Fortnightly Review

Pulse oximetry: a practical review

C D Hanning, J M Alexander-Williams

Pulse oximetry is arguably the greatest advance in patient monitoring since electrocardiography. It enables oxygenation, an important physiological variable that is poorly detected by clinical means, to be monitored continuously, simply, and non-invasively. Hypoxaemia is commonly found in all aspects of medical practice and is a major cause of organ dysfunction and death. Pulse oximetry should be widely available and used routinely in clinical practice both in primary care and in hospital.

Summary points

- Hypoxaemia is common, poorly detected, and harmful
- Pulse oximetry is a simple, reliable, and accurate means of detecting hypoxaemia
- Pulse oximetry should be widely available and routinely used

Sources of error

- Poor perfusion
- Motion
- Excessive light
- Venous pulsation
- Dyshaemoglobins
- Vital dyes, nail varnish, and pigmentation

Principles of operation

An understanding of the principles of operation is essential for the proper use and interpretation of the values displayed by an oximeter. The absorption spectra of oxygenated and reduced haemoglobin differ so that arterial blood appears red while venous blood appears "blue." When two compounds with differing absorption spectra are together in solution, the ratio of their concentrations can be determined from the ratio of the light absorbed at two different wavelengths. The aim of oximetry is to measure the ratio of oxygenated haemoglobin to total haemoglobin in arterial blood, the oxyhaemoglobin saturation. In living tissue, however, light is also absorbed by the tissues and by the haemoglobin in venous and capillary blood. To overcome this, early instruments heated the tissues to increase flow and to "arterialise" the blood in the capillaries and veins and some used up to eight wavelengths to allow for absorption of light by tissues. These instruments were useful research tools but were too cumbersome for clinical use.

The breakthrough was the realisation that the light absorbed varied with each pulse and that if the absorption was measured at one point of the pulse wave and compared with the absorption at another point then the difference between the values was due to arterial blood alone; the contribution of other absorbers could thus be eliminated. The modulation of light absorbance is small, about 0·5-10% of total, and the possibility for inaccuracy and error is thus obvious.

The oximeter probe comprises two light emitting diodes, one red and one infrared, and a detector. The emitters and detector are placed so as to face each other through tissue about 5-10 mm in thickness. The diodes are switched on and off in rapid sequence so that each measurement set includes an estimate of transmission of red light, infrared light, and ambient illumination. After correction for ambient light, the ratio of red to infrared light is determined and the corresponding oxyhaemoglobin saturation is found from an empirically determined table. About 600 individual measurements are made each second and fed into an algorithm in a microprocessor, where they are accepted or rejected and then weighted using formulas unique to each manufacturer. The displayed value is an average based on the previous 3-6 seconds of recording and updated about every 0·5-1 second.

Limitations of oximetry

A pulse oximeter can only function if it can detect a modulation in transmitted light. Thus if perfusion is poor and pulse amplitude small it will be liable to error or unable to obtain a reading. Poor perfusion is the main cause of failure to obtain a satisfactory signal. Similarly, if the transmitted light is modulated by other factors, particularly movement and venous pulsation, then inaccuracy can be expected. Gross movement results in loss of signal, but vibration at frequencies that fall within the possible range of heart rate (0·5-3·5 Hz) may lead to erroneous values. A minor degree of pulsation is normally present in venous blood, and allowance is made for this in the calculation of oxyhaemoglobin saturation. A small (1-2%) difference may be seen between a reading taken from a finger and the ear, particularly if the finger is dependent. Greater inaccuracies will occur if there is venous congestion or tricuspid incompetence leading to substantial venous pulsation.

As only two wavelengths of light are used, the instruments can only detect two compounds, reduced and oxygenated haemoglobin. Other compounds that absorb light at the same wavelengths will thus introduce errors. The most common and potentially most serious is carboxyhaemoglobin, which the oximeter detects as oxyhaemoglobin and thus overestimates the true concentration of oxyhaemoglobin. Other dyshaemoglobins such as methaemoglobin also interfere, as will vital dyes.

