Hochschule Wismar
University of Technology, Business and Design
Faculty of Engineering

Research Seminar

Brief Description and Analysis on "Pulse Oximetry"

Guided By
Prof.Dr.-Ing. Jens Kartil

By:

Ambekar Manzoor Ul Rahman Mohd Iqbal A (Matriculation Nr. **404653**)

Chakravorty Saptarshi Abhijeet (Matriculation Nr. **420718**)

Mehta Jay Hasmukhbhai (Matriculation Nr. **419424**)

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Abstract:

During the first half of the 20th century, there was a need for the measurement of oxygen in the blood to diagnose various ailments in the body of a patient. In that time, the oxygen measurement in blood was done using invasive methods. There was the need for a non-invasive method for measuring oxygen levels so that not only the procedure can be quick and clean but also provide accurate results. During the mid-70s, Japanese bioengineering, developed the first non-invasive method of oxygen measurement, the pulse oximeter which used three wavelengths of light for accurate measurement. Pulse oximeters help diagnose different medical conditions such as Hypoxia, Anemia, heart-related problems, etc. When the oxygen level in the blood drops below 94% that means the patient is suffering from Hypoxia. Such a drop in oxygen levels can happen because of Anemia where there is less hemoglobin in the blood to sufficiently carry oxygen in the body. Pulse oximeter also checks the heart rate in beats per minute and also provides a graph of the rhythm of the heart, which the doctors can analyze for any anomaly in the working of the heart. This shows how important the use of pulse oximeters is in the medical field. A pulse oximeter uses multiple wavelengths of light along with various algorithms derived from scientific laws for measuring the properties of blood. This report gives an overlook of the signal processing part of the pulse oximeter. We have used MATLAB to simulate the algorithms and filters used by the pulse oximeter for the processing of signals acquired during operation to derive accurate results for diagnosis.

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1. Introduction:

In recent years, pulse oximetry has emerged as the most convenient non-invasive method for monitoring arterial saturation. In the past, most of these elements required an invasive way for calibration. But when Takuo Aoyagi revolutionized the modern pulse oximetry, it inspired several innovators to focus on the non-invasive ways of using light to detect an ailment in a human body. Nowadays, its widely used in operation theaters, ICUs, patient transport, ER, birth, and delivery. But due to the COVID-19 pandemic, the requirement and need for non-invasive mobile pulse oximeters have skyrocketed.

Pulse oximeters can lead to a more rapid detection and treatment of countless ailments and possibly avoid serious complications. However, a universal method for calibrating pulse oximeters, does not exist. That would increase the sensitivity and reliability of the pulse oximeters. This paper details the description of pulse oximetry, theoretical background. Moreover, it provides a mathematical analysis of PPG signals with its hardware and software implementation.

This paper elaborates, a brief literature assessment of the pulse oximetry principle and operation. It also gives the outline of methods and elements that contributes to the outcome of pulse oximeters. Five volunteers were monitored, breathing at baseline and predetermined respiratory rates, using a pulse oximeter with five wavelengths. With the help of MATLAB Scripts, the captured data is evaluated, and waveforms were generated for further analysis.

The scripts contain filters which filter out noises and errors. The Savitzky Golay and FIR filters are most useful filters for getting the most accurate output. These data use for patients’ history and other medical research purpose. These may provide the data which can be used to examine the pulse oximeter.

1.1 Pulse Oximetry:

Pulse oximetry was first introduced by Karl von Vierordt in 1876. When Vierordt measured the rate of spectral changes of light in patients. His work was followed by Ludwig Nicolai in 1931 and after that J. R. Squire in 1940. But the most effective change happed by Takuo Aoyagi in 1971 in Niigata.

The contribution of Aoyagi played a major part in Pulse Oximetry. He is an interview said, “I have done the mathematical calculation with Lambert-Beer law and then conceived the idea of eliminating the pulsation of two wavelengths.” He continues, “I realized that both wavelengths have pulsating and non-pulsating parts as I imagined”. In that, he compared two wavelengths and calculate the mean of them. Which he after called this method “Ratio to Ratio method (φ)”. [1]

$$SpO2 = f\phi$$

Where ϕ is,

Ratio of AC/DC of pulsatile to non-pulsatile.

Aoyagi tested serval wavelengths from which he found that 630nm-805nm-900nm are the most accurate wavelengths to measure the pulses. This discovery on Pulse Oximeter played a major part in a patient’s health. Aoyagi patented this in 1979 (Patent 947714).

There was another arterial pulse oximeter was submitted by Masaichiro Konishi and Akio Yamanishi. They did the simple calculation in it and used fingertips for measurement. In 1985 Aoyagi and Yamanishi compared their work and found out with the right equipment all the results and noise in it are desirable. In conclusion, Aoyagi’s method helped 90% of anesthesia-related fatalities to be reduced and during the measurement the “noise”.

Moredon Oximeter gives us ±2% to ±4% accuracy. This accuracy is not applied to infants. Although Pulse Oximeter technology and its data influence treatment and decision making in critical emergency situations.

When oximetry was introduced in the medical field it measures by placing the meter on the ear of the patient. Moreover, the device was not very mobile and it has an error also. Because light reflection from the ear is more than we needed. Ears do not have enough thick tissues. So, it will pass the light very easily.[2]

A modern pulse oximeter uses a finger to measure the data. While it has a thickness as well as enough blood flows to measure the data and it can emit light also. This meter combines the two technologies of spectrophotometry and optical plethysmography. It works on a total of seven wavelengths starting from 650nm to 900nm. And it placed of fingertips of patients. Various patients have their own advantages and disadvantages. For instants infants have unstable heart rates and also their fingers are less stable. This creates an error in measurement. While adults have both stable heart rate and stable finger and hence accuracy will increase. Pulse oximetry measures oxygen saturation in red blood cells and hemoglobin. It can fit in

fingers, toes, ears, forehead. The pulse oximeter emits red light and infrared lights. Which reflects by blood cells and receives by the oximeter. Which in output we get measured heartbeat and oxygen level too. [3]

Detection of oxygen saturation of hemoglobin by spectrophotometry is based on Beer-Lambert law the transmission path length and absorbance of the substance at a specific wavelength. This is based on the formula:

Itrans = Iin C-A
A = DCE

Itrans = intensity of transmitted light
Iin = intensity of incident light
A = absorption
D = distance light is transmitted through the liquid
C = concentration of solute (hemoglobin)
E = extinction coefficient of the solute

The concentration of a known solute in a clear solution can be calculated from the measurement of the intensity of transmitted and incident light of known wavelengths (650nm-900nm). Using the principle of Beer's law, the concentration of a given solute in a solvent is determined by the amount of light that is absorbed by the solute at a specific wavelength.[4]

For Beer's law to be accurate, the solvent and the cuvette must be transparent, and there must be no extraneous solute, which can absorb light. Co-oximeters in the laboratory measure the intensity of light transmitted through a cuvette filled with hemoglobin from lysed RBCs to determine concentrations of each of the different forms of hemoglobin.

