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Practical Applications of Pulse Oximetry

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INTRODUCTION

Pulse oximeters are now a standard part of perioperative monitoring which give the anaesthetist an indication of the patient's cardiorespiratory status. Following successful use during anaesthesia, in the intensive care unit and in the recovery room, oximetry has been increasingly introduced in other areas of the hospital such as general wards, high-dependency areas within wards and sites of interventional procedures (radiology and endoscopy units). Pulse oximeters have pitfalls and limitations and staff training is essential to avoid inadvertent misuse and potential patient harm. This article aims to give an overview of the function and use of pulse oximetry that is appropriate to both regular and occasional users.

Pulse oximeters measure the oxygen saturation of haemoglobin (Hb) in arterial blood, using a probe attached to the patient's finger or ear lobe that is linked to a microprocessor unit. The unit displays the percentage of haemoglobin saturated with oxygen, together with an audible signal for each pulse beat, a calculated heart rate and in some models, a graphical display of the blood flow past the probe. Audible alarms which can be programmed by the user are provided. An oximeter detects hypoxia before the patient becomes clinically cyanosed.

Two basic physical principles form the basis of oximetry:

- First, the absorption of light at two different wavelengths (660 and 940nm) by haemoglobin differs depending on the proportion of haemoglobin molecules that are bound to oxygen ('oxygenated'). By calculating the absorption at the two wavelengths, the processor can compute the proportion of haemoglobin that is oxygenated.
- Second, the light signal following transmission through the tissues has a pulsatile component, resulting from the changing volume of arterial blood with each pulse beat. This can be distinguished by the processor from the non-pulsatile component resulting from venous, capillary and tissue light absorption.

The function of a pulse oximeter is affected by many variables, including:

- ambient light,
- shivering,
- abnormal haemoglobins,
- pulse rate and rhythm,
- vasoconstriction,
- cardiac function.

A pulse oximeter gives no indication of a patient's ventilation, only of their oxygenation, and extreme hypercapnoea may be overlooked if supplemental oxygen is being given. In addition, there may be a delay between the occurrence of a potentially hypoxic event, such as respiratory obstruction, and a pulse oximeter detecting low oxygen saturation. However, oximetry is a useful non-invasive monitor of a patient's cardiorespiratory system, which has undoubtedly improved patient safety in many circumstances.

WHAT DOES A PULSE OXIMETER MEASURE?

The oxygen saturation of haemoglobin in arterial blood

This is a measure of the average amount of oxygen bound to each haemoglobin molecule. The percentage saturation is given as a digital readout together with an audible signal, varying in pitch depending on the oxygen saturation.

The pulse rate

This is given as beats per minute, averaged over 5 to 20 seconds (this period can be varied on some monitors).

In addition, systolic blood pressure can be estimated by noting the pressure at which the oximetry trace reappears during deflation of a proximal non-invasive blood pressure cuff.

WHAT DOESN'T A PULSE OXIMETER MEASURE?

- The **oxygen content** of the blood,

Summary

Pulse oximetry is a simple non-invasive method of monitoring patients which can be used in a wide variety of circumstances, and in the face of limited resources. The pulse oximeter represents a wise choice of monitor since, with appropriate training, it allows assessment of several different patient parameters.

The basic science principles, pitfalls and clinical use of pulse oximeters are discussed.

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- The amount of **oxygen dissolved** in the blood,
- The respiratory rate or tidal volume i.e. **ventilation** (and therefore carbon dioxide clearance),
- The **cardiac output or blood pressure**, although information about blood flow to the peripheries can be inferred.

PRINCIPLES OF MODERN PULSE OXIMETRY

Oxygen is carried in the bloodstream, mainly bound to haemoglobin. One molecule of haemoglobin can carry up to four molecules of oxygen, which is then 100% saturated with oxygen. The average percentage saturation of a population of haemoglobin molecules in a blood sample is the oxygen saturation of the blood. In addition, a very small quantity of oxygen is carried dissolved in the blood, which can become important if the haemoglobin level is extremely low. The latter, however, is not measured by pulse oximetry.