The intensity of light emitted is regulated so that the detector is not saturated and allowance is made for differences in the thickness and light transmission of different tissues. Excessive ambient light, however, may saturate the detector and give erroneous readings. Xenon and infrared lamps are most likely to give

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problems, but intense daylight and fluorescent and incandescent light may also affect the performance.

Pulse oximeters are calibrated empirically by observations on normal volunteers. The instruments are thus most accurate (2% error) at oxyhaemoglobin saturations of 70-99% as it is unethical to test volunteers at lower values. However, this limited accuracy is quite acceptable in adult practice as any calculated oxyhaemoglobin saturation under 70% represents serious hypoxaemia requiring urgent action.

Applications of pulse oximetry

DETECTING HYPOXAEMIA

The human eye is poor at detecting hypoxaemia. The traditional sign is cyanosis, which is defined as a concentration of more than 5 g/100 ml of reduced haemoglobin in capillary blood and depends on arterial oxygenation, skin perfusion, and haemoglobin content. The presence of central cyanosis, a blue coloration of the tongue and mucous membranes, is thought to be a more reliable indicator of hypoxaemia as these tissues are less likely to be poorly perfused. This definition translates to an oxyhaemoglobin saturation of about 75% with normal perfusion, which is clinically important hypoxaemia. The ability to detect cyanosis depends on the experience and eyesight of the observer, the colour balance of the ambient lighting, and the skin pigmentation of the subject. Places where hypoxaemia may be expected (operating theatres, accident departments, endoscopy suites) should have lighting with blue coloration ("northern daylight") to facilitate detection. Several studies—the earliest was by Comroe and Bothelo in 1947[1]—have shown that even under ideal conditions skilled observers cannot detect hypoxaemia until the oxyhaemoglobin saturation is under 80%. The pulse oximeter thus extends our clinical senses rather than replacing them.

What is clinically important hypoxaemia?

Determining the safe degree of hypoxaemia for an individual subject is impossible. The brain is the most sensitive organ, and visual, cognitive, and electroencephalographic changes develop when the oxyhaemoglobin saturation is less than 80-85% in normal subjects. However, there is no evidence that short term hypoxaemia to this degree produces any long term deficit. Elderly subjects with impaired cerebral perfusion would be expected to be more susceptible, but there are no long term studies with sensitive measures of outcome. Prolonged or repetitive hypoxaemia is probably worse than a single episode, but again there are no means of calculating an index of risk of hypoxic damage from degree and duration of exposure. Similar problems exist with defining a safe exposure to radiation or pollutants or with deciding a degree of hypertension that merits intervention.

Patients with nocturnal hypoxaemia, often to a profound degree, do not seem to develop life threatening complications such as cor pulmonale and polycythaemia until a modest degree of daytime hypoxaemia occurs (oxyhaemoglobin saturation <90-92%). Similarly, clinical experience suggests that patients with acute (or chronic) respiratory failure with oedema are often refractory to diuretic treatment until their oxyhaemoglobin saturation is greater than 90%. Whether this represents cardiac or renal impairment due to hypoxaemia is open to debate.

Examination of the oxyhaemoglobin dissociation curve (fig 1) shows that the "knee" of the curve is at about 90%. Below this value oxyhaemoglobin saturation decreases more rapidly as oxygen tension declines. On most pulse oximeters the default setting for the low oxyhaemoglobin saturation alarm is 90%, and this should be regarded as the target for oxygenation in most patients. The decision to accept a lower value should be based on individual circumstances, not least the chronicity of the hypoxaemia.

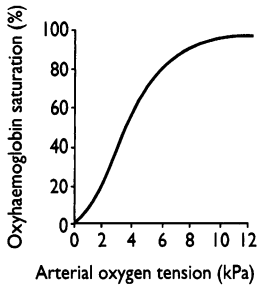

FIG 1—*Oxyhaemoglobin dissociation curve*

Clinical situations

Pulse oximetry is indicated in any circumstance where hypoxaemia may occur. There are few branches of medical practice where this may not occur, and it has been suggested that measurement of oxyhaemoglobin saturation should be included in the routine vital signs of temperature, pulse, respiratory rate, and blood pressure. This approach has much to commend it, although it has not yet been shown whether it would be of overall benefit. Certainly, a "spot" measurement would be useful in any situation where hypoxaemia might be contributing to the clinical picture—for example, confusion and delirium—and is preferable to a blood gas analysis (see below). A great advantage of pulse oximetry is the ease with which continuous monitoring can be undertaken. The alarms will warn of hypoxaemia or extremes of heart rate, and the pattern of oxygenation can be recorded either with the internal memory present in many instruments or by connection to a chart recorder or computer. This is particularly helpful in the investigation of sleep related hypoxaemia —for example, in chronic obstructive airways disease or obstructive sleep apnoea.