1.2 Properties of Blood and Tissues:

1.2.1 Blood:

As we all know Blood flows through our artillery system to provide oxygen, nutrients to the lungs and tissues. Blood contains red blood cells, white blood cells, plasma, platelets.

White blood cells, on the other hand, are very few in numbers almost 1-2% compared to red blood cells. White blood cells protect us from infection. It is an immediate response to any injury. Plasma is made of fat, protein, sugar, salt, and water. Its main purpose is to transport waste, antibodies, clotting protein, nutrients. Platelets are small fragments of cells. Their main work is to help the bold clotting process by gathering at the site of an injury, sticking to the lining of the injured blood vessel, and forming a platform on which blood coagulation can occur. [5]

Red blood cells contain two main parts protein hemoglobin and oxygen which is carried from the lungs and while returning to the lungs it carries carbon dioxide. Their count in blood is about 40-45%. In red blood cells, Hemoglobin is one type of protein. which carries oxygen throughout the body. Nitric oxide and carbon monoxide can also bind with hemoglobin. Carbon monoxide binds to hemoglobin much more strongly than oxygen. Its presence keeps oxygen from binding to hemoglobin. Hemoglobin is made up of four amino acid chains. Amino acids are the building blocks of proteins. Each of these chains contains heme. This is a compound that contains iron. One of the functions of heme is to transport oxygen in the bloodstream. [6]

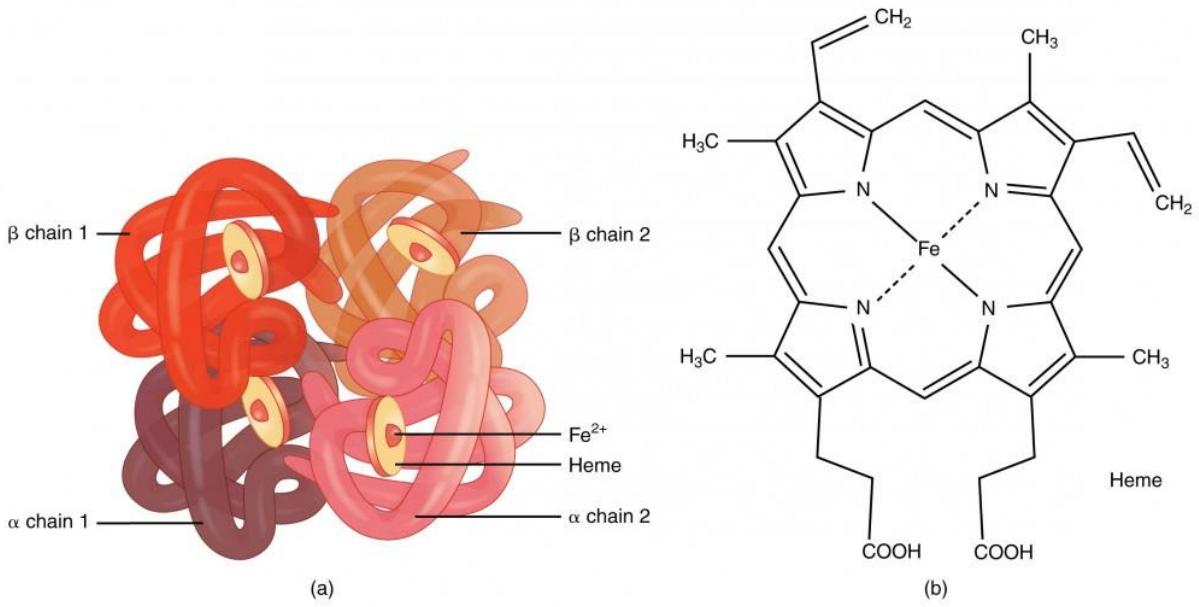

Figure 1: Hemoglobin structure [23]

Hemoglobin consists of four folded chains of a protein called globin, designated alpha 1 and 2, and beta 1 and 2 (Figure a). Each of these globin molecules is bound to a red pigment molecule called heme, which contains an ion of iron (Fe2+) (Figure b).

Changes in the levels of RBCs can have significant effects on the body’s ability to effectively deliver oxygen to the tissues. Ineffective hematopoiesis result in insufficient numbers of RBCs and results in one of several forms of anemia. In patients with insufficient hemoglobin, the tissues may not receive sufficient oxygen, resulting in another form of anemia.

1.2.2 Tissues:

Tissues are mainly are four types Epithelial tissues, Connective tissues, Muscle tissues, and Nerve tissue. Tissue is a structure of similar cells gathered as a structure and doing the same work at a time.

The main job of tissues is to work on the brain’s signal and move accordingly. Moreover, some acidic chemicals in serval parts of the body, tissue protects skin, artilleries, and many more sensitive parts. [7]

Epithelial tissues, these tissues are widespread throughout the body. They form the covering of all body surfaces, line body cavities, and hollow organs, and are the major tissue in glands. They perform a variety of functions that include protection, secretion, absorption, excretion, filtration, diffusion, and sensory reception. Epithelial cells may be squamous, cuboidal, or columnar in shape and may be arranged in single or multiple layers.

Connective tissues bind structures together, form a framework and support for organs and the body as a whole, store fat, transport substances, protect against disease, and help repair tissue damage. They occur throughout the body. Connective tissues are characterized by an abundance of an intercellular matrix with relatively few cells. [8]

Muscle tissue is composed of cells that have the special ability to shorten or contract in order to produce movement of the body parts. The tissue is highly cellular and is well supplied with blood vessels. The cells are long and slender so they are sometimes called Muscle fiber, and these are usually arranged in bundles or layers that are surrounded by connective tissue. Actin and myosin are contractile proteins in muscle tissue.

Nervous tissue is found in the brain, spinal cord, and nerves. It is responsible for coordinating and controlling many body activities. It stimulates muscle contraction, creates an awareness of the environment, and plays a major role in emotions, memory, and reasoning. To do all these things, cells in nervous tissue need to be able to communicate with each other by way of electrical nerve impulses. The cells in the nervous tissue that generate and conduct impulses are called neurons or nerve cells. These cells have three principal parts: the dendrites, the cell body, and one axon.

