KNOW YOUR EQUIPMENT: Pulse oximeter

Verghese Cherian
Associate Professor of Anesthesiology Hershey Medical Center

The cascade of oxygen from the atmosphere ($P_{atmosphere}O_2$-153 mmHg) to the mitochondria ($P_{mitochondria}O_2$- 2-10mmHg) passes through the lung ($P_{alveoli}O_2$- 101mmHg) and the arterial blood (PaO_2-98mmHg). Although, measuring the PaO_2 is the gold standard of assessing oxygenation, it requires a sample of arterial blood. Since majority of oxygen carried in the blood is combined with hemoglobin, measuring the percentage of hemoglobin saturated with oxygen is a surrogate measure of oxygenation and it can be done non-invasively, using a pulse oximeter.

Physiological Fundamentals

Uptake and delivery of oxygen is one of the primary roles of the cardio-respiratory system. It is prudent to clarify some of the commonly (mis)used terminology about oxygen carriage. **Oxygen Content** (CAO_2) is the amount of oxygen carried by 100ml of blood; both combined with hemoglobin and dissolved in plasma, and it is expressed as 'ml in 100ml of blood'.

$$CAO_2 = (1.34 \times SaO_2 \times Hb) + 0.0031 \times PaO_2$$

Where 1.34 is the oxygen binding capacity of hemoglobin (Hüfner constant), and 0.0031 is the solubility of oxygen in blood (ml/100ml blood/mmHg of PO_2)

Oxygen Saturation (SaO_2) is the percentage saturation of hemoglobin with oxygen as measured using an arterial blood sample, as opposed to **SpO_2** which is measured by a pulse oximeter. It is normally expected to be 100%.

Partial pressure of oxygen (PaO_2) is the pressure of oxygen in the arterial blood and is normally close to 100mmHg when breathing room air.

Oxygen Delivery (DO_2) is the amount of blood that exits the heart every minute and so is a product of arterial oxygen content and cardiac output.

Types of Hemoglobin

Hemoglobin A (Hb A) makes up about 95%-98% of hemoglobin found in adults and it contains two alpha (α) chains and two beta (β) protein chains.

Hemoglobin A2 (Hb A2) makes up about 2%-3% of hemoglobin found in adults and it has two alpha (α) and two delta (δ) protein chains.

Hemoglobin F (Hb F) or fetal hemoglobin makes up to 1%-2% of hemoglobin found in adults and it has two alpha (α) and two gamma (γ) protein chains. It is the primary hemoglobin produced by the fetus during pregnancy and its production usually falls shortly after birth and reaches adult level within 1-2 years.

Forms of Hemoglobin

Hemoglobin occurs in various forms in human body

1. Oxy-hemoglobin (OHb) when combined with oxygen
2. Deoxy-hemoglobin (deOHb) when it gives off the oxygen
3. Carbamino-hemoglobin (CO_2Hb) when it combines with CO_2
4. Carboxy-hemoglobin (COHb) when it combines with carbon monoxide (normally <2%, but can increase to 2-4% in smokers)
5. Meth-hemoglobin (MetHb) when the iron in the heme group is in the Fe3+ (ferric) state and not the Fe2+ (ferrous) of normal hemoglobin. (Normal levels - 1-2%)

Components of a Pulse oximeter

The pulse oximeter probe consists of two light emitting diodes (LED) that transmits light at two specified wavelengths and a detector, located on the other side of the tissue, which measures the amount of light transmitted through the tissue, which is usually the fingertip. The probe is

connected to a processor and the monitor displays the pulse waveform, the pulse rate and the oxygen saturation which is denoted as '**SpO_2**'. The monitor also gives an audible beep with each pulse, the pitch of which changes with the value of oxygen saturation. The pitch drops as the saturation falls and rises as it recovers.

