Research Seminar Report

"Pulse Oximetry Principles and the Processing of Photo-Plethysmographic Signals (PPG) using MATLAB"

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Submitted on 30.12.2021

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Abstract

Photoplethysmography is a non-invasive, optical method to visualize sub dermal blood volume.

In this report, we use a pulse oximeter by clipping it to a person's finger and receive the PPG data in order to measure different elements such as blood oxygen saturation and heart rate. Furthermore, a comparison between two different datasets of patients is done.

The whole process in receiving PPG data is like the light is irradiated into the skin and the transmitted or reflected light is measured. Blood volume fluctuations cause changes in the intensity of the measured light and several rhythmic vital parameters can be observed (i.e. heart rate). By means of different light wavelengths an additional spectral analysis of the blood can be performed. Since the red and infrared absorption/reflection spectra of reduced and oxygenated hemoglobin distinguish significantly, PPG is also often used for an easy measurement of blood oxygen saturation (e.g., in pulse oximetry)

The important part of the project would be bio signal processing, which is done in MATLAB. Different processing is done on the data including digital filtering, windowing and spectral analysis, and time frequency analysis.

Index

1. Introduction

Pulse oximetry measures the oxygen saturation (SaO_2) in a non-invasive way. By oxygen saturation we mean the measurement of the amount of oxygen dissolved in blood, based on the detection of Hemoglobin and Deoxyhemoglobin. pulse oximeters use two LEDs at different wavelengths and a photodiode to estimate the actual difference in the absorption spectra of HbO_2 and Hb. The bloodstream is affected by the concentration of HbO_2 and Hb, and their absorption coefficients are measured using two wavelengths 660nm (red light spectra) and 940nm (infrared light spectra). As hemoglobin is deoxygenated at 660 nm, oxygenated hemoglobin is oxygenated at 940 nm. A photodetector in the sensor detects the non-absorbed light from the LEDs. This signal is inverted using an inverting operational amplifier (OpAmp) [1]. The most common approach is transmissive pulse oximetry. A sensor device is placed on a thin part of the body, usually a fingertip, earlobe, or an infant's foot. The blood flow to fingertips and earlobes is higher than to other tissues, facilitating heat transfer. It measures the changes in absorbance at each wavelength in order to determine the absorbances due to arterial blood alone, excluding venous blood, skin, bone, muscle, fat, and nail polish [2].

PPG technology is used in a wide range of commercially available medical devices for measuring oxygen saturation, blood pressure, and cardiac output, as well as assessing autonomic function and detecting peripheral vascular disease. PPG is a simple and low-cost optical technique that can be used to detect changes in blood volume in the microvascular bed of tissue. It is often used noninvasively to measure blood volumes at the skin surface [3]. A PPG is often obtained by using a pulse oximeter which illuminates the skin and measures changes in light absorption [4].

1.1 Human Cardiovascular System

The cardiovascular system is a part of the circulatory system that circulates blood around the body. The circulatory system also includes the lymphatic system, which circulates lymph, but the terms circulatory system and cardiovascular system are commonly used interchangeably to describe blood circulation. A heart is essentially a pump that moves blood through vessels. The heart is essentially a pump that moves blood through the vessels. The best-known function of the circulatory system is perhaps the transport of inhaled oxygen from the lungs to the body's tissues, and the removal of carbon dioxide in the opposite direction to be exhaled. The oxygen-poor blood that leaves the body is pumped to the lungs, where it picks up oxygen and releases carbon dioxide. The oxygen-rich blood then returns to the left side of the heart. This is called the pulmonary system. The left side of the heart pumps oxygen-rich blood to the body's tissue, where it unloads oxygen and

picks up carbon dioxide. The deoxygenated blood then returns to the right side of the heart to complete the cycle. This part is the systemic circuit. Apart from transporting gases, the blood also supplies the body's tissues with nutrients and removes metabolic wastes.

1.2 Respiration and Oxygen Supply of the Tissue

Oxygen is continuously supplied to body cells for metabolic processes that are necessary to maintain life. For that, the respiratory system works with the circulatory system and removes the waste products of metabolism. It also helps to regulate the pH of the blood [5].

