A Report on Pulse Oximetry
by Jason Glass

Introduction:

This report will conduct a review and analysis of pulse oximetry and its uses in modern science. The science of how wave propagation and optical properties of materials are in oximetry will be explored. The implementation of oximeter circuits will be discussed. In addition specific errors and their sources in pulse oximetry will be discussed. Following that the latest state of oximetry will be examined in clinical study.

History of Oximetry and Pulse Oximetry.

The invention of *oximetry*, the sensing of oxygen concentration levels in the blood, can largely be credited to Glenn Allen Millikan. He developed the first oximeter to help train Royal Air Force pilots during World War II. Pilots were allegedly passing out from oxygen deprivation which was only currently quantifiable by the presence of cyanosis, the blue discoloration of the skin due to low blood oxygen levels [1]. Cyanosis itself is a poor medical diagnostic as patients can be hypoxic without cyanosis and vice versa. There existed no quantitative analysis technique to measure levels of oxygen saturation in the blood before the invention of the oximeter.

Millikan developed an earpiece oximeter which used red and infrared light to determine the SaO_2, oxygen saturation, levels in the patient. This measurement was an application of Beer's Law (Figure 1).

$$I = I_t^{\in -\alpha}$$

Figure 1 – Beer's Law

Beer's law states that for a solute dissolved in a clear solvent the levels of solute can be determined through use of a light source with a known wavelength. The absorbance, α, is equal to d*C*∈. Where d is light path length through the solvent medium, C is the unknown concentration and ∈ is the extinction coefficient, otherwise known as the complex portion of a material's refractive index. The ratio of

transmitted to incident light is dependent on this imaginary portion of the refractive index as this complex value represents how much of a wave interfacing with the material will be blocked and absorbed. Materials with a high imaginary index will very quickly dissipate the wave while values equal to zero will propagate a wave forever with no "quantum friction." A value less than zero represents a material which can be used to propagate a wave as a laser by reflection.

Beer's Law is applied in Pulse Oximetry as the ratio of transmitted and incident red and infrared light beams. These wavelengths are chosen because vascular tissue absorbs blue, green and yellow wavelengths of light to a far greater extent than red and infrared. This means that a sensor would not adequately be able to determine a differential signal of a hypothetical blue and green signal as both waves would be almost completely absorbed regardless of SaO_2 levels. The following chart (Figure 2) shows the relative absorption coefficients of Hb, Hemoglobin and HbO_2, Oxyhemoglobin.

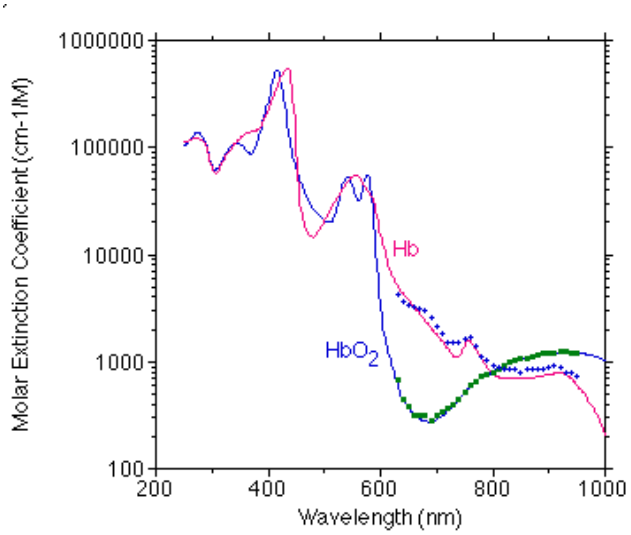

Figure 2: Absorption Spectrum of Hb and $Hb0_2$

<http://omlc.org/spectra/hemoglobin/moaveni.gif>

The commonly used wavelengths of red and infrared light in oximeters occur at 660 nm and 940 nm for the uses of pulse oximetry. In the above chart the greatest difference in extinction coefficients is between 600nm and 800nm and 800nm and 1000nm. Thus red and infrared light represent two wavelengths which will produce significant differential results for varying SaO_2 levels.