Oxygen which is carried by RBCs provided to tissue so it can function properly and measure how much oxygen a human has, we can measure it by tissue here means finger tissue. Pulse oximeter put on the finger and it projects infrared lights and when it’s received by the receiver. We can measure how much oxygen a human has. While there could be a chance of errors. These errors are based on scattering and absorption. Epithelial tissues are located in our fingers. They are thin and but from them, we can measure oxygen very easily. In the early stages of the pulse oximeter. Blood oxygen level was measured by ear putting pulse oximeter

on top of the ear. Those tissues are very light. That caused a major error in measuring blood oxygen.

As per the patient's age, the mass of tissues would be thinner or thicker. In the infant, the mass will be low so there will be saturation in measurement, and as the age of patients will increase, the tissue becomes thicker but the light reflectivity becomes less compared to younger age, and this causes absorption effect. [9]

1.3 Photoplethysmography:

The principle of photoplethysmography is illustrated in a transducer, incorporating a light source and a light detector, is placed in opposition to the skin. The emitted light is partly reflected by the skin, partly absorbed by the tissue, and partly back-scattered by the underlying blood vessels. Blood flowing in the skin modulates both the light which is scattered and that which is absorbed. The combination of these effects leads to the detection of pulsation in received light which is in synchronism with the cardiac cycle.

In photoplethysmography, a light sensor and receiver are used. From pulse, oximeter lights emit on the skin and it gets reflected by blood and this reflected light are received by the receiver in the pulse oximeter. These lights measure pulsatile and non-pulsatile components in the blood which can be measured by 600nm-805nm wavelength that projects by a pulse oximeter.

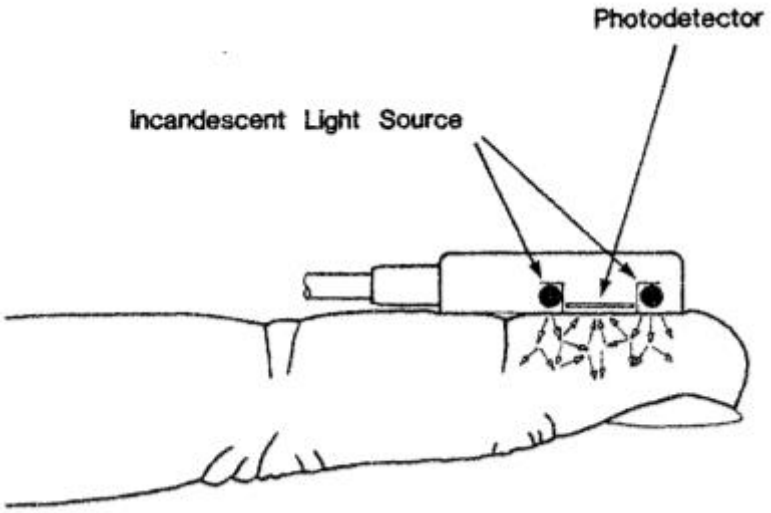

Figure 2: Optical sensor concept [10]

The optical absorption properties of whole blood differ considerably from those of hemolyzed blood, a difference that arises from the complications of scattering caused by the erythrocytes. using ox blood, measured the transmittance of blood at various wavelengths using blood samples of differing thicknesses and oxygen saturation. They showed that light transmittance through blood does not obey the simple Beer-Lambert law, but that the optical density of blood is a non-linear function of the concentration of the absorbing material (hemoglobin). blood layer thicknesses greater than 2.5 x 10-4m. [10]

1.4 Photometric measurement:

The photometric measurement principle is used to measure the glucose concentration in a blood sample. photometric measurement principle, where the blood sample is placed on a chemical test strip that reacts with the blood glucose, resulting in a color change. By illuminating the test area and capturing the reflections, the color change can be measured and associated with the underlying glucose level. [11]

The level of light transmission LT through or light reflectance LR from RBC suspensions during aggregation reflects the time course of this process. The time course of LT or LR recorded following the dispersion of existing aggregates in RBC suspensions can be analyzed and various indices reflecting both the kinetics and the overall intensity of aggregation can be calculated. Such measurements of RBC aggregation using LR data from RBC suspensions have been termed “syllectrometry” and have been developed into a commercial instrument. LT data have also been successfully used in various instruments developed to quantitate RBC aggregation, Both LT and LR methods utilize similar approaches to calculate parameters reflecting the time course and the intensity of aggregation.

To measure hemoglobin concentration and hemoglobin oxygen saturation in whole blood flowing through single blood vessels in the microcirculation. This problem has been addressed for in vitro situations as well as for large blood vessels in oximetry. Consider a hemoglobin solution containing a mixture of oxyhemoglobin (HbO2) and deoxyhemoglobin (Hb). The different color of oxyhemoglobin and deoxyhemoglobin is a manifestation of their different and characteristic absorption spectra. as shown in Fig. The wavelengths at which the absorption curves cross is called isosbestic wavelengths.[12]

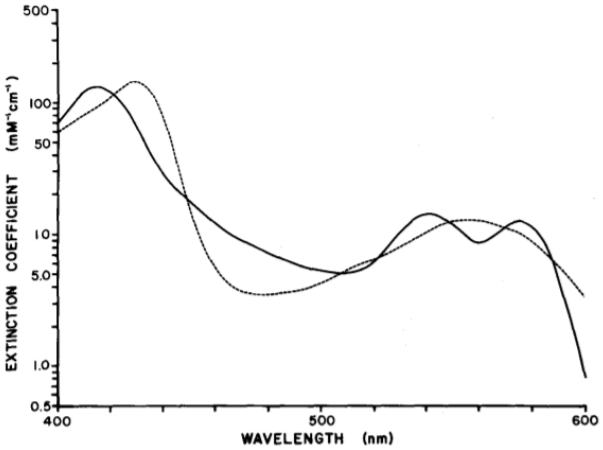

Figure 3: Hemoglobin measurement at different wavelengths [24]

Since hemoglobin is contained within red blood cells, it is necessary to consider what influence this discrete packaging has on the light transmission properties of whole blood. Two effects arise as a consequence of this situation: the sieve effect and light scattering.