The relationship between the arterial partial pressure of oxygen (PaO_2) and the oxygen saturation is described by the haemoglobin-oxygen dissociation curve (see Figure 1). The sigmoid shape of this curve represents the fact that unloading of oxygen is facilitated in the peripheral tissues, where the PaO_2 is low and oxygen is required for cellular respiration. The curve may be shifted to the left or right by various patient characteristics, such as pH, temperature and recent blood transfusion.

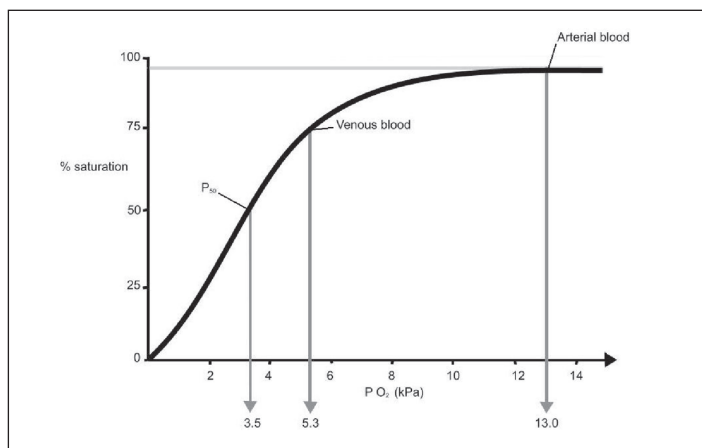


Figure 1. The haemoglobin-oxygen dissociation curve

A pulse oximeter consists of a peripheral probe, together with a microprocessor unit, displaying a waveform, the oxygen saturation and the pulse rate. Most oximeters also have an audible pulse tone, the pitch of which is proportional to the oxygen saturation - useful when one cannot see the oximeter display. The probe is placed on a peripheral part of the body such as a digit, ear lobe or the nose. Within the probe are two light-emitting diodes (LEDs), one in the visible red spectrum (660nm) and the other in the infrared spectrum (940nm). The beams of light pass through the tissues to a photodetector. During passage through the tissues, some light is absorbed by blood and soft tissues, depending on the concentration of haemoglobin. The amount of light absorption at each light frequency depends on the degree of oxygenation of haemoglobin within the tissues (see Figure 2). Note that an *isosbestic* point describes a wavelength at which absorption of light by a substance remains constant as the equilibrium between its component substances is shifted.

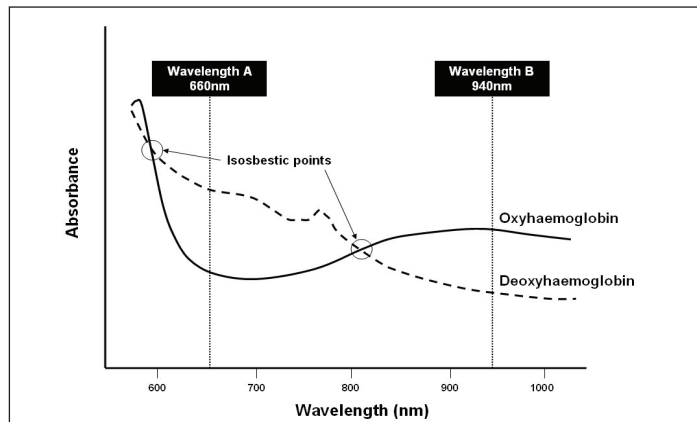


Figure 2. The spectrum of absorbances for haemoglobin and oxyhaemoglobin, showing the isosbestic points

The microprocessor can select out the absorbance of the pulsatile fraction of blood, i.e. that due to arterial blood, from constant absorbance due to non-pulsatile venous or capillary blood and other tissue pigments. Several recent advances in microprocessor technology have reduced the effects of interference on pulse oximeter function. Time division multiplexing, whereby the LED's are cycled: red on, then infrared on, then both off, many times per second, helps to eliminate background 'noise'. Quadrature division multiplexing is a further advance in which the red and infrared signals are separated in phase rather than time and then recombined in phase later. In this way, an artefact due to motion or electromagnetic interference may be eliminated since it will not be in the same phase of the two LED signals once they are recombined.