Millikan's development of a reliable and invasive blood oxygen saturation level sensor, otherwise known as oximeter, allowed for clinical assessment of hypoxia to be greatly improved. Before the quantitative method of oximetry was established, assessment of hypoxia was largely limited to the subjective diagnosis of cyanosis, blue skin discoloration due to low oxygen saturation. In 1988 CJ et al, conducted a study to determine the reliability of physician identified hypoxia events versus an oximeter. The marked level of a hypoxia event was 85% or less $Sa0_2$ levels for no shorter than 30 seconds. The oximeter group recorded 24 events to the non-oximeter groups 11. Also the oximeter detected events even in the absence of noticeable cyanosis or bradycardia [3]. For reference (Figure 3) see relative diagnostic hypoxemia ranges for $Sp0_2$ levels. For clarification hypoxemia, low $Sp0_2$ in the blood, is a precursor to the life threatening condition of hypoxia, low $Sp0_2$ in the tissue.

SpO2 Reading %	Interpretation
95-100	Normal
91-94	Mild Hypoxemia
86-90	Moderate Hypoxemia
<85	Severe Hypoxemia

Figure 3: Diagnostic Hypoxia Criteria

< http://nataej.org>

Further improvements were made to Millikan's design to eliminate the need to calibrate the equipment for multiple patients. His design required an air cuff to be inflated around the ear for calibration purposes. This removed all the blood from the ear to record a reference measurement for the sensor. The cuff removed all the venous blood from the measurement as the earliest oximeters

could not differentiate between venous and arterial blood. Another source of error was also the non-vascular tissue in the ear such as cartilage which does not obey Beer's law as a clear solvent.

In the 1970's Hewlett-Packard marketed an 8-band oximeter that did not require outside calibration as its 8 wavelengths of light created a system of equations that did not require a reference measurement to be taken. However this technology never found commercial success due to its high price and the time-consuming process of taking eight separate measurements [4].

The emergence of *pulse* oximetry came about in the 1970's from the research of Takuo Aoyagi in Japan who was working on a non-invasive way to measure arterial blood oxygen levels. He was measuring the transmission of light through the ear with a dye that was being circulated by the blood. He found that the signals varied largely with the pulses of arterial blood and that his method would not work. However he inadvertently discovered pulse oximetry.

Operating under the assumption that anything which pulses and absorbs light in the ear is arterial blood he was able to derive an equation which described SaO_2 strictly based off the pulsatile component of the signal he measured. Unfortunately his commercial design while no longer needing to be calibrated still suffered from a bulky earpiece and poor accuracy.

The development of the modern pulse oximeter took place under further models of the device which were released in the 70's and 80's out of companies such as Biox and Nelicor who made changes like using LED's for the light sources and further reducing the size and price of the circuitry with IC technology [5]. The addition of a microprocessor unit to perform more advanced analysis on the data helps modern oximetry contribute to fields including anesthesiology and dermatology.

Physics of Beer's Law in Pulse Oximetry

This section of the report will conduct in depth analysis of Beer's Law and discuss the results of several simulations run to show the intensity of light propagating through blood at multiple wavelengths.

Beer's Law (Figure 1) is used to describe the intensity of a light wave which propagates through a medium as defined by a solute dissolved in a clear solvent. In the case of oximetry this medium is blood, which is defined as a solution of Deoxyhemoglobin and Oxyhemoglobin, ignoring the various other analogs of Hemoglobin in blood. Beer's Law defines a logarithmic decay for any light wave propagating through the defined solution. As previously mentioned the extinction coefficient $\in$ is actually the complex portion of the refractive index (Figure 4).

$$N' = n_1 - n_2$$

Figure 4: Complex Refractive Index

$n_1$is the real portion and n_2 is equivalent to $\in * i$ to get the imaginary portion of the index. The electromotive force of a wave is defined below (Figure 5) as a sinusoidal quantity. N and n' represent the real and imaginary portions of the refractive index and z is the depth propagated from time equals zero, c is the speed of light in a vacuum.