The Sieve Effect. When light passes through a suspension of absorbing particles, such as whole blood, light rays that do not encounter red blood cells arrive at the detector unattenuated by absorption. If the detection region is large compared with the dimensions of the red blood cells, as is usually the case in conventional spectrophotometry, then the transmitted light intensity is higher than it would be if all the hemoglobin were uniformly dispersed in a solution. This phenomenon is called the sieve effect and is also known as absorption flattening because the heights of peaks in an absorption spectrum for a suspension are depressed relative to those for a homogeneous solution of the same average concentration. The magnitude of the sieve effect depends on two properties of a suspension: the fractional volume occupied by absorbing cells (hematocrit in the case of whole blood) and the amount of light absorbed by a single cell (optical density of a red blood cell).

The desire to obtain optical densities near that for minimum photometric error and the range of microvessel diameters (path lengths) and hematocrits generally encountered in the microcirculation dictates that more than one wavelength range must be used to determine hemoglobin concentration and oxygen saturation. For capillaries to microvessels of about 20 μm diameter, wavelengths near the Soret band are necessary. This choice carries with it two potential problems: the sieve effect and oxygen saturation-dependent scattering. For microvessels in the 20 to 100/μm diameter range, wavelengths in the 500 to 600 nm range are appropriate. This is the simplest wavelength range in which to work as both the sieve effect and oxygen-saturation dependent scattering are negligible while absorption and scattering are separable. For diameters larger than about 100/μm, it is necessary to use wavelengths above 600 nm. The major problem encountered is that absorption and scattering are no longer separable, making more difficult the extraction of hemoglobin concentration and oxygen saturation values from light transmittance data. Since most microcirculatory investigations deal with vessels whose diameters are less than I00 #m, this last problem is not of practical importance.

2. Optical measurement of blood and tissue:

Red blood cells are the main contributor to the optical properties of blood, their volume percentage (i.e., hematocrit), hemoglobin concentration, and oxygen saturation directly influence the absorption and scattering properties of blood. Whereas the absorption coefficient μa is proportional to the hematocrit, the scattering coefficient μs saturates for hct > 10 %, i.e., μs is underestimated for high hct values with respect to a linear relationship between the two parameters. Meinke et al., in our opinion correctly, ascribed this saturation effect to a decrease of the mean distance between red blood cells, because it violates the assumption of independent single scattering. This group also reported non-linear deviations of g for hct>10%.

The scattering of blood is primarily caused by the complex refractive index mismatch between red blood cells and plasma. Although most measurements on the optical properties of blood are performed on blood samples where the plasma has been replaced by saline/phosphate buffer, Meinke et al. measured that this affects the complex refractive index mismatch considerably, resulting in an overestimation of the scattering coefficient of 5.5–9.4 % with respect to red blood cells in plasma. [13]

The principle of causality dictates that the real and imaginary parts of the complex refractive index are connected as expressed by the Kramers–Kronig relations. The imaginary part is proportional to the absorption coefficient, which in turn depends on the SO2. Thus, the real part of the complex refractive index is also SO2 dependent and so are the scattering properties. This influence is most prominent in the visible wavelength region where differences in μa due to changes in SO2 are high, leading to deviations up to 15 % in μs and 12 % in g between fully oxygenated and fully deoxygenated blood

In Tissue, there are serval property reflation, refraction. Absorption, scattering. Absorption Extraction of energy from light by a molecular species. Transitions between two energy levels of a molecule that are well defined at specific wavelengths could serve as spectral fingerprints of the molecule. Absorption of energy is the primary mechanism that allows light from a source (laser) to produce physical effects on a tissue for treatment purposes. Absorption occurs when the photon frequency matches the ‘frequency’ associated with the molecules’ energy transition. Each electronic energy level is associated with many vibrational energy levels. Absorption of UV and visible light promotes transition between electronic energy levels. The absorption of infrared light promotes transitions between vibrational energy levels. [14]

Scattering, change of the direction of propagation and/or energy of light by a molecular species Scattering depends on the Diagnostic applications: Scattering depends on the size, morphology, and structure of the components in tissues (e.g., lipid membrane, collagen fibers, nuclei). Variations in these components due to disease would affect scattering properties thus providing a means for affect scattering properties, thus providing a means for diagnostic purposes. Scattering signals can be used to determine optimal light dosimetry and provide useful feedback during therapy.

3. Pulse Oximeter:

3.1 Introduction:

The pulse oximeter is a device that helps us measure the heart rate in beats per minute and oxygen saturation in blood in percentage in a non-invasive manner. Oximeter was originally developed by Glen Millikan during the 1940s by using red and infrared light. The first oximeters which the users had to wear on their ear lobes were created to warn pilots about hypoxia when flying in high altitudes.

In 1974, Takuo Aoyagi, a Japanese Bioengineer, invented the pulse oximeter. Mr. Aoyagi and his colleagues developed the device by using photoplethysmography, a way to detect the change of volume of blood inside the tissues. They used this technique along with spectrophotometry to synchronize spectrophotometry measurements of hemoglobin saturation with the peak and the valley of the pulsating waveform. The first commercially available pulse oximeter created by Mr. Aoyagi used the ear lobe for its operation.

In 1977, the first commercially available finger pulse oximeter was developed by the Minolta company. Which used fingertip for measurement. Using the fingertip provided greater pulse amplitude which resulted in linear and more accurate response to hypoxia. [15]

Figure 4: The OXIMET MET-1471 by Minolta in 1977 [25]

Currently, Pulse oximeters are used all around the world to check heartbeat rate and oxygen levels in the blood. During the ongoing Covid19 pandemic, the wide commercial availability of pulse oximeters enabled people to check their heartbeat rate and oxygen level in their homes. People are able to check for symptoms and warn themselves if there is a drop in the oxygen levels resulting in hypoxia prompting for a covid test.

The pulse oximeter is also used for diagnosing heart failure or heart attack. Doctors can look and check the waveform of the heartbeats of a patient for anomalies. It can also help diagnose Anemia: Where the hemoglobin count in the blood becomes too low because of which the oxygen level in the blood lowers down to lethal levels.

The pulse oximeter is used to detect Critical Congenital Heart Disease (CCHD) in infants. After the introduction of using pulse oximeters to detect CCHD in 2011, there was a substantial fall in false positives for CCHD in infants.[16]

3.2 Working and Structure of Pulse Oximeter:

Modern pulse oximeters have a clip-like body made of plastic which incorporates a processor, a small OLED screen for displaying data, two Light Emitting Diodes (LEDs), and a photodiode. The LEDs face the photodiode at the other end, and the space between the LEDs and the photodiode is for the patient to put his finger inside for measuring heart rate and oxygen saturation as shown in the figure below.