Respiration is the sequence of events that results in the exchange of oxygen and carbon dioxide between the atmosphere and the body cells. Every 3 to 5 seconds, nerve impulses stimulate the breathing process, or ventilation, which moves air through a series of passages into and out of the lungs. After this, there is an exchange of gases between the lungs and the blood. This is called external respiration. The blood transports the gases to and from the tissue cells. The exchange of gases between the blood and tissue cells is internal respiration. Finally, the cells utilize oxygen for their specific activities: this is called cellular metabolism, or cellular respiration. Together, these activities constitute respiration [5].

2. Blood Composition and Blood flow:

2.1 Blood Composition

Every organ functions and thrives because blood vessels carry blood there. The blood cells carry oxygen and nutrients. White cells protect humans from infections and the yellow liquid plasma in which they are suspended carries an array of proteins that regulate bleeding and clotting. In other words, blood is composed of formed elements including platelets, red blood cells, and different kinds of white blood cells, which are suspended in a fluid called plasma. The densest section of the blood is comprised of erythrocytes, or red blood cells, and the least dense section will be the yellowish plasma. These two sections are separated by the buffy coat, a white layer containing platelets as well as leukocytes, otherwise known as white blood cells.

2.2 Blood Flow

The cardiovascular system is an internal flow loop with multiple branches in which a complex liquid, known as blood, circulates. The blood is distributed by blood vessels to different organs and supply themselves with nutrition. The arteries, far from inert tubes,

adapt to varying flow and pressure conditions by enlarging or shrinking to meet changing hemodynamic demands [6].

By blood flow we mean that blood starts from the heart and enters the aorta, which is the largest artery of the body. Afterward, the blood goes into smaller arteries and at last, it goes into capillaries, where oxygen transfer occurs. The capillaries connect to venules, and the blood then travels back through the network of veins to the right side of the heart. The venous system returns the deoxygenated blood to the right heart where it is pumped into the lungs to become oxygenated and CO_2 (Carbone Dioxide) and other gaseous wastes exchanged and expelled during breathing. Blood then passed through the left side of the heart where it begins the process again. This process is known as "blood flow" [7].

3. Optical Properties of Human Blood

Development in new optical methods in medicine requires knowledge of the optical properties of human tissues. Since most human tissues contain blood, the latter is an important object of investigation. Light propagation in tissues is determined by their intrinsic optical properties. Those are the absorption coefficient μ_a, the scattering coefficient μ_s , and the scattering phase function f(μ) [8].

Normal human blood consists of red blood cells (RBCs or erythrocytes, ±4,500 × 103/μL blood), white blood cells (leukocytes, ±8 × 103/μL blood), platelets (thrombocytes, ±300 × 103/μL blood) and blood plasma (containing water, electrolytes, plasma proteins, carbohydrates, lipids and various extracellular vesicles). The hematocrit (hct) is defined as the volume percentage of red blood cells in blood and on average amounts to 40% for adult women and 45% for adult men. Red blood cells are composed mainly of hemoglobin, with a concentration of ±350 g/L in a cell volume of ±90 fL. In healthy human adults, the average hemoglobin concentration in blood accounts for 140 g/L in women and 155 g/L in men [9].

Accounting for an absorption contribution of two to three orders of magnitude higher than the other blood components, red blood cells are by far the most dominant absorbing element in the blood in the wavelength range of 250–1,100nm [9]. Practically, all light absorption by the red blood cells is due to hemoglobin, which exhibits specific absorption features for its various derivatives: bound to oxygen (oxyhemoglobin, HbO_2), unbound to oxygen (deoxyhemoglobin, Hb), bound to carbon monoxide (carboxyhemoglobin), oxidized (methemoglobin), fatal and more [10]. From these hemoglobin derivatives, oxyhemoglobin and deoxyhemoglobin are the most abundant types in healthy human adult

blood. The oxygen saturation of blood is defined as the ratio of the HbO_2 concentration to the total haemoglobin concentration, oxygen saturation $(SO_2) = [\,HbO_2\,] / ([\,HbO_2\,] + [\,Hb\,])$, and amounts to ~97.5% in arterial blood and ~75% in venous blood. Of all blood particles, red blood cells also predominate the scattering of blood with two to three orders of magnitude, arising from the difference in refractive index between red blood cells and the surrounding blood plasma. In the wavelength range beyond 1,100nm, blood absorption is dominated by the absorption of water. Only when water is removed from the blood, several absorption features due to the presence of hemoglobin, albumin and globulin can be identified as small absorption peaks between 1,690 and 2,400nm [11].