$$E(z,t) = E_0 e^{iw(\frac{n+in'}{c}z-t)} = E_0 e^{iw(-\frac{n}{c}z-t)} e^{-\frac{n\prime}{c}z}$$

Figure 5: Propagation of a Wave

The portion of the exponential with n is the frequency envelope of the wave. The real portion of the refractive index determines how fast light will propagate as defined by Figure 6, v is the velocity of light in the medium compared to the speed of light in a vacuum. The higher the refractive index the slower light will propagate through the medium.

$$n = \frac{c}{v}$$

Figure 6: Relation of refractive index and velocity

The portion of Figure 5 containing n' the complex portion of the refractive index, defines the decay of the light wave propagating through a medium. The higher the complex portion of the index the faster the light will be converted into heat by the medium. Figure 2 shows the extinction coefficients of Hb and $Hb0_2$ at various wavelengths and it can be seen that red light propagates more advantageously through $Hb0_2$ and infrared light through Hb. These parameters are used to define a system of equations which in a strictly Hb and $Hb0_2$ system can be used to solve for the concentration of blood oxygen.

The following plots (Figure 8 and Figure 9) were simulated from parameters which are considered normal for a typical human. Beer's Law (Figure 1) was applied for a blood oxygen concentration of 20ml/dL over a path length of 1 cm, the width of a finger. Red (650 nm), Blue (450 nm) and Infrared (1000 nm) light intensity was simulated propagating through human skin with extinction coefficients determined from Figure 2. The input intensity was considered to be unity and thus removed from the simulation. Only relative quantities were established.

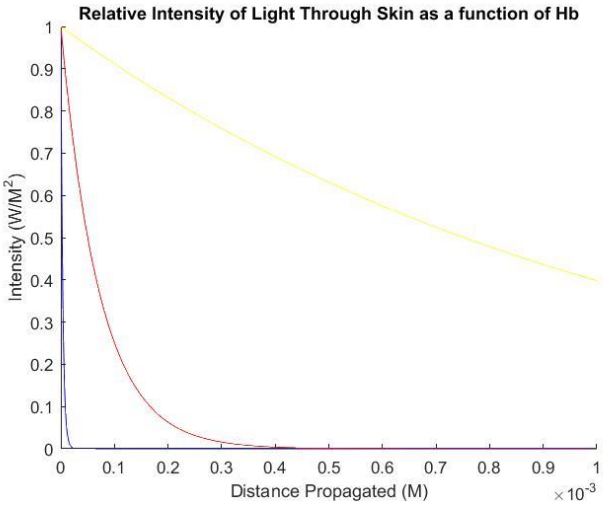

Figure 8: Intensity as a function of Hb

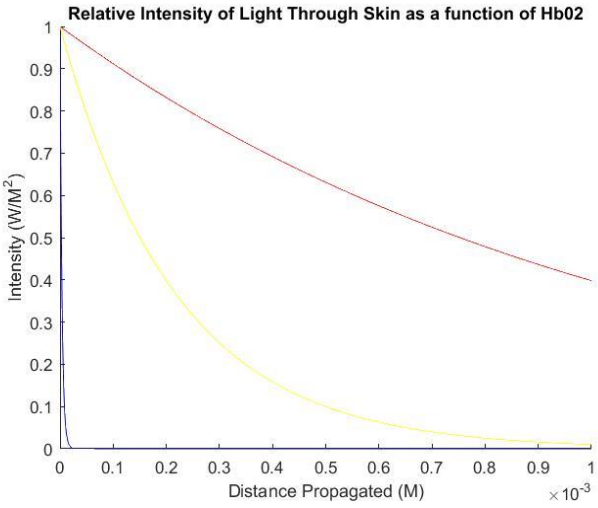

Figure 9: Intensity as a function of $Hb0_2$

The above simulations (Figure 8 and Figure 9) show how infrared and red light propagate at different intensities through skin when looking at both the extinction coefficients of Hemoglobin and Deoxyhemoglobin. Furthermore blue light was included to show that for both mediums blue light has too high and extinction coefficient and will not propagate through the tissue with enough relative intensity to measure a signal.