Continuous oximetry is now regarded as essential monitoring during anaesthesia and critical care of adults and neonates. It is increasingly found in other acute care areas such as accident units and endoscopy suites and should become part of routine practice in all parts of medical practice. The inclusion of an estimate of haemoglobin concentration in routine testing is an acknowledgment of our clinical difficulty in detecting anaemia. Oxygenation should be determined with equal or greater frequency as a recognition of the impossibility of clinical detection of hypoxaemia and its harmful effects.

Oximetry or blood gas analysis?—An oximeter can replace arterial puncture and blood gas analysis in most cases where assessment of oxygenation is the main indication. Arterial puncture is necessary if the arterial carbon dioxide tension or acid-base state is sought, but many procedures that are currently performed could be avoided with a considerable saving in cost, time, and discomfort to patients. Correct technique and attention to detail are important in blood gas analysis and are often lacking in those who rarely perform such procedures. Oximetry is less prone to user error and thus may give a more accurate measure of oxygenation. The oxygenation of hypoxaemic patients also varies considerably with the pattern of breathing. A few deeper breaths can have a considerable effect, while a brief apnoea can result in a rapid decline. Except in the most skilled hands, the pain and stimulation of an arterial puncture is sufficient to increase the oxygenation of all but the most stuporous patients. Blood gas analysis thus usually overestimates oxygenation.

A protocol for managing hypoxaemia is a useful guide for medical and nursing staff, and an outline is given in the box. It must not be forgotten that, while early administration of oxygen is important, a search for the cause of the hypoxaemia is essential and should be started immediately.

Improving oximeter signals

- Warm and rub the skin
- Apply a topical vasodilator
- Try a different probe site, especially the ear
- Try a different probe
- Use a different machine

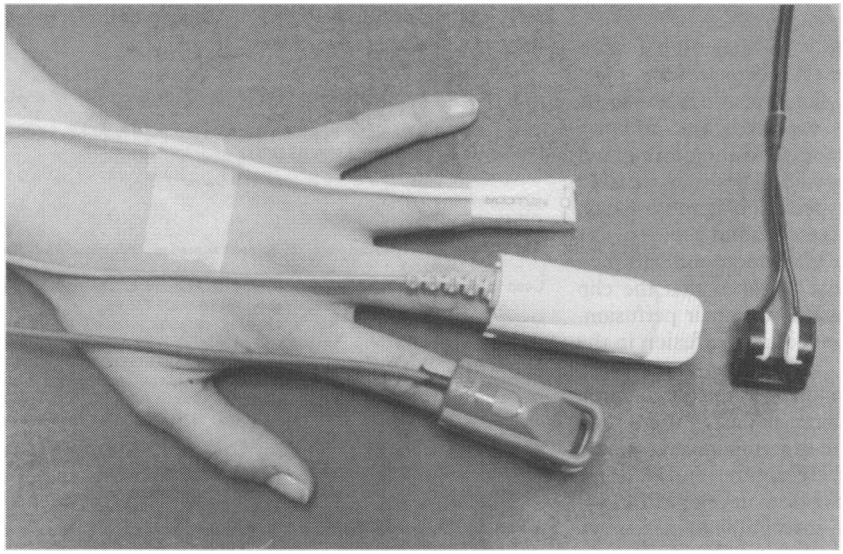

FIG 2—*Self adhesive and clip type finger probes and an ear probe. (Note method of fixation of cable on back of hand)*

REGULATION OF OXYGEN TREATMENT

Oxygen is a drug and, as with all drugs, should be administered in a dose just sufficient to produce the desired effect. Additional oxygen is probably innocuous but is wasteful. Oximetry can be used to regulate oxygen supply and also allows cheaper, more comfortable variable performance oxygen delivery systems, such as nasal spectacles, to be used safely and effectively. It also provides evidence to encourage nursing staff to urge reluctant patients to accept oxygen treatment.