Physical Principles

Beer-Lambert Law

The pulse oximeter operates on the principle of absorption of light by the solutes in a solution. The *Beer-Lambert* law states that the amount of light absorbed by a solute is proportional to the concentration of the solute and the distance the light is transmitted through the solution.

$$I_{trans} = I_{Inc}\, e^{-dC\varepsilon}$$

- I_{trans} – Intensity of transmitted light
- I_{inc} – Intensity of incident light
- e – Base of natural logarithm
- d – Distance traveled by the light
- C – Concentration of the dissolved substance
- ε – Extinction coefficient of the solute

Extinction coefficient

Figure 1: Extinction coefficient of different forms of Hemoglobin (Hb), according to wavelength of light

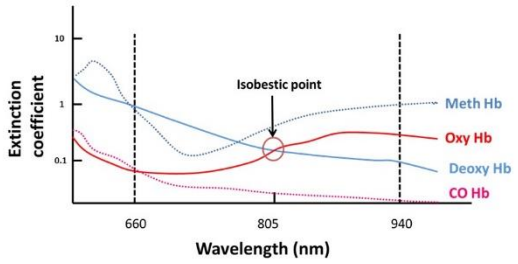


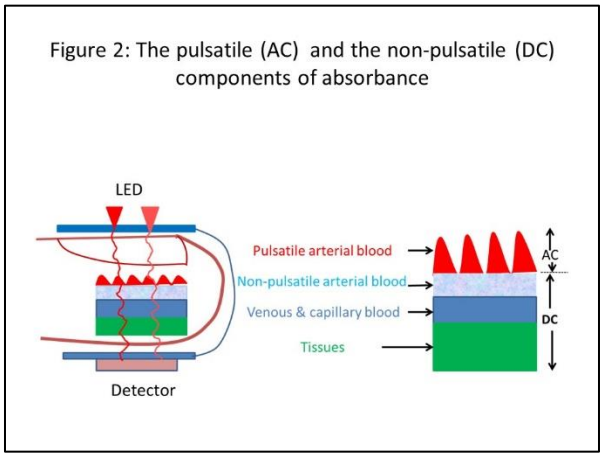
Figure 1 illustrates, for a range of wavelengths of light, the extinction coefficients of the four forms of hemoglobin (Hb), namely deOHb, OHb, COHb and MetHb. Since in normal individuals the amount of MetHb and COHb are

negligible, the pulse oximeter has to differentiate between OHb and deOHb. It is obvious from the graph that the best separation of absorbance curves occurs at wavelengths 660 nm (red) and 940 nm (infrared). At 940 nm the light absorbance of OHb is one and a half times more than that of deOHb, while at 660 nm deOHb absorbs ten times as much as OHb.

The points at which two lines cross indicate the wavelength at which the absorbance is equal. This is known as the *isobestic point*, and for deOHb and OHb it occurs at 805nm and 590nm. At 660nm wavelength, the extinction coefficients of COHb and MetHb are similar to those of OHb and deOHb, respectively.

Pulsatility

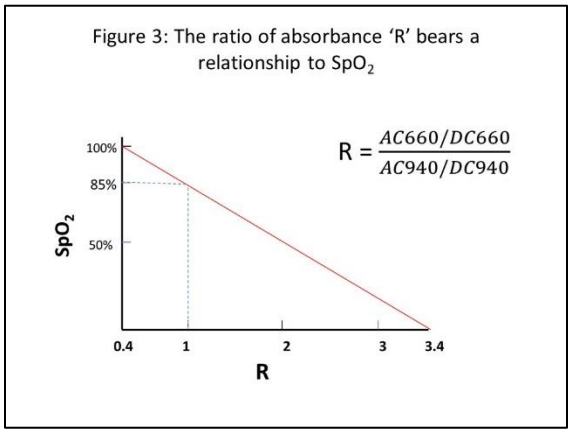
The purpose of the pulse oximeter is to detect the amount of OHb in the arterial blood. When compared to measuring oxygen saturation *in vitro* from an arterial blood sample, the challenge in measuring it *in vivo* is to separate the light absorbance by the venous blood and the tissue proteins from that by the arterial blood.



The pulse oximeter uses an ingenious technology and takes advantage of the pulsatility of arterial blood. (*Figure 2*) It emits and analyses light signals at a very rapid rate (400-600/s) and this can detect the peaks and troughs of the arterial pulse wave. Since, with each pulse there is a surge of arterial blood across the measuring point and therefore an increase in distance of absorbance, the amount of light absorbed would increase, cyclically. Historically, the pulsatile component is referred to as AC

and the non-pulsatile as DC. The ratio of the absorbance of the pulsatile (AC) to that of the non-pulsatile (DC) at both the wavelengths is calculated.

$$R = \frac{AC660/DC660}{AC940/DC940}$$



The ratio (R) of absorbance at 660 nm and 940 nm bear a linear relationship to oxygen saturation. (Figure 3) This calibration curve is created by having volunteers breathe hypoxic gas mixtures to measure R values over a range of SpO_2 values between 100% and 70%. The accuracy of most pulse oximeter is ±2-3% over this range. At high O_2 saturations, this ratio is less than one. At approximately 85% saturation this ratio is equal to one. The values for R for SpO_2 below 70% are mathematically calculated and therefore are less accurate clinically.