To further go into the mathematical breakdown of Pulse Oximetry the equation governing how current is measured in the oximeter will be analyzed.

The oximeter effectively converts sensor data representing blood oxygen concentration levels into voltages which are recorded. The pulsing and non-pulsing portion of the light intensity perceived at the signal are an ac and dc component of the signal (Figure 10).

$$I_{dc+ac} = I_0 10^{-(ecd_{dc}+ecd_{ac})}$$

Figure 10 – Dc and Ac component of intensity signal

This equation can be rearranged to determine the logarithmic ratio of red and infrared input signals (Figure 11). The final ratio is simply the extinction coefficient ratio of red and infrared light. The signal derived from the arterial tissue is ac and the venous tissue measurement dc due to their different hemodynamic models. The venous and other obstructive absorbing tissue are constant during their absorption. However in arterial tissue blood is being pumped so the absorption is occurring as a time derivative where absorption varies with the quantity of Hb and $Hb0_2$ currently present in the tissue. The AC arterial signal is considered the pulsatile absorption and the DC signal is the non-pulsatile absorption.

$$\log\left(\frac{I_{dc+ac}}{I_{dc}}\right) = -ecd_{ac}$$

$$\frac{\log\left(\frac{I_{dc+ac}}{I_{dc}}\right)_{red}}{\log\left(\frac{I_{dc+ac}}{I_{dc}}\right)_{infrared}} = \frac{-ecd_{ac-red}}{-ecd_{ac-infrared}} = \frac{e_{red}}{e_{infrared}}$$

Figure 11: Ratio of red and infrared inputs to outputs

This relationship (Figure 11) will be used later to bridge the relationship between red and infrared light propagation and blood oxygen concentration levels (Figure 12). Furthermore the extinction coefficients of Hb and $Hb0_2$ can be defined in terms of the path length and intensity of transmitted light I_0 into $Hb0_2$ that comes out as I_1 incident to Hb and I is the light transmitted through Hb [7]. These relationships (Figure 13) will be used to simplify later steps of the derivation.

$$S0_2 = \frac{[Hb0_2]}{([Hb0_2] * [Hb])}$$

$$e_{Hb} = \frac{1}{d[Hb]}\log\left(\frac{I_0}{I_1}\right), \quad e_{Hb0_2} = \frac{1}{d[Hb0_2]}\log(\frac{I_1}{I})$$

Figure 12: Blood Concentration Levels

Figure 13: Absorption related to intensity

When the two absorption relations are combined with the blood concentration level equation the relation for intensity as a function of blood oxygen concentration levels can be determined (Figure 14).

$$K = [Hb0_2] + [Hb], \quad Log\ I = dK\left(e_{Hb-}e_{Hb0_2}\right)S + LogI_0 - dKe_{Hb}$$

Figure 14: Relation of Intensity to Oxygen Concentration, S

Solving Figure 14 for both red and infrared values of light produces the final simplified oxygen concentration level in Figure 15. Adding in the relations for K_1 and K_2 gives the final solution if the

relations from Figure 11 are used (Figure 16). Values followed by an '*' mark values which refer to an infrared component.

$$S = \frac{E_{Hb}*}{E_{Hb}-E_{Hbo_2}} * \frac{\log(\frac{I_0}{I})}{\log({}^{I_0*}/_{I*})} - \frac{E_{Hb}}{E_{Hb}+E_{Hbo_2}}, K_1 = \frac{E_{Hb}*}{E_{Hb}-E_{Hbo_2}}, K_2 = \frac{E_{Hb}}{E_{Hb}+E_{Hbo_2}}$$

Figure 15: Simplified Final Concentration

$$S = K_1\left(\frac{e_{red}}{e_{infrared}}\right) - K_2$$

Figure 16: Final Blood Oxygen Concentration

The value K_1 and K_2 determine the system as the extinction coefficient ratio between red and infrared light is a constant. The K values represent the relative weights of red and infrared light transmitted and using known measured values of Hemoglobin and Deoxyhemoglobin extinction coefficients the blood oxygen concentration levels can be determined.