Oxygen treatment is often restricted in patients with respiratory failure for fear of increasing the arterial carbon dioxide tension in patients who rely on their hypoxic ventilatory drive. However, hypercarbia is less physiologically damaging than hypoxaemia, and an increased arterial carbon dioxide tension can usually be judged clinically from symptoms such as sweating and headache. Oximetry allows oxygen therapy to be carefully titrated to achieve an acceptable oxyhaemoglobin saturation of about 90%. If the carbon dioxide tension increases to unacceptable levels then analeptic agents such as doxapram or mechanical ventilatory support can be considered. Intermittent oxygen therapy, which has been favoured by some, is akin to intermittent drowning.

DETECTION OF HYPEROXIA

Hyperoxia is potentially harmful to premature infants, and it was hoped that pulse oximetry would allow this problem to be avoided. An arterial oxygen tension of no more than 11 kPa is generally advocated. However, a calculated oxyhaemoglobin saturation of 92% has been found to be associated with values of arterial oxygen tension of 5·3-13 kPa because of inaccuracies in the measurement and variations in the shape of the oxyhaemoglobin dissociation curve.[2] It is thus apparent that the pulse oximeter, while an excellent guide to hypoxaemia, is not an absolute indicator of hyperoxia. However, once the relation between measured oxyhaemoglobin saturation and arterial oxygen tension has been determined for an individual infant the oximeter can be used to monitor the target oxygenation.

TESTING ADEQUACY OF CIRCULATION

The absolute amplitude of the plethysmograph waveform is an indicator of the adequacy of peripheral perfusion and has been used in evaluating ischaemic tissue. In many instruments, however, the display of signal amplitude is automatically scaled and the absolute value is not available. Transcutaneous oxygen tension is probably a better indication of viability in assessing ischaemic limbs and tissue flaps.

Practical application

ENSURING A GOOD SIGNAL

Poor perfusion due to cold or hypotension is the principle cause of an inadequate pulse wave. Inadequate light transmission due to tissue oedema, skin pigmentation, or too thick a tissue sample is unusual since the introduction of very bright light emitting diodes. Poor perfusion can be determined either from warning messages from the instrument itself or from the shape of the pulse waveform. A sharp waveform with a clear dicrotic notch indicates good perfusion, while a waveform that resembles a sine wave indicates poor perfusion. If poor perfusion is suspected the accuracy of the displayed value should be viewed with caution, and an attempt should be made to increase perfusion at the chosen site or at a different site (see below). Local perfusion may be increased most easily by applying heat. Alternatively, vigorous rubbing or the application of a topical vasodilator, such as oil of wintergreen or a small amount of glyceryl trinitrate cream, may be effective. Constrictive clothing or sphygmomanometer cuff will impair perfusion and cause venous congestion and should be removed.

Management of hypoxaemia

Oxyhaemoglobin saturation	*Management*
90-95%	Measure oxyhaemoglobin saturation regularly, especially at night If value is unexpected, check signal quality and probe Investigate cause of hypoxaemia
80-90%	As above *and* give oxygen until oxyhaemoglobin saturation $\geq 90\%$
$< 80\%$	As above *and* start continuous monitoring Consider ventilatory support

The emitters and detectors must be opposite each other, and light must not reach the detector other than through the tissue. Thus care must be taken that a digit is fully inserted into a finger probe and that flexible probes are applied correctly. Probes should be protected from excessive ambient light.

AVOIDING MOTION ARTEFACT

Most movement artefact occurs by movement of the probe in relation to the skin. The probe should be adequately secured to the skin at a monitoring site where movement is minimised. Conscious patients commonly hold the digit with probe affixed in the air, to the detriment of the signal. They should be encouraged to rest the hand or foot gently on a soft surface. If tremor persists then an alternative site should be used. For prolonged monitoring when movement is expected, self adhesive probes on the fingers or toes are usually best, but a clip type of probe on the lobe of the ear is preferred by some (fig 2). If clip type finger probes are to be used then a lightweight version is preferred and the cable should be secured firmly to the back of the hand.