4. Factors Influencing the Optical Properties of Blood

Red blood cells are the main contributor to the optical properties of blood, therefore their volume percentage, hemoglobin concentration and oxygen saturation directly influence the absorption and scattering properties of blood. Whereas the absorption coefficient μ_a is proportional to the haematocrit, the scattering coefficient μ_s saturates for hct > 10 %, i.e. μ_s, is underestimated for high hct values with respect to a linear relationship between the two parameters. The scattering of blood is firstly 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 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. The principle of causality dictates that the real and imaginary parts of the complex refractive index are connected. The imaginary part is proportional to the absorption coefficient, which depends on the SO_2. Thus, the real part of the complex refractive index is also SO_2 dependent and also the scattering properties. This influence is most prominent in the visible wavelength region where differences in μ_a due to changes in SO_2 are high, leading to deviations up to 15% in μ_s and 12% in g between fully oxygenated and fully deoxygenated blood [11].

Various sources have reported that the shear rate due to blood flow and aggregate formation (e.g. rouleaux formation) significantly influence the optical properties of blood due to non-Newtonian flow characteristics [11].

There are also other factors which influences on optical properties such as osmolarity, temperature, inter-person variability and pathologic disorders such as sickle cell anemia. A special case is that for adults versus fetuses, whose blood is composed of different types

of hemoglobin (adult versus fatal hemoglobin) that exhibit slight variations in their absorption features [11].

5. Lambert-Beer Law

The Bouguer-Beer-Lambert (BBL) law, as it provides an accurate description of the effects arising from interaction between light and matter. Therefore, any deviation from it is usually interpreted as variation of the chemical interactions in the sample or a change in molecular structure on the level of a unit cell.

The Beer-Lambert Law shows the relationship between the attenuation of light through a substance and the properties of that substance. it is a linear relationship between the absorbance and the concentration, molar absorption coefficient and optical coefficient of a solution:

$$A = \varepsilon c l$$

A	Absorbance	
ε	Molar absorption coefficient	$M^{-1}cm^{-1}$
c	Molar concentration	M
l	optical path length	cm

Fig 1: Formula for absorbance

5.1 Applications of Lambert-Beer Law

By spectrophotometry, Lambert Beer's law can be applied to the spectrophotometric analysis of a mixture1, without requiring extensive preprocessing of the sample. A simple example is determining bilirubin [2] in plasma samples. Bilirubin is measured at one wavelength relatively unique for bilirubin and then at another wavelength to eliminate or correct interferences or deviations. The molar absorptivity of a substance can be determined by measuring its concentration, or by measuring its concentration.

5.2 Attenuation Coefficient

In optically turbid media, such as skin tissues, photon propagation can be described by the Boltzmann photon transport equation, which is independent of time and energy. For this

equation, the scattering coefficient, absorption coefficient, and phase function of the medium need to be expressed [13].

Radiation can interact with the matter either by interacting with electrons in the material or by interacting with atoms in the material, depending on other circumstances and other factors. Specifically, for tissue equivalent systems, the linear dimension is most relevant, but in general, attenuation coefficients are expressed in terms of the unit mass dimension, which is simply the linear coefficient multiplied by the density, the likelihood of an electron interacting with an atom, and the probability of an atom interacting with an electron. In addition to these attenuation coefficients, there are also atomic attenuation coefficients, mass attenuation coefficients, and electronic attenuation coefficients. The following table shows the relationship among attenuation coefficients.

Coefficient	Symbol	Unit
Linear	M	m^{-1}
Mass	μ/ρ	$m^2 kg^{-1}$
Electronic	e^{μ}	m^2 per electron
Atomic	a^{μ}	m^2 per $atom^3$

Chart 1: Description of coefficients

The attenuation coefficient for linear transmission is μ. Basically, it is the probability of a photon interfering with a linear path within the absorber per unit of linear path length. As opposed to the linear thickness of the absorber, the attenuation coefficient is often more convenient to express in some other way [13].