Internals of a Pulse Oximeter

This section will breakdown the circuitry that makes up an oximeter unit (Figure17).

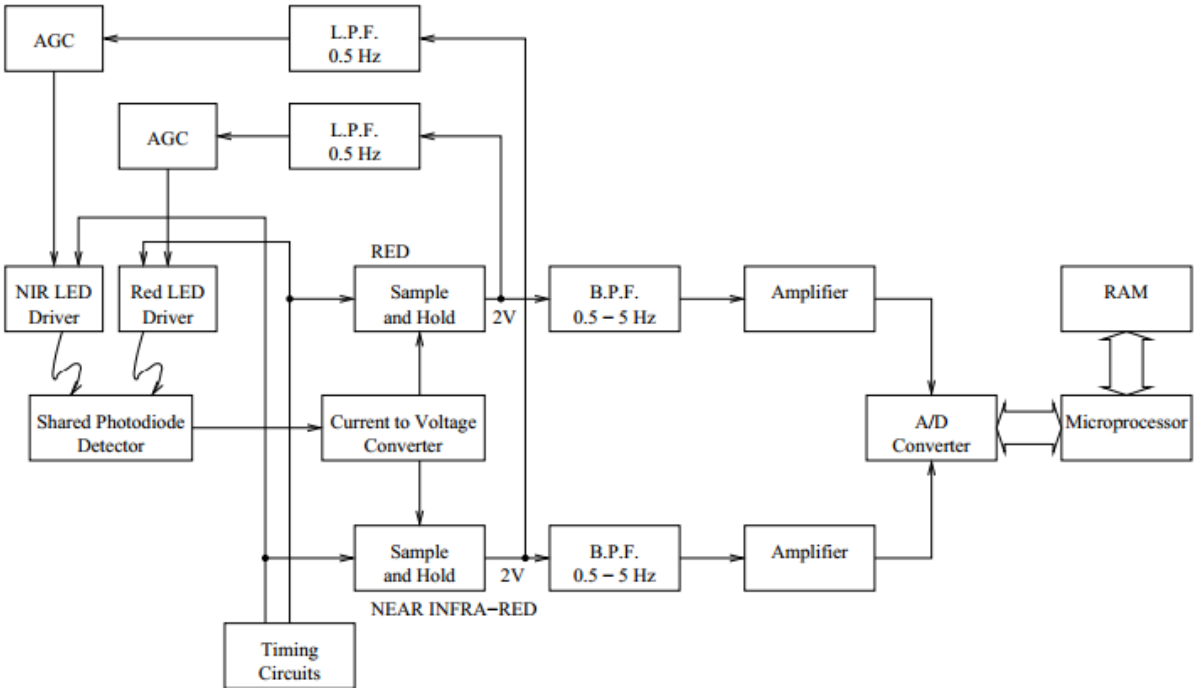

Figure 17: Standard LED Pulse Oximeter Block Diagram

<https://www.robots.ox.ac.uk>

Due to the modern sizing constraints on oximeter devices, designs must be efficient; being made for finger and earlobe usage. The LEDs used can easily be built for red and infrared operation but the actual intensity of the LED are low. Some current red LEDs contain internal lensing technology and infrared LED can be pulsed to achieve peak power [4]. Without the enhancement technique it would be necessary to use bulky and expensive photomultiplier tubes for measurements. An industry standard Hamamatsu H11432 Photomultiplier tube is 38 mm [8]. The enhancement techniques however consume more power as a product of boosting the power intensity.