Saturation values are averaged out over 5 to 20 seconds. The pulse rate is also calculated from the number of LED cycles between successive pulsatile signals and averaged out over a similar variable period of time, depending on the particular monitor.

From the proportions of light absorbed at each light frequency, the microprocessor calculates the ratio of the two. Within the oximeter memory is a series of oxygen saturation values obtained from experiments performed on human volunteers, given increasingly hypoxic mixtures of gases to breathe. The microprocessor compares the ratio of absorption at the two light wavelengths measured with these stored values, and then displays the oxygen saturation digitally as a percentage and audibly as a tone of varying pitch. As it is unethical to desaturate human volunteers below 70%, it is vital to appreciate that oxygen saturation values below 70% obtained by pulse oximetry are unreliable.

Reflection pulse oximetry uses reflected rather than transmitted light on a single-sided monitor. It can therefore be used more proximally anatomically e.g. forehead, bowel, although it may be difficult to secure. Other than using specific reflection spectra, the principles are the same as for transmission oximetry.

PRACTICAL TIPS TO THE SUCCESSFUL USE OF PULSE OXIMETRY

- Plug the pulse oximeter in to an electrical socket, if available, to recharge the batteries.

- Turn the pulse oximeter on and wait for it to go through its calibration and check tests.
- Select the probe you require with particular attention to correct sizing and where it is going to go. The digit should be clean (remove nail varnish).
- Position the probe on the chosen digit, avoiding excess force.
- Allow several seconds for the pulse oximeter to detect the pulse and calculate the oxygen saturation. Resist the temptation to impatiently move the probe from finger to finger without waiting for the reading to register.
- Look for a displayed waveform. Without this, any reading is meaningless.
- Read off the displayed oxygen saturation and pulse rate.
- If in doubt, rely on your clinical judgement, rather than the value the machine gives.

Be cautious interpreting figures where there has been an instantaneous change in saturation - for example 99% falling suddenly to 85%. This is not physiologically possible.

Alarms

- Prior to each case check that the alarms are set at an appropriate level.
- If the 'Low Oxygen Saturation' alarm sounds, check the positioning of the probe and that there is a good pulse waveform. Look to see if the patient is clinically cyanosed and check that the patient is conscious if that is appropriate. Check the airway and make sure the patient is breathing adequately. Lift the chin or apply other airway manoeuvres as appropriate. Give oxygen if necessary. Call for help.
- If the 'Pulse Not Detected' alarm sounds, look for the displayed waveform on the pulse oximeter. Feel for a central pulse. If there is no pulse, call for help and start the procedures for Basic and Advanced Life Support. If there is a pulse, try repositioning the probe, or put the probe on a different digit.
- On most pulse oximeters, the alarm limits for oxygen saturation and pulse rate can be altered according to your needs. However, do not alter an alarm just to stop it sounding - it could be telling you something important!

USES OF PULSE OXIMETRY

- A simple, portable 'all-in-one' monitor of oxygenation, pulse rate and rhythm, suitable for use in all settings.
- As a safe, non-invasive monitor of the cardiorespiratory status of high-dependency patients - in the emergency department, during general and regional anaesthesia, postoperatively and in the intensive care unit. This includes procedures such as endoscopy, where drugs such as midazolam are frequently given to more elderly patients. Pulse oximeters detect the presence of cyanosis more reliably than even the experienced doctors using their clinical judgement.
- During the transport of patients, especially when noise is an issue,

for example in aircraft, helicopters or ambulances. The audible tone and alarms may not be heard, but if a waveform can be seen, together with an acceptable oxygen saturation, this gives a global indication of a patient's cardiorespiratory status.