When photons incident on monoenergetic beam, that time the linear attenuation coefficient indicates (μ) the fraction of incident photons that are undetected. In addition to coherent scattering, Compton scattering, and photoelectric effects, this entails all possible interactions. Transmission is its complement. It is expressed numerically in units of m^{-1} or cm^{-1} [14].

As the atomic number and physical density of the absorbing material increase, the linear attenuation coefficient increases. Generally, the emissivity decreases with increasing photon energy (except at K-edges) [14].

6. Calculation of μ

The intensity of the beam at distance x (cm) within a material is calculated using the following equation:

$$I_x = I_0 . e^{-\mu x}$$

Where I_x is the intensity at depth of x cm, I_0 is the original intensity, and μ is the linear attenuation coefficient.

Rearranging and taking the log of both sides gives the equation for μ.

$$\mu = ln\ (I_0/I_x)/x$$

6.1 Scattering Coefficient Versus Absorption Coefficient

By calculating the absorption coefficient, we can measure how many photons are absorbed in a beam of light. By calculating the scattering coefficient, we can estimate how many photons are scattered by particles in the beam of light. Each parameter is expressed as a number based on the spread or absorption of photons per distance. As a result of scattering and absorption, extinction or attenuation is calculated. The attenuation coefficient * can be derived from the scattering and absorption coefficients [15].

6.2 Scattering Phase Function

A small particle scattering distribution is uniquely determined by both the angular scattering ratio and the refractive index contrast between the particle and the surrounding medium. Multiple scattering becomes more important as the particle concentration increases. As a result, one must often resort to empirical phase functions to describe angular scattering patterns [16].

In phase function theory, the wavelength at which light is scattered by a particle defines the angle distribution of its intensity. An angle θ has been chosen as it relates to the incident beam. Based on a normalized integral of the scattered intensity at all angles, the phase function is the intensity (radiance) at θ [17].

7. Red Blood Cells and Oxygen Saturation in Blood

For blood analysis, it is necessary to have knowledge of spectroscopic methods. Human red blood cells (RBCs) exhibit light scattering and absorption properties. As well as laser medicine, hematology, and medical routine diagnosis, it has many diagnostic and therapeutic applications. Oxygenation of hemoglobin, which affects the optical behavior

of red blood cells, is a crucial diagnostic parameter in heart surgery, intensive care, and neonatology [18].

Application examples include measurement of the blood oxygen saturation in cardiopulmonary systems[1] or measurement of the brain's oxygen supply [18].

According to the radiation transport theory, the optical properties of red blood cells can be described by the intrinsic optical parameters: absorption coefficient μ_a, scattering coefficient μ_s, and anisotropy factor g, together with the appropriate phase function. Various approaches have been taken to determine the optical properties of blood cells. In most cases, the investigated wavelength range did not extend to 1100 or 1200 nm. Due to the high optical density of blood, especially at physiological concentrations, it has not been possible, in most cases, to determine the parameters μ_s and g separately. Only the effective scattering coefficient $\mu_{s'} = \mu_s(1-g)$ could be determined for single wavelengths or for small spectral ranges where the absorption of hemoglobin is low. Using the double integrating sphere technique combined with an inverse Monte Carlo simulation (iMCS), all three optical parameters for a flowing red blood cell suspension could be determined independently in the spectral range of 250 to 2000nm, including the spectral areas of high hemoglobin absorption and the two distinct absorption peaks of water [18].

The optical behavior of blood is known to be dependent on various physiological parameters, one of which is the oxygen saturation of hemoglobin. The absorption behavior of hemoglobin is determined by the oxygen saturation and alters when there is a change in oxygen saturation. It is also known that changes in μ_a can influence the scattering properties, especially the anisotropy factor g. In view of the physiological significance of oxygen saturation and the growing use of optical methods in medicine, it is interesting to know whether oxygen saturation can affect the scattering properties [18].