A single silicon photodetector can serve as the detection circuit for both the infrared and red light signals. In addition the pulses from the two LED arrays can be made to pulse for an arbitrary width at a frequency which is high enough to avoid aliasing with the pulsatile component of the analysis signal. The frequency of the heart is never more than a few Hz so using a frequency like 1 kHz or higher for the LED cycle will more than be sufficient to achieve high quality data. The LED can be run with low 1A currents on a low power cycle. The photodetector produces a current in response to the light signals that can be upconverted with a op-amp that converts current to voltage [4].

The signal is held in a "sample-and-hold" circuit which is used to coordinate the passing of the infrared and red signals which are not processed in synchronization without the additional circuit. The signals are then put through a bandpass filter of 0.5 to 5 Hz and fed into amplifiers which lead to a microprocessor connected to a lookup table.

It is not even necessary to fully mathematically solve the oximeter equation to get the $Sa0_2$ levels as the intensity of the red and infrared waves alone correspond to a single state in the lookup table.

Common Pulse Oximeter Sources of Error

Pulse oximetry while being a lifesaving technology in its current state still has many unsolved problems and design limitations. Some of the design issues are biological and some user related. Other flaws are related to common operating conditions. One of the most prominent problems with Pulse oximetry is the accuracy of the measurements at $Sa0_2$ levels under 70%. Once the level starts to drop lower the presence of unmeasured molecular groups like carboxyhemoglobin, COHb, and methemoglobin, MetHb. These molecules absorb light from the source LED without being considered in the resulting equation [6]. MetHb absorbs nearly equal amounts of red and infrared light which causes

an artificial $Sa0_2$ level of 85% to be read. This is due to the ratio of pulsatile and nonpulsatile absorbances to be nearly equal to one when the $Sa0_2$ level is at 85%.

COHb signal distortion can be a problem when performing pulse oximetry on chronic smokers as their blood may contain artificially higher levels of COHb. Fifty percent of cigarette smokers have a carboxyhemoglobin concentration of 6%. Each 1% of circulating COHb causes the sensor to over-read saturation levels by 1% [6].

Another common source of error in oximeter readings is simply noise pollution. If light from the room in which the measurement is being taken bleeds into the sensor data distortion will occur. Any bright light sources on the red and infrared wavelength will cause large errors in measurement if the sensor is overloaded with the light noise. For this reason most modern oximeter devices are designed with a correction technique to reduce background noise. The LEDs are shutoff so that for a moment the sensor is only sensing the background noise. This corrective measurement can then be subtracted from the recorded data to reduce error.

Another important source of error is the variable biometrics of those who use the machine. The measurement of blood oxygen concentration is a in part determined by empirical data derived from patients whose $Sa0_2$ were monitored for clinical study. The oximeter requires a strong pulse form which makes it easy for the machine to distinguish from the pulsatile and non-pulsatile absorbances. The lack of a strong measurable pulse form makes the recordable difference between the I_{dc} caused by venous tissue and the I_{AC} in arterial tissue to be reduced. Without a clear change from the I_{AC} the difference cannot be adequately measured. The pulse oximeter is most likely to fail in circumstances where it is most needed due to the weak pulse limitation.

Another life threatening limitation is the failure of the sensor to work at very high partial pressures of oxygen. When the blood is near 100% saturation it becomes harder for the sensor to make

differential measurements which are accurate in regards to the changes in pressure of O_2 [6]. This makes it impossible for the device to make important distinctions between safe levels of $Sa0_2$ and states of hyperoxia, an excess of oxygen.

A last fatal limitation is the failure of some oximeters to detect the presence of a pulse at all. The signal will not necessarily be altered by the lack of a satisfactory blood pulse form that changes in time. The pulse oximeter has limitations in fatal situations that prevent it from being an all-encompassing diagnostic. In addition it suffers from a variety of user error.

The signal from an oximeter can be distorted by the positioning of the LED array behind a thick or dark layer of nail polish. The nail polish can block the signal and change the received and transmitted ratio of signals without being accounted for. A study conducted in 1988 by Cote et al, determined that nail polish should be removed before oximeter use [9]. However a 2007 study by Hinkelbein et al, determined that for all tested colors: black, purple, and dark blue the margin of error was less than 5% [10]. Thus contradicting the earlier work of Cote et al and giving a more quantitative basis for how nail polish affects oximetry readings.