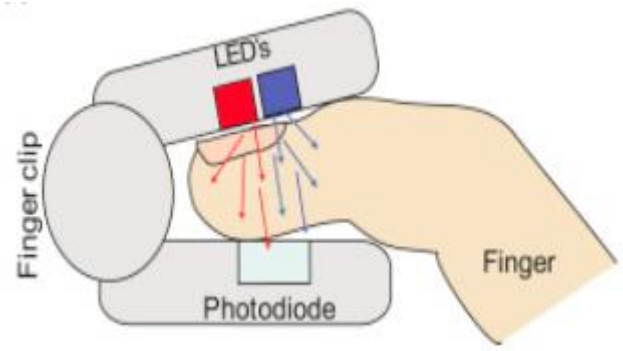

Figure 5: Pulse Oximeter [17]

While one of the LEDs emits red light with a wavelength around 670nm, and the other LEDs emits infrared light with a wavelength around 905nm. During operation, both LEDs shine, emitting light at their respective wavelengths, which go through either the fingertip or the ear lobe. In the tissue, the light at these wavelengths gets absorbed differently by oxygenated and deoxygenated blood. While oxygenated blood absorbs more infrared light, deoxygenated blood absorbs more red light. Further, both the LEDs switch on and off alternatively so that the photodiode can respond to both of the wavelengths of light. The amount of light for both the wavelengths which do not get absorbed by blood is measured. Based on this measurement a signal for both the respective wavelengths is formed and is then normalized. Such signals can have irregularities because of other properties of tissues, so the signals are made continuous by subtracting the minimum transmitted light from the transmitted light for both wavelengths. The ratio of the signals for the oxygenated and deoxygenated hemoglobin is calculated by the processor. The oxygen level is calculated by comparing the calculated ratio with a look-up table based on the Beer-Lambert law.[18]

3.2.1 Beer-Lambert law:

Beer-Lambert’s law is behind the main working principle of the pulse oximeter. The law is a combination of two other laws which describe the absorption of light when it passes through a transparent material.

i. Beer’s law:

Beer’s law states that the intensity of transmitted light is inversely proportional to the concentration of the material it is passing through. The decrease in the intensity of transmitted light is exponential as the concentration of the material increases. The law gives forth a formula as:

$$A = ln(Io/I)$$

Where "*A"* is the absorbance of the material, "*Io"* is the intensity of incident light on the material, and "*I"* is the intensity of transmitted light.

ii. Lambert’s law:

Lambert’s law states that the intensity of transmitted light by a material is inversely proportional to the distance traveled by the light through the substance.[19]

Beer-Lambert’s law states that light absorbed by substance a directly proportional to the concentration of the substance and distance traveled by the light through the substance. The law gives forth the following formula:

$$A = e*c*l$$

Where *A* is the absorbance of the solution under test, *e* is the molar absorption coefficient (M^-1cm^-1) of the substance, *c* is the molar concentration of the substance in the solution (M) and *l* is the path traveled by the light.

4. Analysis:

The data samples have been collected from several patients with different medical conditions. We have used different calculation techniques to calculate the heart rate, oxygen saturation, and other properties of blood. The pulse rate can be calculated in the time domain or frequency domain.

As the data is collected using five separate wavelengths, it can be used to derive several properties of blood and tissue. For example, only by using a single wavelength we can calculate the heart rate. Although, it is better to use multiple wavelengths to calculate blood oxygenation.

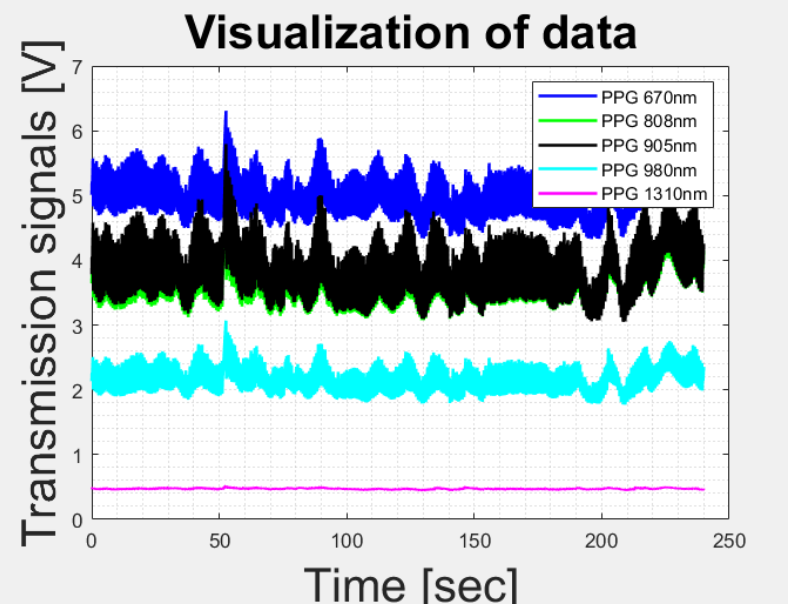

Figure 6: PPG original signal

PMD1 device has a 16-bit AD converter. Therefore, the output of transmission signals of raw data is between -32767 and +32767. Sensor’s data is converted to the digital format using an AD converter and is remodelled into voltage range. The following Figure shows the individual wavelengths into voltages.

4.1 Reducing Noise and Smoothening the Signal:

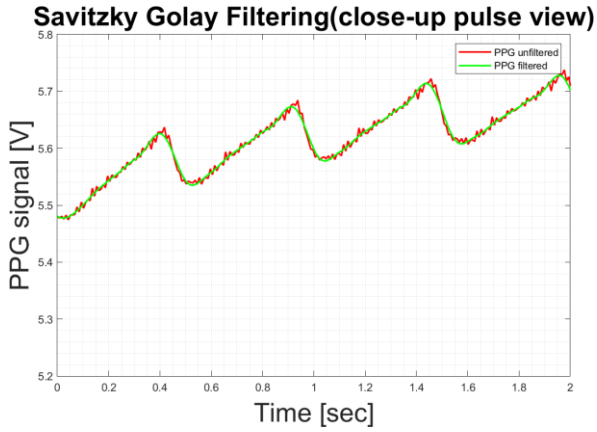

Figure 7: Savitzky Golay Filter Pulse View

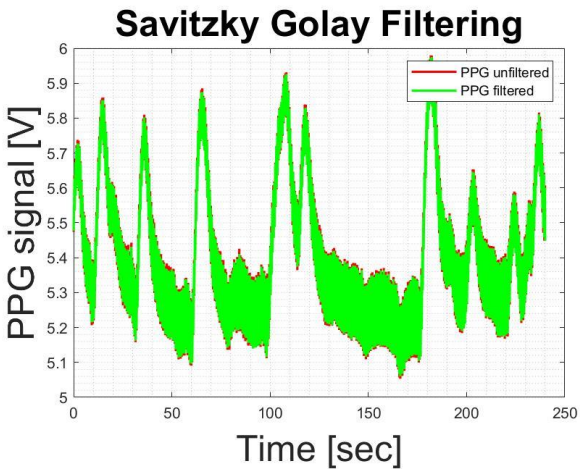

Figure 8: Savitzky Golay Filter

Several filtering methods can be used based on the specific requirements and input data set. We have used the “Savitzky Golay filtering” technique in Figure 7 and Figure 8. Savitzky Golay filter is a low pass filter that smoothens out the signal without much destroying its original properties. [20][21]

Here the PPG data is collected from 10 weeks old child. The signal for 808nm is used because it is independent of the oxygen saturation in the blood. Unfiltered data (Figure 7, Figure 8 in red) consists of a sequence of progressively narrower bumps due to noise.

