# Uses and limitations of pulse oximetry

Mark D Stoneham

**Pulse oximeters are a useful method of monitoring patient welfare in many circumstances. However, the technique of pulse oximetry has limitations, and there is little or no formal training available. Patient safety could be compromised if pulse oximeters were used by staff with inadequate knowledge.**

**Dr Mark D Stoneham** is Senior Registrar in the Department of Anaesthesia, Stoke Mandeville Hospital, Aylesbury, Buckinghamshire HP21 8AL

Pulse oximeters are now a standard part of perioperative monitoring (Eichorn et al, 1986; Association of Anaesthetists of Great Britain and Ireland, 1992) and give the operator a non-invasive indication of the patient's cardiorespiratory status. Following their successful use in intensive care, the recovery room and during anaesthesia, they have been introduced in other areas of medicine, e.g. general wards (Bowton et al, 1991), apparently without staff undergoing adequate training in their use (Anonymous, 1994; Stoneham et al, 1994). The technique of pulse oximetry does have pitfalls and limitations and it is possible that patient safety may be compromised if the technique is used by staff who have not received adequate training. This article is therefore intended for the 'occasional' user of pulse oximetry.

Pulse oximeters measure the arterial oxygen saturation of haemoglobin. The technology involved is complicated (Moyle, 1994) but there are two basic physical principles. First, the absorption of light at two different wavelengths by haemoglobin differs depending on the degree of oxygenation of haemoglobin. Second, the light signal produced 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 microprocessor from the non-pulsatile component resulting from venous, capillary and tissue light absorption (Tremper and Barker, 1989).

The function of a pulse oximeter is affected by many variables including: ambient light, shivering, abnormal haemoglobins, pulse rate and rhythm, vasoconstriction and cardiac function. A pulse oximeter gives no indication of a patient's ventilation, only of his/her oxygenation, and thus can give a false sense of security if supplemental oxygen is being given. In addition, there may be a considerable time delay between the occurrence of a potentially hypoxic event, e.g. 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?

1. The *oxygen saturation* of haemoglobin in arterial blood which 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 which varies in pitch depending on the oxygen saturation.
2. The *pulse rate* in beats per minute, averaged over 5–20 seconds.

A pulse oximeter gives *no* information on any of the following variables (Stoneham et al, 1994):

1. The oxygen content of the blood
2. The amount of oxygen dissolved in the blood
3. The respiratory rate or tidal volume
4. The cardiac output or blood pressure.

## 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 and is then fully 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 levels are extremely low.

The relationship between the arterial partial pressure of oxygen ($PaO_2$) and the oxygen saturation is described by the

haemoglobin–oxygen dissociation curve (Nunn, 1993) (*Figure 1*). The sigmoid shape of this curve facilitates unloading of oxygen in the peripheral tissues where the $PaO_2$ is low and oxygen is required for respiration.

A pulse oximeter consists of a peripheral probe, together with a microprocessor unit which displays 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; this is 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 (660 nm) and the other in the infrared spectrum (940 nm). 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 the haemoglobin within the tissues (*Figure 2*).

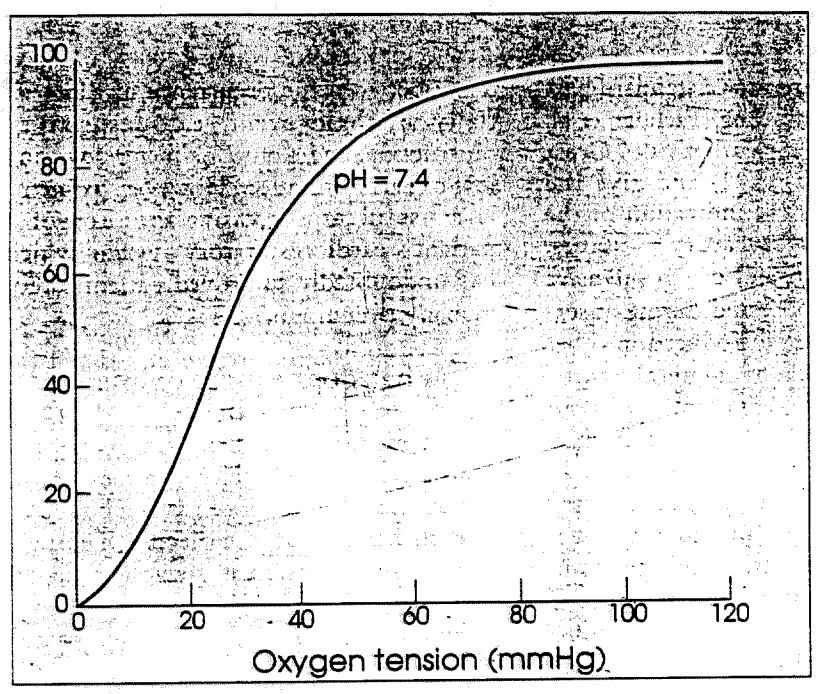


Figure 1. Haemoglobin–oxygen dissociation curve.