Measurement signals may also be altered by motion artifacts caused by patients during the processing of data in the oximeter. Thus patients are recommended to be as still as possible during oximeter use.

Current State of Pulse Oximetry

One of the parties to receive the largest benefit from the wide-scale implementation of oximetry devices is neonatal care units. Oxygen concentration levels are incredibly important in neonatal care as often those born prematurely need supplemental oxygen to aid their underdeveloped lungs and circulatory system [11]. Neonatal oximetry is a specialized field of oximetry as an infant has a different hemodynamic profile compared to a young child or adult.

Fetal blood may contain extra species of Hemoglobin known as Fetal Hemoglobin, HbF. The HbF can be falsely read as an increase of COHb, carboxyhemoglobin [11]. This leads to a decrease in the HbO_2 measurement. This can cause circumstances where an oximeter reads dangerous levels of oxygen concentration levels but the neonatal patient is experiencing adequate oxygen deliverance as HbF has a higher affinity for oxygen at lower pressures compared to $Hb0_2$ (Figure 18).

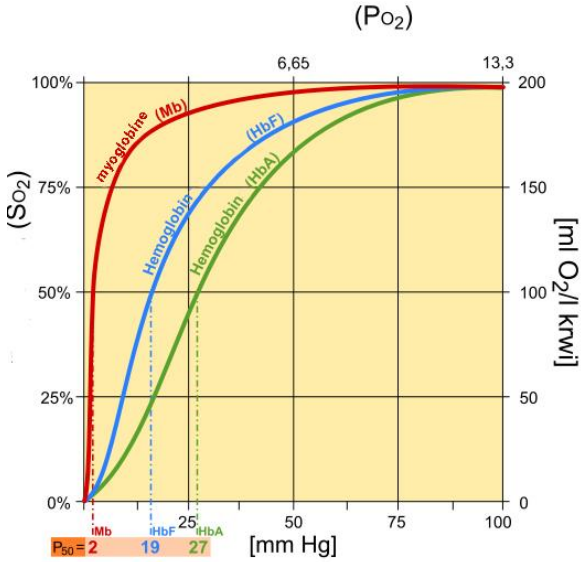

Figure 18: Fetal Hemoglobin Disassociation Curve

<Michal Komorniczak Medical Illustrations>

This relationship is necessary because in a developing fetus the HbF is competing with the mothers Hb to oxygenate and deliver oxygen. The baby needs to have a more affinitive mechanism for oxygen uptake than the mother to "leech" a significant amount of oxygen from the mother, the baby serves as drain of oxygen on the mother without an improvement in the mother's oxygen uptake system. Anecdotal evidence indicates that pregnant women do in fact breathe more often and with increased force compared to non-pregnant individuals [12].

Pulse Oximetry has also found marked use in conjunction with compression therapy to treat patients with ulceration or dermatitis. A Hand-Held Doppler ABPI is the standard assessment tool for screening suitable patients for this process. However in a 2002 study by Biancha et al, it was found that Oximeters could detect sufficient arterial pulse in tissue areas where the Doppler indicated no treatment was possible due to insufficient blood flow. [13] Pulse Oximetry also has a host of qualitative benefits that while hard to quantify present a well-rounded view on how the technology affects the lives of a typical user.

A qualitative study in 2002 by Jones et al, found that as a primary care tool Oximeters are a reassuring measurement to both patient and Doctor and that minimal training is required to use them readily [14]. For a group of 229 61-80 year-olds 65% had oximetry readings taken and 30 patients were in a significant hypoxia state below 90% saturation. The readings were found to assure both parties in 60%. Oximetry is considered a standard of care in most medical settings.

Conclusion

Pulse oximetry is a clever application of wave diffraction principles that has helped to invasively advance medical care across the globe. Blood Oxygen concentration levels are a measurement which can provide important information on patient circulation and ventilation with low cost and high speed, albeit with questionable accuracy.

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