- To assess the viability of limbs after plastic and orthopaedic surgery and, for example, following vascular grafting, or where there is soft tissue swelling. As a pulse oximeter requires a pulsatile signal under the sensor, it can detect whether a limb is getting a blood supply.
- As a means of reducing the frequency of blood gas analysis in intensive care patients, particularly in paediatric practice where vascular (arterial) access may be more difficult.
- To limit oxygen toxicity in premature neonates supplemental oxygen can be tapered to maintain an oxygen saturation of 90% - thus avoiding the damage to the lungs and retinas of neonates. Although pulse oximeters are calibrated for adult haemoglobin, HbA, the absorption spectra of HbA and HbF are almost identical over the range used in pulse oximetry, so the technique remains reliable in neonates.
- During thoracic anaesthesia, and particularly one-lung anaesthesia, to determine whether oxygenation via the remaining lung is adequate or whether increased concentrations of oxygen must be given.
- Fetal oximetry - a developing technique that uses reflectance oximetry, using LEDs of 735nm and 900nm. The probe is placed over the temple or cheek of the fetus, and needs to be sterile and sterilisable. They are difficult to secure and the readings are variable, for physiological and technical reasons. Hence the trend is more useful than the absolute value.

LIMITATIONS OF PULSE OXIMETRY

- Oximetry is **not a monitor of ventilation**. Carbon dioxide levels will rise where a patient's minute volume is low. When supplementary oxygen is given, the oxygen saturations may remain normal as hypercarbia causes decreased conscious level, respiratory acidosis with the risk of cardiorespiratory collapse. Knowledge of this pitfall is essential for safe use of pulse oximetry.
- Pulse oximetry may be less effective in **critically ill or injured patients**. Tissue perfusion may be poor (due to hypovolaemia, severe hypotension, cold, cardiac failure, some cardiac arrhythmias or peripheral vascular disease) and thus the oximeter probe may not detect a pulsatile signal. More central sites for probe positioning include the nose, and the lips, although placement at these sites for prolonged periods may cause pressure necrosis. Application of a paediatric probe to an oropharyngeal airway has been shown in case reports to provide effective oximetry (Figure 3).¹
- **Waveform presence**. If there is no waveform visible on a pulse oximeter, any percentage saturation values obtained are meaningless.

In the following situations the pulse oximeter readings may not be accurate.

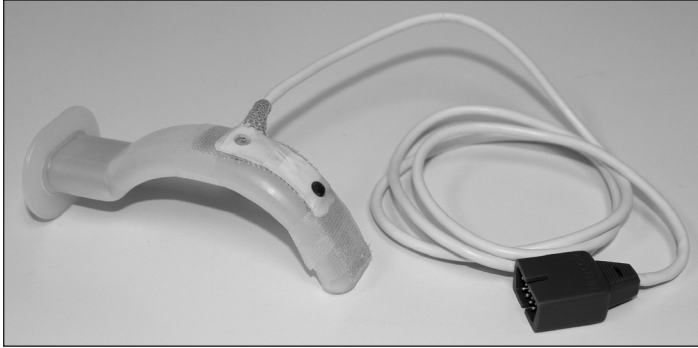


Figure 3. Pharyngeal pulse oximetry may be achieved in shocked patients using a paediatric pulse oximetry probe taped to an oropharyngeal (Guidel) airway¹