The result of applying 6th order polynomial with 41 Sampling-point Savitzky Golay filters to the same data set is shown as in (Figure 7, Figure 8 in green). Within limits, Savitzky Golay filtering managed to provide smoothing without loss of resolution. It did this by assuming that relatively distant data points have a usable redundancy that can be used to reduce the level of noise. Higher-order filters do best at preserving feature heights and widths but do less smoothing on broader features.

4.2 Calculating the Heart Rate:

After filtering the data samples, we can plot the heart rate in beats per minute. Heart rate can be calculated in the time domain or the frequency domain.

4.2.1 Heart Rate in Frequency Domain:

Following is an example of calculating the heart rate in the frequency domain with the help of “Discrete Fast Fourier Transform”.

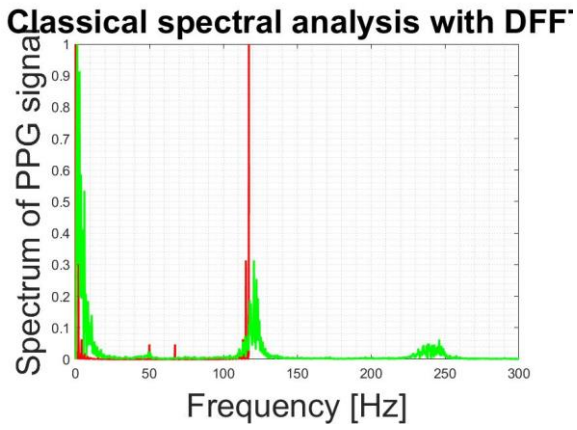

Figure 9:
Unfiltered and filtered DFFT Signal

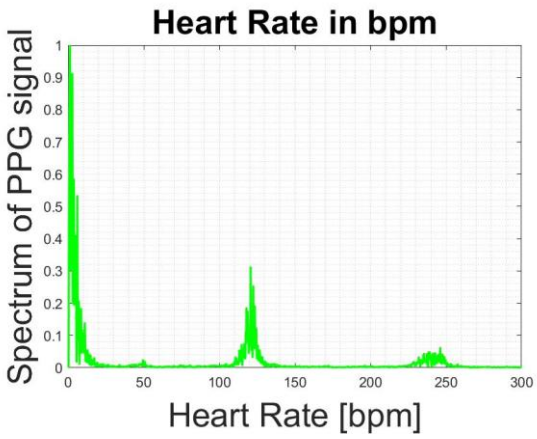

Figure 10:
Heart Rate (for 10 week’s infant)

Fast Fourier Transform is a representation of the signal in the time domain to the frequency domain. A Fourier transform of a signal can tell us what frequencies are present in your signal and in what proportions.

In Figure 9, we can observe the DFFT signal for infant patient. Here the first spike at lower frequency represents the DC part of the spectrum, while the second spike represents the pulsating AC component which is the heart rate. Using this information, we can calculate the heart rate by converting the date from frequency to time domain. As shown in Figure 10, we get 120 beats per minute for the assigned infant volunteer which shows that the heartbeat for this volunteer is in the normal range for the age group.

4.2.2 Heart Rate in Time Domain:

In the following example, the heart rate can be calculated in the time domain with the help of Derivative.

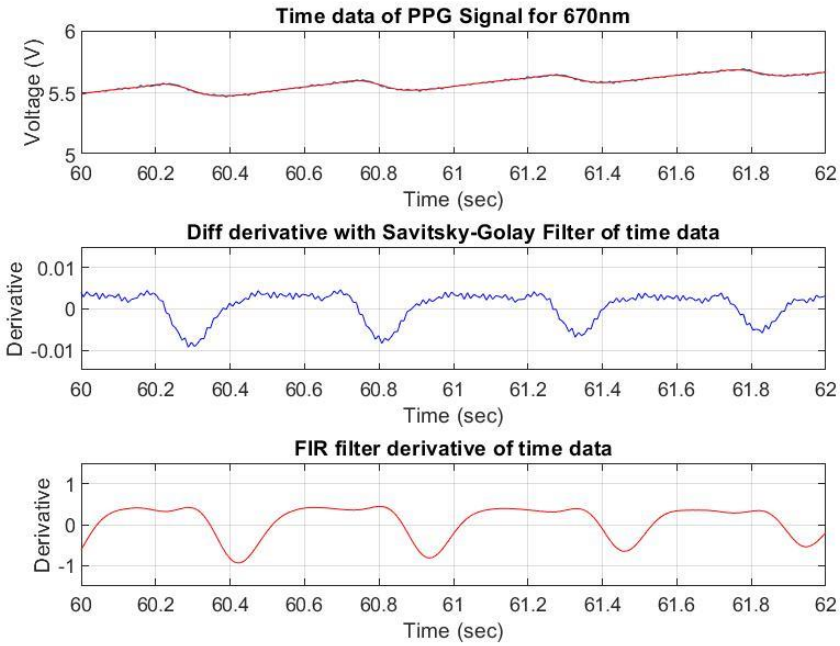

Figure 11: Derivative of the signal (for adult volunteer)

The top graph shows the filtered time data of the PPG signal for 670nm. A middle graph in the blue color depicts the first derivative of time data (670nm PPG signal) using the diff function. We have used the filtered signal using the Savitsky Golay filter for the derivative operation. The calculations are done using the two-point central difference algorithm, which acts as a differentiator for lower frequencies and as its own integral (or low pass filters) for higher frequencies.

The last graph in Figure 11 indicates the derivative of the same 670nm PPG signal using an FIR filter. Here the difference can be observed in the signal to noise ratio as compared to derivate derived from diff function.