Clinical Points

Pulse oximeter is an extremely useful tool and has been part of the minimum monitoring standard prescribed by the ASA in 1986.

A pulse oximeter measures the percentage of oxygen saturation and not the oxygen content, or the PaO_2. Due to the nonlinearity of the Hb dissociation curve, at low saturations such as at high altitude, small changes in PaO_2 can produce large changes in SpO_2. The pulse oximeter provides only the 'functional' SaO_2 and not the 'fractional' SaO_2.

Fractional Saturation – OHb / deOHb + OHb + MethHb + COHb

Functional Saturation – OHb / deOHb + OHb

Factors that affect the functioning of a pulse oximeter

1. At low pulse amplitude, the SpO_2 reads low relative to SaO_2
    - hypothermia, hypovolemia, hypotension, vasoconstriction, blood pressure cuff inflation, tourniquet, cardiac arrest, arrhythmia
2. Presence of COHb and MethHb affects pulse oximeter readings
    - The standard pulse oximeter with two wavelength of emitted light is suited to differentiate OHb from deOHb. Presence of MethHb or COHb can interfere with accurate measurement of OHb. COHb is interpreted by the pulse oximeter as a mixture of approximately 90% OHb and 10% deOHb. Thus at high levels of COHb, the pulse oximeter overestimates the true saturation. (Figure 1) MethHb absorbs equal amounts of red and infrared light, resulting in an R ratio of 1, which is extrapolated as 85% saturation. Therefore, as MethHb increases the pulse oximeter approaches 85% irrespective of the true saturation.
    - To measure COHb and MetHb, a 'Co-oximeter' is used wherein a sample of blood is analyzed by 4 wavelengths of light.
3. Dyes and pigments
    - Serum bilirubin elevation does not affect the accuracy of pulse oximeter
    - Nail polish, especially black, dark blue and purple colors reduces the SpO_2
    - Acrylic finger nails, if not dark colored, does not have significant effect
    - Dyes administered intravenously, such as 1% methylene blue, 0.25% indo-cyanine green and 0.8% indigo-carmine, transiently (1-2 minutes) decrease the SpO_2 in about 30-45s after the injection

4. Ambient light does not affect significantly, as it is compensated for, in modern pulse oximeters
5. Physical movement of the finger as during peripheral nerve stimulation or shivering can create artifacts, as can electrosurgical cautery
6. Radiofrequency interference from a MRI magnet would generate heat from the current passing through the wires in the probe, and has been reported to cause burns under the probe. Therefore, the probes that are MRI compatible do not have any wires in them; instead the light is transmitted through fiberoptic cables.

The pulse oximeter is an integral part of the standard monitoring used by all anesthesiologist, and is currently available in various shapes and sizes. (Figure 4) It is extremely important to have a good understanding of its functioning, the interpretation of its display and limitations.

Figure 4: Pulse oximeters are available in various sizes

References:

1. Chitlian HV, Kaczka DW, Vidal Melo MF. Respiratory Monitoring, In Miller RD(ed), Anesthesia. 8th edition, Elsevier, Philadelphia 1541-1579
2. Thomas C, Lumb AB: Physiology of haemoglobin, Contin Educ Anaesth Crit Care Pain 12:251-256, 2012.
3. Wilson I. Pulse Oximetry-Part1 Anaesthesia tutorial of the week 123. www.totw.anaesthesiologists.org

We anesthesiologists are surrounded by equipment which we use to administer anesthesia, monitor our patients and rely upon during an emergency situation. It is therefore crucial to have a good understanding of the physical principles of these tools and a working knowledge of its usefulness, limitations, source of errors and ways to trouble-shoot them. ‘KNOW YOUR EQUIPMENT’ series will be an attempt towards this.