- **Venous congestion**, particularly when caused by tricuspid regurgitation, may produce venous pulsations which may produce low readings with ear probes. Venous congestion of the limb may affect readings as can a poorly positioned probe. When readings are lower than expected, it is worth repositioning the probe. In general, however, if the waveform on the flow trace is good, then the reading will be accurate.
- **Bright overhead lights** in theatre may cause the oximeter to be inaccurate, and the signal may be interrupted by surgical diathermy. **Shivering** may cause difficulties in picking up an adequate signal.
- Pulse oximetry cannot distinguish between different forms of haemoglobin. **Carboxyhaemoglobin** (haemoglobin combined with carbon monoxide) is registered between 90 to 100% oxygenated haemoglobin and 10% desaturated haemoglobin - therefore the oximeter will overestimate the saturation. A technique called CO-oximetry (see below) is the only available method of estimating the severity of carbon monoxide poisoning.
- The presence of **methaemoglobin** (rarely caused by prilocaine overdose) prevents the oximeter working accurately and the readings will tend towards 85%, regardless of the true saturation.
- Methylene blue may be used in surgery to highlight the parathyroids, to guide dissection of the sentinel axillary lymph node in surgery for breast cancer or to treat methaemoglobinaemia. Methylene blue causes a shortlived reduction in saturation.
- Nail varnish may cause falsely low readings.

Pulse oximetry is not affected by jaundice, dark skin or anaemia.

- **'Lag monitor'** - the partial pressure of oxygen may have fallen a great deal before the oxygen saturation starts to fall. If a healthy adult patient is given 100% oxygen to breathe for a few minutes and then ventilation ceases for any reason, several minutes may elapse before the oxygen saturation starts to fall. There is also a **response delay** due to signal averaging. This means that there is

a delay after the actual oxygen saturation starts to drop because the signal is averaged out over 5 to 20 seconds.

- **Patient safety** - there are reports of skin burns or pressure damage under the probe because some early probes had a heater unit to ensure adequate skin perfusion. The probe should be correctly sized, and should not exert excessive pressure. Special probes are now available for paediatric use.
- The **penumbra effect** re-emphasises the importance of correct probe positioning. This effect causes falsely low readings and occurs when the probe is not symmetrically placed, such that the pathlength between the two LEDs and the photodetector is unequal, causing one wavelength to be 'overloaded'. Repositioning of the probe often leads to sudden improvement in saturation readings. The penumbra effect may be compounded by the presence of variable blood flow through cutaneous pulsatile venules. Note that the waveform may appear normal despite the penumbra effect, as it measures predominantly one wavelength only.

ALTERNATIVES TO PULSE OXIMETRY

Bench CO-oximetry

This is the gold standard and is the classic method by which a pulse oximeter is calibrated. The CO-oximeter calculates the actual concentrations of haemoglobin, deoxyhaemoglobin, carboxyhaemoglobin and methaemoglobin in the sample and hence calculates the actual oxygen saturation. CO-oximeters are much more accurate than pulse oximeters - to within 1%, but they give a 'snapshot' of oxygen saturation, are bulky, expensive and require constant maintenance, as well as requiring a sample of arterial blood to be taken.

Blood gas analysis

This requires an invasive sample of arterial blood. It gives the 'full picture', including arterial partial pressure of oxygen and carbon dioxide, arterial pH, actual and standardised base excess and actual and standardised bicarbonate concentrations. Many blood gas analysers report a calculated saturation which is less accurate than that provided by the pulse oximeter.

SUMMARY

Pulse oximeters give a useful non-invasive estimation of the arterial haemoglobin oxygen saturation. They are useful in anaesthesia, recovery, intensive care (including neonatal) and patient transport, providing an adjunct to clinical assessment of a patient. It is important to recognise and remember that pulse oximeters give no direct indication of a patient's ventilation, only of their oxygenation and that there is a time-lag in detection of a hypoxic event. Sources of inaccuracy include ambient light, shivering, vasoconstriction, shock and the presence of abnormal haemoglobins.

FURTHER READING

1. Yu H, Liu B. Successful use of pharyngeal pulse oximetry with the oropharyngeal airway in severely shocked patients. *Anaesthesia* 2007; **62**: 734-6