Figure 12: Heart rate in time domain

In the above Figure 12, the heart is derived with the help of a first-order derivate of the signal. It is achieved by observing the time delay between two peak values and calculating beats per minute using the following formula.

$$\text{Heart rate in BPM} = (1/Ts) * 60$$

Where Ts is,

Peak to peak time delay

The heart rate data is changing at a faster rate in Figure 12 (magenta) as the sampling frequency is more. The data is smoothened in Figure 12 (green) with the help of a filter so that it is better for visibility.

4.3 Time Frequency Analysis:

4.3.1 Wigner Ville Distributions:

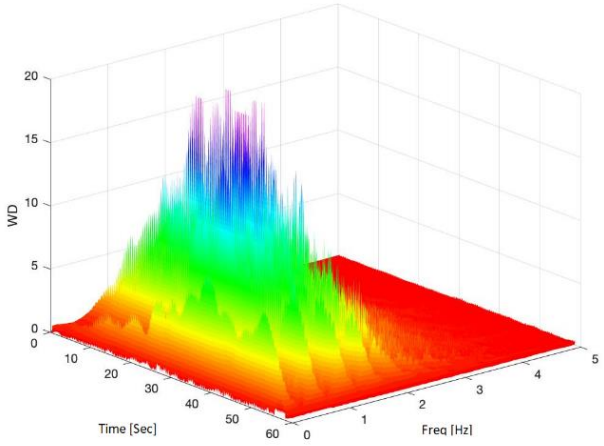

Figure 13: Time Frequency Analysis

Time frequency (TF) analysis based on the Smooth Pseudo Wigner Ville distribution was used to compare the time-varying spectral properties of both signals. For getting a smooth and precise signal, initially we filtered and then normalise it by taking the mean value. The ‘wvd’ function [22] returns the Wigner-Ville distribution when the signal (PPG) is sampled at a rate of fs, sample rate.

4.4 Calculating the Arterial Oxygen Saturation:

To compute the oxygen saturation in arterial blood we need to distinguish between the light absorbed by tissues or other non-pulsating DC elements, and light absorbed during arterial blood pulsations.

The DC component of the signal can be calculated by taking the discrete set of median value of the signal. And the AC component can be derived by rectifying the DC component from the signal.

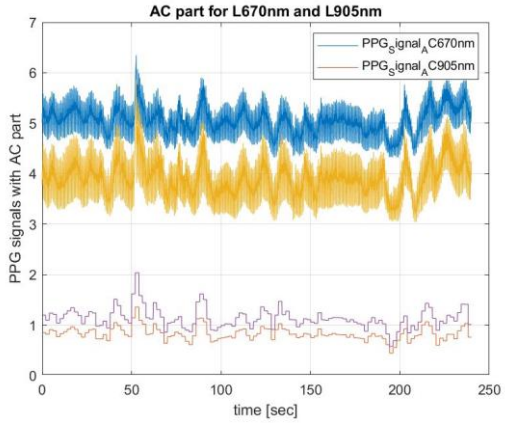

Figure 14: AC Component

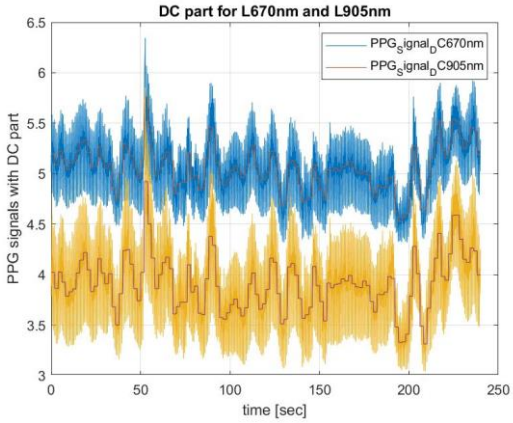

Figure 15: DC Component

As seen in Figure 14 and Figure 15, two separate wavelengths are used to calculate the blood oxygen saturation. This is because the 670nm and 905nm wavelengths have very different absorption rates of oxyhemoglobin and deoxyhemoglobin, this will result in good sensitivity of the desired oxygen saturation.

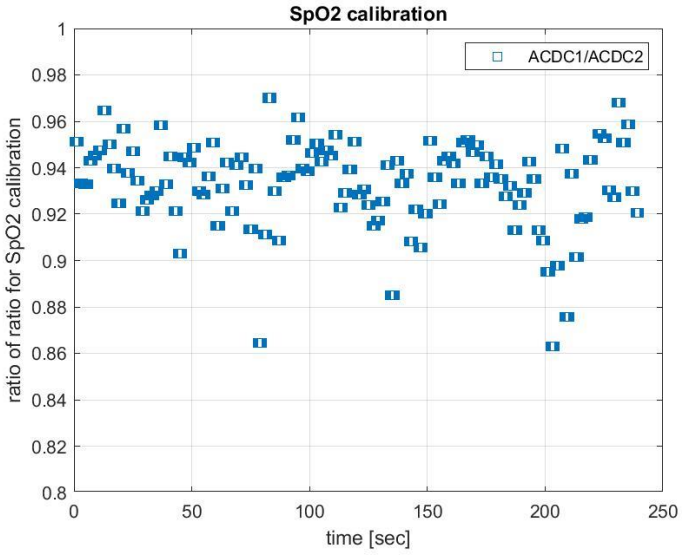

Figure 16: SpO2 calibration using quotient calculation (for adult volunteer)

SpO2 measurement is achieved by the following equation:

$$SpO_2 = aR^2 + bR + c$$

where a, b, and c are calibration coefficients, and R is determined by the following equation:

$$R = \frac{AC_{red} \,/\, DC_{red}}{AC_{ired} \,/\, DC_{ired}}$$

Here red AC and DC components are measured using 670nm wavelength, and IR AC and DC components are measured using 905nm wavelength.

The calibration coefficients to measure the oxigen saturation in the human body can be simplified as below equation,

$$SpO_2 = 1.5 - R$$

As seen in Figure 16, the arterial oxygen saturation for an adult volunteer is around 95%, which is the normal range for a healthy patient. Whereas for hypoxic patients it is around 85-94%, and for severely hypoxic patients it is below 85%.

5. Conclusion:

This report provides an elaborative review and analytical explanation of pulse oximetry. Where it discusses the evolution and importance of pulse oximetry and gives an insight into various methods of pulse oximetry. It also provides an insight into the working and background of modern pulse oximeters. In which we analyzed various data from several patients with different medical conditions. Various simulations categorizing five different volunteers were analyzed and their corresponding wave diagrams were plotted with the help of MATLAB. The data was measured with the help of five different wavelengths, in contrast to using two, red and infrared wavelengths in a conventional pulse oximeter.