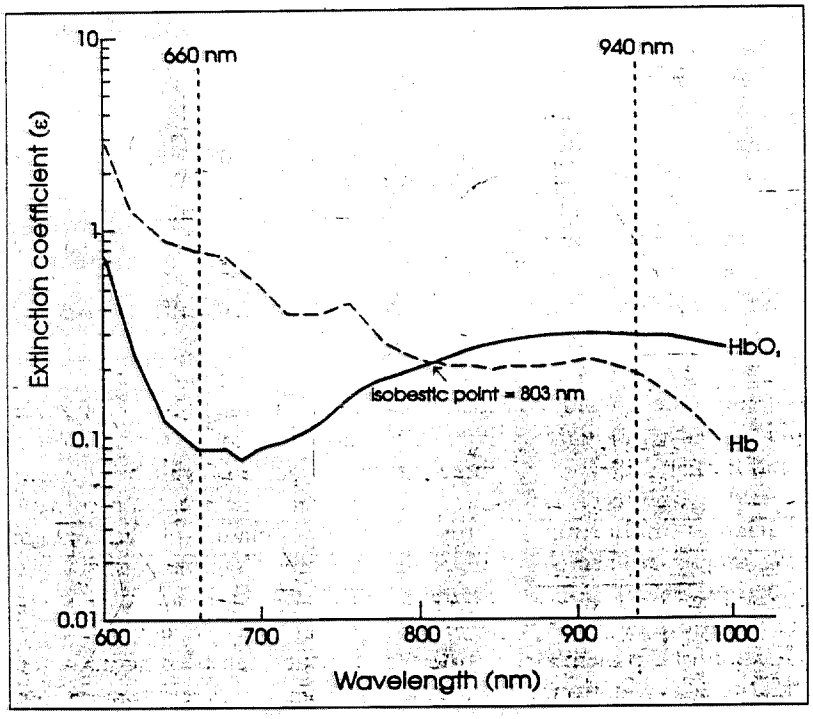


Figure 2. Absorption spectra of oxygenated haemoglobin (HbO) and deoxygenated haemoglobin (Hb) with wavelengths of the two commonly used light-emitting diodes.

The microprocessor can distinguish the absorbance from the pulsatile fraction of blood (that due to arterial blood) from constant absorbance caused by non-pulsatile venous or capillary blood and other tissue pigments (*Figure 3*). Several recent advances in microprocessor technology have reduced the effects of interference on pulse oximeter function (Trueblood, 1991; Zander and Mertzlufft, 1991). Time division multiplexing, whereby the LEDs are cycled many times per second (red on, infrared on, both off), 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 as a result of 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 5–20 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.

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 in which human volunteers were given increasingly hypoxic mixtures of

* The Beer-Lambert Law relates this accurately:

$$I = I_0 e^{-kcl}$$

where $c$ = concentration of absorbing dye; $I$ = light intensity measured; $I_0$ = light intensity transmitted by light-emitting diode; $k$ = proportionality constant; $l$ = path length through dye

gases to breaths. 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%, oxygen saturation values below 70% obtained by pulse oximetry are unreliable.

## History of pulse oximetry

In the USA in 1935, Carl Matthes built the first device which continuously measured human blood oxygen saturation by transilluminating human tissue with light (Severinghaus and Astrup, 1986). He used two light wavelengths, one of which was used to compensate for the thickness of the tissue and the light intensity. As early as 1951, the ability of oximeters to detect low oxygen saturation levels before there was clinical evidence of cyanosis was recognised (Stephen et al, 1951). Early oximeters were all designed to be placed on the ear. They were delicate and had to be recalibrated for each patient. They did not measure true 'arterial' oxygen saturation because of interference from capillary and venous blood.

Hewlett-Packard invented an ear oximeter, the probe of which could be heated to 'arterialize' the ear in 1970, but it was in 1974 that Takuo Aoyagi discovered that he could isolate the 'arterial' oxygen saturation by looking for pulsations in the signal coming through the tissues. Aoyagi is regarded as the father of pulse oximetry.