8. Color of Blood

While the blood of humans and some animals are red, the blood of some animals - and humans under certain conditions - is another color. In all cases, blood is responsible for transporting vital substances. The body of a human transports some substances differently than the body of an animal. Deoxygenated blood appears dark red or maroon in humans and oxygenated blood looks bright red. In red blood cells, hemoglobin molecules are responsible for color. The pigment hemoglobin is a respiratory pigment.

These chemical transports oxygen to the tissues, which require it for energy production. If the blood is not red, it may be an indication of illness. As a result of a buildup of abnormal hemoglobin, human blood can appear brown or green. There is a wide range of colors of

blood among animals, including red, blue, green, yellow, orange, violet, and colorless blood. There are some animals that have hemoglobin like us, some with different respiratory pigments, and some without any respiratory pigments at all. Regardless of their respiratory pigments, however, all animals currently transport oxygen by breathing [18].

8.1 Color of Blood in Veins

Even though the shades of red in the body vary, all blood is red. Even though the veins in illustrations of the circulatory system are traditionally colored blue, blood in veins is not blue. Veins that are close to the surface of our bodies, such as those located on the backs of our hands, appear blue to the naked eye. Blood itself is not responsible for the blue appearance, but rather how light interacts with the skin as it enters and exits the body [18].

An artificial or natural light source that emits "white" light is composed of all of the visible light spectrum's colors. Each color has a different wavelength and energy. When the different wavelengths strike the skin and the cells below the skin's surface, they are affected differently. Several studies have shown that the light that strikes the veins and their deoxygenated blood and then reaches our eyes is more likely to be in the high-energy blue region of the spectrum than in the low-energy red region. Therefore, the veins appear blue to us [18].

9. Pigment Structure of Blood

Hemoglobin is composed of four polypeptide chains that are joined together to form a complex structure. There are two alpha chains and three beta chains. Alpha and beta chains possess completely different amino acid sequences. Each chain, or subunit, of the molecule, contains a heme group. The hemoglobin molecule consists of heme groups, which are pigmented and have iron in them. Oxygen and iron combine reversibly in this molecule. The human body produces red blood cells that contain hemoglobin. An adult female's blood contains between 4 and 5 million of these cells, while an adult male's blood contains between 5 and 6 million. There are about 270 million molecules of hemoglobin in every red blood cell or erythrocyte. Blood appears red because of the high concentration of molecules [18].

As we breathe in, oxygen binds to iron contained in hemoglobin molecules. Red blood cells result from this reaction. Hemoglobin that has been oxygenated is transported from the lungs through the arteries, into the narrower arterioles, and finally into tiny capillaries. Oxygen is released from the capillaries to the tissue cells, which use it to produce energy. The hemoglobin changes from bright red to dark red or maroon when it gives up its oxygen to the cells. In order to receive fresh oxygen in the lungs, deoxygenated hemoglobin is taken back to the venules and veins [18].

10. Function of a Pulse-Oximeter

The pulse oximeter is known as an electronic small device that measures the oxygen saturation through the human red blood cells. Pulse oximeters can be used by attaching to the fingers, nose, forehead, ears, toes, or foot [19].

Pulse oximetry is an easy and fast way to determine if the oxygen is sent well from the lungs and heart to the other parts of the body. This can help find out whether the heart and lungs are operating properly or not. These devices known as pulse oximeters can be used in order to measure or show warning signs and notices for chronic heart or lung diseases. Therefore, it can have an important rules in determining whether the patient should look for a medical attention for different viruses such as the coronavirus [20]. One of the prime objectives in order to have an acute and critical medical care is to ensure that the oxygen is delivered to tissues adequately. There is not an available routine method for directly measuring and monitoring tissue oxygenation; instead, clinicians have to rest on existing indirect measures [21].

Estimate of a patient's oxygen in tissue status is crucial, though it is not the only factor to be considered. Blood oxygenation is mostly evaluated non-invasively by pulse oximetry devices. This provides convenient and a safe continuous method for nursing of oxygen saturation in capillary (peripheral) blood (SpO_2). However, it has some limitations [21].
Blood gas analysis of arterial parts delivers a completer and more precise standard assessment of blood oxygenation grade. It allows generation of oxygen saturation in arterial blood (sO_2) and also more oxygen-related parameters such as the partial pressure of oxygen in arterial blood, known as pO_2 and the total oxygen concentration of arterial blood (ctO_2) [21].