Choice of oximeter

Early studies suggested that there were considerable differences between the oximeters from different manufacturers in their ability to reject artefact and poor perfusion. Continuing development and refinement of the software mean that there is now little to choose between different makes under conditions commonly encountered, and the choice depends on features offered, range of probes available, and price.

CHOICE OF PROBE AND SITE

A finger is the first choice of site, and a non-disposable clip type probe is adequate for most purposes, particularly when single readings are to be taken or little movement is expected. Self adhesive probes are most useful for long term monitoring and when motion artefact is expected. Toes may be used instead of fingers, but poor perfusion is more likely. The lobe or pinna of the ear is the second choice of site with a clip probe. Fixation is often more difficult than with the digits, and care must be taken that the clip does not exert sufficient pressure to impair perfusion. It is usually easier to achieve adequate perfusion in the ear than in the digits.

The bridge of the nose, the lips, and the tongue have been advocated when perfusion is poor, but there is no evidence that they are any better than conventional sites. Reflectance probes, where emitter and detector are adjacent to each other, have been developed but are not recommended as they are susceptible to inaccuracy and artefact.

CHOICE OF INSTRUMENT

When choosing an instrument, consider the likely areas of use. If spot measurements are intended—for example, in general practice or in general wards—the emphasis should be on size, battery capability, and robustness. In contrast, if continuous monitoring of sick patients is expected then a good range of probes, provision of a waveform display, and comprehensive alarms will be important. The recording of data will require an analogue or serial connection or an internal memory. The instruments store either the average or the lowest value within an epoch that may range from one second to one minute. The latter is suitable if an overall impression of oxygenation is required but not when episodic hypoxaemia is being sought—such as with sleep apnoea, where the periodicity of the apnoeas may be less than a minute.

1 Comroe JH, Bothelo S. Unreliability of cyanosis in recognition of arterial anoxemia. *Am J Med Sci* 1947;**214**:1-6.
2 Hay WW, Brockway JM, Eyzaguirre M. Neonatal pulse oximetry: accuracy and reliability. *Pediatrics* 1989;**83**:717-22.

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Development of review criteria: linking guidelines and assessment of quality

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Review criteria are designed to enable clinicians and others to assess care. However, there is no established method for developing criteria, and they are often confused with guidelines. Criteria should comprise measurable activities that are appropriate for the setting in which they are to be used. They should also be based on research evidence and prioritised according to the strength of that evidence and effect on outcome. Good criteria can be used to aid implementation of guidelines by providing a standard against which to monitor performance and enabling clinical audit.

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In the continuing debate about the most effective methods for assessing high quality care reference is often made to "guidelines" and "review criteria." Although the purpose of guidelines is to assist in making clinical decisions and criteria are used in the assessment of care[1] (box 1), these crucial distinctions are not always clearly made, leading to confusion about their development and application in clinical practice. Furthermore, much less attention has been given to methods for developing and using review criteria compared with guidelines. In improving care, sound measures for the assessment of quality are as necessary as "systematically developed statements to assist practitioner and patient decisions."[1] The aims of this paper are, firstly, to make explicit the desirable attributes of criteria and, secondly, to propose a framework for linking them with the process of development of guidelines.

The respective roles of guidelines and criteria can be clarified by the following example. The guidelines of the British Hypertension Society state that "great emphasis should be placed on encouraging patients to stop smoking as the coexistence of smoking as an additional risk factor in hypertensive patients confers a much increased risk of subsequent cardiovascular events."[2] To convert this guideline into review criteria it would need to become "the records show that at least annually (*a*) there has been an assessment of smoking habit and (*b*) appropriate advice has been given to smokers." The criteria make clear what information is required to assess clinician compliance, how the information is to be obtained, and the time period in which smoking habit should be assessed. It illustrates how criteria used for assessment need to be more detailed and specific than guideline statements used to assist decision making.

The importance of establishing a method for developing criteria lies in part in the role they can have in the implementation of guidelines. Guidelines have been produced by clinicians (that is, doctors, nurses, and other professionals directly providing clinical care)