at 92% during normal walking in the hall without supplemental oxygen.

Comment:

In this instance, the patient had adequate oxygenation at rest, but significant hypoxemia from mild exercise during the early recovery stage. This was likely due to remaining ventilation-perfusion mismatch which is common following major pulmonary embolization. The transient nature of this physiologic abnormality was documented by the near normal oxygen saturation while walking more briskly in the hall only 3 days later. The determination of near normal and perfectly adequate oxygen saturation just prior to discharge was also reassuring to both patient and physician.

Pulse Oximetry During Formal Exercise Testing

It has been a common practice to place an indwelling arterial needle or line to evaluate arterial oxygenation during formal exercise testing on a treadmill or with a bicycle ergometer. In these instances, interest focuses on the adequacy of oxygenation during progressive exercise and far less interest in PCO_2 and pH. With the advent of practical noninvasive oximetry, exercise testing has become far more convenient and palatable to the patient since indwelling arterial lines or needles can be avoided. The simple oximetry procedure takes less physician or technician time as well.

Oximetry During Pulmonary Rehabilitation

Pulse oximetry is useful under any exercise condition where hypoxemia may occur. This is particularly true in pulmonary rehabilitation where breathing training, breathing exercises and physical reconditioning are employed. Oximetry can be used as a biofeedback mechanism showing how oxygenation may improve with pursed lip breathing, leaning forward, or simple concentration on exhalation to promote lung emptying. Patients and their families can see how an altered breathing pattern can improve oxygenation.

Oximetry is also useful during graded exercises on a treadmill and during ambulation in the halls or on stairs. Oximetry is particularly useful for monitoring activities of daily living such as stooping, bending, dressing or grooming. The physician, therapist and patient can learn together which activities are associated with hypoxemia and can correlate these activities with dyspnea. Activity modification and the use of a more efficient breathing pattern can help reduce hypoxemia during these life situations. Observable arterial oxygenation information can guide the physician, nurse or therapist in aiding the patient during various steps in pulmonary rehabilitation.

The oxygen flow requirements for a 72 year old patient with advanced COPD at rest and exercise could be determined as illustrated. Home oxygen is part of a comprehensive rehabilitation program for selected patients with advanced COPD.

Pulse Oximetry During Sleep

It is now known that many patients, even those who are presumed normal, may have substantial hypoxemia during the hours of sleep. Documentation of hypoxemia with nighttime oximetry monitoring may be the first step in explaining why the patients are hypersomnolent, have mental aberration during the daytime, are hypertensive, have cardiac arrhythmias, polycythemia and impotence. Simple bedside monitoring with pulse oximetry could be used as a screening technique to diagnose patients with sleep related hypoxemia. Some of these patients may then be referred to sleep laboratories for more definitive studies.

Pulse Oximetry During Bronchoscopy

Another growing use of oximetry is during bronchoscopy. It may prove beneficial in high risk patients who have the potential of developing significant hypoxemia during the procedure. The bronchoscopist or assistant can continuously monitor oxygen saturation during a procedure which could be complicated by significant hypoxemia and cardiac arrythmias, particularly in patients with respiratory insufficiency.

Pulse Oximetry in the Home

Today there are nearly one million people in the United States with chronic respiratory insufficiency who require home oxygen. Questions regarding the adequacy of flow from concentrators, liquid systems and tanks often arise. The adequacy of oxygen flows during activities of daily living should also be verified. Using arterial oxygen saturation data from the pulse oximeter, the oxygen flow rate can be titrated and documented in the home. Pulse oximetry can also be used for patient education and indoctrination.

The Future of Pulse Oximetry

This brief monograph has only described the major uses of simple noninvasive oximetry in clinical practice ranging from emergency applications to home use. As technology advances, further applications will emerge.

A fact of life in the world's medical care today is increasing cost consciousness. The oximeter offers the possibility of monitoring oxygenation without the time and costs normally associated with the lab analysis of arterial blood. Increased interest in patient safety is propelling pulse oximetry into virtually every operating theater and recovery unit in the United States. Another cost-effective approach suited to today's environment is central ward monitoring particularly in the I.C.U. Perhaps nowhere is oxygenation monitoring more important than in the neonatal ICU. Here, pulse oximetry offers a fast, noninvasive, continuous technique for oxygenation monitoring without the delay and patient trauma inherent in other oxygenation monitoring techniques.

Many techniques that have only been available in the hospital are now moving to the physician's office. New, computerized devices such as the pulse oximeter, added to spirometry, should enable a comprehensive evaluation of pulmonary function in the office. This can probably reduce the unnecessary use of more complete pulmonary function testing when appropriate. This office approach to pulmonary function testing can foster both diagnostic testing and help monitor therapy with an eye toward convenience and cost savings.

Oral surgery is another field where continuous oxygenation monitoring can seek to ensure patient safety.

The possibility of using oximetry to self adjust the oxygen flow from concentrators or other oxygen supply systems is another application. Perhaps oximetry signals can even be used to help automatically adjust mechanical ventilators in the hospital or home!

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