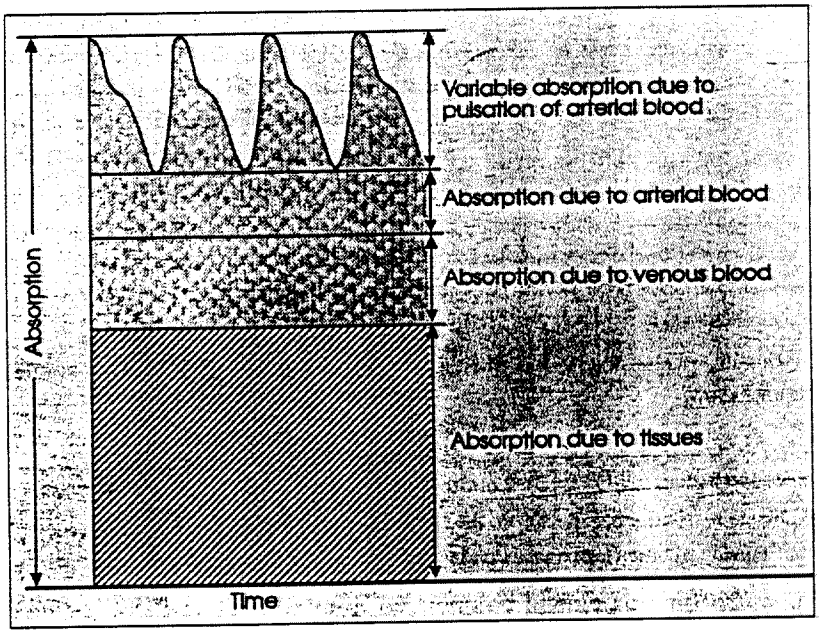


Figure 3. Components of absorption signal.

Much later, Scott Wilber produced a lightweight probe with a cable connecting it to the main instrument and also stored human volunteer data in the oximeter to improve the reliability of saturation estimates. Since that time, the major advances have been in making the oximeter signal increasingly resistant to interference from external motion artefacts and electromagnetic radiation.

## Uses of pulse oximetry

### Monitoring of high-dependency patients

Pulse oximetry allows the safe, non-invasive monitoring of the cardiorespiratory status of high-dependency patients, e.g. those in intensive care, the recovery room and undergoing general and regional anaesthesia. This includes procedures such as endoscopy, where frail patients are given sedative drugs such as midazolam. Pulse oximeters detect the presence of cyanosis more reliably than even the best physicians when using their clinical judgment (Comroe and Botelho, 1947; Stephen et al, 1951).

### Transport of patients

Pulse oximetry is used during the transport of patients, especially when this is noisy, e.g. 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.

### Limb viability assessment

Pulse oximetry may be used to assess the viability of limbs after plastic and orthopaedic surgery, e.g. following vascular grafting, or where there is soft tissue swelling. A pulse oximeter requires a pulsatile signal under the sensor and can therefore detect whether a limb is getting a blood supply.

### Reducing the use of blood gas analysis

The technique can be used as a means of reducing the frequency of blood gas analysis in intensive care patients, especially 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 damage to the lungs and retinas of neonatal babies.

*'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. A pulse oximeter in these circumstances warns of a potentially fatal complication several minutes after it has happened.'*

### During thoracic anaesthesia

When one lung is being collapsed down, it is important to determine whether oxygenation via the remaining lung is adequate or whether increased concentrations of oxygen must be given.

## Limitations of pulse oximetry

### Critically ill patients

Pulse oximetry may be less effective in very sick patients, because tissue perfusion may be poor and thus the oximeter probe may not detect a pulsatile signal.

### Waveform presence

If there is no waveform visible on a pulse oximeter, any percentage saturation values which are obtained are meaningless.

### Inaccuracies

There are a number of different problems which should be considered (Ralston et al 1991a, b; Webb et al, 1991):

1. Bright overhead lighting, shivering and motion artefact may give pulsatile waveforms and saturation values when there is no pulse.
2. Abnormal haemoglobins such as those produced in methaemoglobinaemia, e.g. following overdose of prilocaine, cause readings to tend towards 85%.
3. Carboxyhaemoglobin as a result of carbon monoxide (CO) poisoning causes saturation values to tend towards 100%. A pulse oximeter is extremely misleading in cases of CO poisoning for this reason. CO-oximetry is the only available method of estimating the severity of CO poisoning.
4. Dyes and pigments, including nail varnish, may give artificially low values.
5. Vasoconstriction and hypothermia cause reduced tissue perfusion and failure to register a signal.
6. Rare cardiac valvular defects such as tricuspid regurgitation cause venous pulsation and therefore venous oxygen saturation is recorded by the oximeter.
7. Oxygen saturation values less than 70% are inaccurate as there are no control values for comparison.
8. Cardiac arrhythmias may interfere with detection of the pulsatile signal by the oximeter and with calculation of the pulse rate.