Here used different calculation techniques to calculate the heart rate, oxygen saturation, and other properties of blood. The pulse rate is calculated in the time domain using derivative operation and frequency domain using the FFT filter. Initially, the data reading taken from sensors may contain noise, due to environmental conditions and human errors. The MATLAB program filters out noise from the data and provides the desired output, which helps in further calculations. This is done with the help of the Savitzky Golay filter. The heart rate in the time domain is calculated by taking the derivative, which ratifies the DC component and amplifies the AC component of the signal. This paper also provides heart rate calculations in the frequency domain. Furthermore, the oxygen saturation in the human body is estimated by calculating the ratio of ratios method, this is achieved by separating AC and DC components of two wavelengths (red 670nm and infrared 905nm). This gives accurate data of SpO2 levels in the pulsating blood.

In the near future use, a pulse oximeter can be calibrated to measure several elements which still requires an invasive method of measurement. This includes deriving the hemoglobin concentration in RBCs, non-invasive carbon dioxide monitoring, and pH monitoring.

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7. Appendix:

1) Explain the law of Lambert-Beer. What kind of media does the law apply to? Does it also apply to human tissue and why or why not?

i. The Law of Lambert-Beer states that the relationship between the quantity of light absorbed by a substance dissolved in a fully transmitting solvent is directly proportional to the concentration of the substance and the length of the path of light through the solution. Consider a case, in which light is transmitted through a solution. To check the absorbance of light by the substance, the following equation is derived with the help of the law:

$$A = e*c*l$$

Where A is the absorbance of the solution under test, e is the molar absorption coefficient ($M^{-1}cm^{-1}$) of the substance, c is the molar concentration of the substance in the solution (M) and l is the path traveled by the light. We can also determine the concentration of the solution by using the absorbencies and a calorimeter.

ii. The law does not apply to media that are non-homogeneous and turbid.

iii. Yes, the law applies to human tissue because blood is one of the major light absorbers and diffusers in living tissues. Light gets scattered by the red blood cells in the blood. This phenomenon can be used to find out the hemoglobin count and therefore the oxygen absorption in the blood.

2) What do the terms absorption coefficient, scattering coefficient, scattering phase function and anisotropy mean in connection with light propagation in tissue?

i. The absorption coefficient describes the intensity attenuation of the light passing through a material. It can be understood as the sum of the absorption cross-sections per unit volume of a material for an optical process. If the absorption coefficients are high, then light can only travel a short distance into the material before getting absorbed by the material. For medical applications, in order to understand the propagation of light through human tissue accurate calculation of absorption coefficients is important.

ii. The scattering coefficient is a measure of the ability of particles to scatter photons out of a beam of light. In the biological tissues, scattering occurs due to turbidity or the suspended micro-particles. The efficiency of the Mie and Rayleigh scattering, both taking place in tissues, depends on the light wavelength. In particular, the optical path in a scattering tissue is wavelength-dependent and therefore influences absorption.

iii. The scattering phase function, or phase function, gives the angular distribution of light intensity scattered by a particle at a given wavelength. This function is important to find out the specific wavelength of light that can be used to measure the optical properties of blood.

iv. Anisotropy is the quality of exhibiting properties with different values when measured along axes in different directions. Most biological cells and tissues are anisotropic because of suspended micro-particles. Therefore, when the law of Lambert-Beer is applied for light traveling through human tissue, absorbance is not linearly related to concentration.

3) Which optical properties of hemoglobin can be used to determine oxygen saturation in blood?

The optical properties of hemoglobin that can be used to determine oxygen saturation in the blood are scattering coefficient, absorption coefficient, and anisotropy factor, together with the appropriate phase function.

4) Why does oxygen-rich (arterial or capillary) blood appear light red and oxygen-poor (venous) blood darker?

The color of human blood ranges from bright red when oxygenated to a darker red when deoxygenated. It owes its color to hemoglobin, to which oxygen binds. Hemoglobin has a heme component consisting of a ferrous ion with which oxygen binds. Deoxygenated blood is darker due to the difference in the shape of the red blood cell when oxygen binds to hemoglobin in the blood cell versus does not bind to it.

5) What are the standard values for arterial oxygen saturation in humans? Which forms of hemoglobin are known to you and how do they develop?

Normal arterial oxygen saturation is approximately 75 to 100 millimeters of mercury (mm Hg). Values under 60 mm Hg usually indicate the need for supplemental oxygen. Normal pulse oximeter readings usually range from 95 to 100 percent. Values under 90 percent are considered low. The phenomenon of low arterial oxygen saturation is called hypoxia.

There are four different hemoglobin species that are commonly recognized: oxyhemoglobin (O2-Hb), deoxyhemoglobin (HHb), methemoglobin (MET-Hb), and carboxyhemoglobin (CO-Hb). Oxyhaemoglobin is formed when oxygen binds to the heme component of the hemoglobin. Deoxyhaemoglobin is the form of hemoglobin without the bound oxygen to the heme component. Methemoglobin is a form of hemoglobin that has been oxidized, changing its heme iron structure from the ferrous (Fe2+) to the ferric (Fe3+) state. Unlike normal hemoglobin, methemoglobin does not bind oxygen and as a result, cannot deliver oxygen to the tissues. Carboxyhemoglobin (COHb) is a stable complex of carbon monoxide that forms in red blood cells when carbon monoxide is inhaled.

6) Explain the measuring principle and function of a pulse oximeter. Which wavelengths are suitable for measuring oxygen saturation and why?

Pulse oximeters work by the principles of spectrophotometry: the relative absorption of red light which is absorbed by deoxygenated blood and infrared which is absorbed by oxygenated blood) light of the systolic component of the absorption waveform correlates to arterial blood oxygen saturation.

Several wavelengths can be used to measure the oxygen saturation in the blood. Although, at least 2 wavelengths are needed to improve sensitivity (isosbestic and non-isosbestic). While oxyhemoglobin absorbs red light which has the wavelength of 670nm, deoxyhemoglobin absorbs infrared light which has the wavelength of 905nm. The pulse oximeter has to distinguish between the light absorbed by non-pulsatile tissues (constant / DC), and light absorbed during arterial blood pulsations (non-constant / AC). The microprocessor in the oximeter analyses both the DC and AC components at 670nm and 905nm, and calculates the ratio of absorption at these frequencies (R/IR ratio).