NB. Age, sex, anaemia, jaundice and dark skin have little or no effect on oximeter function.

### Lag monitor

The partial pressure of oxygen can fall a great deal before the oxygen saturation starts to fall (Verhoeff and Sykes, 1990; Broome et al, 1992). 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. A pulse oximeter in these circumstances warns of a potentially fatal complication several minutes after it has happened. For this reason, the pulse oximeter has been described as 'a sentry standing at the edge of the cliff of desaturation' (Tremper and Barker, 1989). This effect is explained by the sigmoid shape of the haemoglobin–oxygen dissociation curve (See *Figure 1*).

### Not a monitor of ventilation

A recent case report highlighted the false sense of security provided by pulse oximetry (Davidson and Hosie, 1993; Hutton and Clutton-Brock, 1993). An elderly woman was receiving oxygen by face mask postoperatively in the recovery room. She became increasingly drowsy, despite having an oxygen saturation of 96%. The reason was that her respiratory rate and minute volume were low because of residual neuromuscular block and sedation, yet she was receiving high concentrations of inspired oxygen, so that her oxygen saturation was maintained. She ended up with an arterial carbon dioxide concentration of 280 mmHg (normal 40 mmHg) and was ventilated for 24 hours on intensive care. Thus oximetry gives a good estimation of adequate oxygenation, but no direct information about ventilation, particularly, as in this case, when supplemental oxygen is being administered.

### Response delay

This is caused by signal averaging, and means that there is a delay after the actual oxygen saturation starts to drop because the signal is averaged out over 5–20 seconds.

### Patient safety

There have been one or two case reports of skin burns or pressure damage under the probe because some early probes had a heater unit to ensure adequate skin perfusion (Bannister and Scott, 1988).

## Alternatives to pulse oximetry?

### Bench CO-oximetry

This is the gold standard, and is the classic method by which a pulse oximeter is calibrated (Zander and Mertzlufft, 1991). A

CO-oximeter directly analyses a sample of arterial blood. Several different wavelengths of blood are transmitted across the blood sample and the absorption of each is measured. The CO-oximeter calculates the concentrations of haemoglobin, deoxyhaemoglobin, carboxyhaemoglobin and methaemoglobin in the sample and hence calculates the 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

Arterial blood gas analysis also requires an invasive sample of arterial blood. It gives the 'full picture', including $PaO_2$, $PaCO_2$, arterial pH, actual and standardised base excess and actual and standardised bicarbonate concentrations. Blood gas analysers are bulky and expensive instruments, require considerable maintenance and also need an experienced person to interpret the results meaningfully.

## KEY POINTS

- **Pulse oximeters give a non-invasive estimation of the arterial haemoglobin oxygen saturation.**
- **Pulse oximetry can be useful in: anaesthesia, recovery, intensive care (including neonatal) and patient transport.**
- **There are two principles involved in pulse oximetry:**
  1. **Differential light absorption by haemoglobin and oxyhaemoglobin**
  2. **Identification of the pulsatile component of the signal.**
- **No direct indication of a patient's ventilation can be obtained — only of their oxygenation.**
- **A pulse oximeter is a lag monitor, which describes the time delay between a potentially hypoxic event such as respiratory obstruction and a pulse oximeter detecting low oxygen saturation.**
- **Inaccuracies of pulse oximetry are caused by: ambient light, shivering and vasoconstriction, abnormal haemoglobins, and alterations in pulse rate and rhythm.**
- **Advances in microprocessors have led to improved signal processing.**

## Practical tips for 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 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.
- Look for a displayed waveform. Without this, any reading is meaningless.
- Read off the displayed oxygen saturation and pulse rate.
- Be cautious in interpreting figures where there has been an instantaneous change in saturation, e.g. 99% falling suddenly to 85%. This is not physiologically possible.
- If in doubt, rely on your clinical judgment rather than the value given by the pulse oximeter.

## Alarms

- If the Low Oxygen Saturation alarm sounds, check that the patient is conscious if 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!

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