Depending on which type of the blood gas analyzer is used, arterial oxygen saturation (sO_2) is calculated directly by CO-oximetry, or calculated from pO_2 [21].

11. Understanding of Results

The pulse oximeter devices detect a quick measurement of the saturation of oxygen level in the human body deprived of using needles or taking a blood sample. Depending on the light absorption features of saturated hemoglobin, a pulse oximeter provides an indication of oxygen saturation. Then, the measured amount shown on the screen mirrors the red blood cells saturated with oxygen. This number provides the doctors and nurses with an idea of what the treatment can be. The other benefit of measuring the tissue oxygen level is that it can help to determine whether the patient is in need of supplemental oxygen or

not. This saturation number, which normally should be over 90% to 92%, is different from a value called the pO_2. The normal value of pO_2 should be over 60% to 65%, which can be measured by obtaining artery blood [19].

12. Transport of Oxygen in Blood

Oxygen is an essential factor to life. The function and survival of all tissue cells depend on the nonstop generation of energy in the form of adenosine triphosphate (ATP). The ATP is produced in the cells by aerobic metabolism of dietary fuels, which is known as principally glucose, to carbon dioxide and water. If the process of oxygen supply is interrupted, this energy-generating process will be shortened or stops, which can result in cell injury and eventually cell death or organ failure [21].

The most common reason of cell injury or cell death is Inadequate oxygen within tissues (called Hypoxia). It is central to, or at least a contributory factor in the etiology and/or pathogenesis of most potentially life-threatening diseases or conditions seen in acute and critical care medicine [21].

Since we need to understand how arterial blood gas outcomes can help in assessing patient risk of tissue hypoxia, an elementary information of oxygen transport in blood is needed. A major function of the respiratory and cardiovascular systems is to deliver oxygen to the tissue cells. This delivery process starts from the alveolar-capillary membrane of the lungs [21].

present oxygen in alveolar air spreads from alveoli to blood going through the pulmonary capillaries that surround each alveolus. Blood, which is now loaded with oxygen, is taken from the lungs through the arterial system to the tissues microvasculature, in which oxygen releases to tissue cells. The blood without oxygen is conveyed from the microvasculature of tissue by venous system back to the right part of the heart, and forward via the pulmonary artery to the lungs, for new oxygenation [21].

Oxygen cannot be easily soluble in blood and the maximum amount of oxygen that can be transported just dissolved in blood is not as enough as satisfying the body's oxygen need [21].

In reality, only 1% to 2% of the oxygen carried in blood is dissolved in the blood; it is this small fraction that is reflected in the measured partial pressure of oxygen in arterial blood (pO_2). The remaining 98% to 99% is transported in erythrocytes bound in reverse to the protein hemoglobin [21].

The oxygen delivery function of hemoglobin, i.e. its ability to pick up oxygen in the lungs and release it in the microvasculature of tissues is made possible by a reversible change in the structure of the hemoglobin molecule that alters its affinity for oxygen, and thereby the amount of oxygen each molecule carries [21].

Several environmental features in blood show the relative affinity of hemoglobin for oxygen. The foremost significant of those is pO_2. The presence of hemoglobin in blood with comparatively high pO_2 has much larger affinity for oxygen than hemoglobin present in blood with fairly low pO_2. The oxygen dissociation curve (ODC) defines this relationship graphically (see Fig. 1) [21].

The percentage of total hemoglobin saturated with oxygen (i.e. oxygen saturation, sO_2) is the quantity of hemoglobin affinity in this graph [21].

As can be clearly seen from the graph, at the high pO_2 that prevails in the blood exposed to alveolar air in the lung (~12 kPa), hemoglobin is almost 100% saturated with oxygen; almost all of the available oxygen-binding sites on the entirety of hemoglobin molecules are employed with oxygen. In contrast, in the milieu of the tissues where pO_2 is much lower, hemoglobin affinity for oxygen is also much lower, and oxygen is released from hemoglobin to the tissues [21].

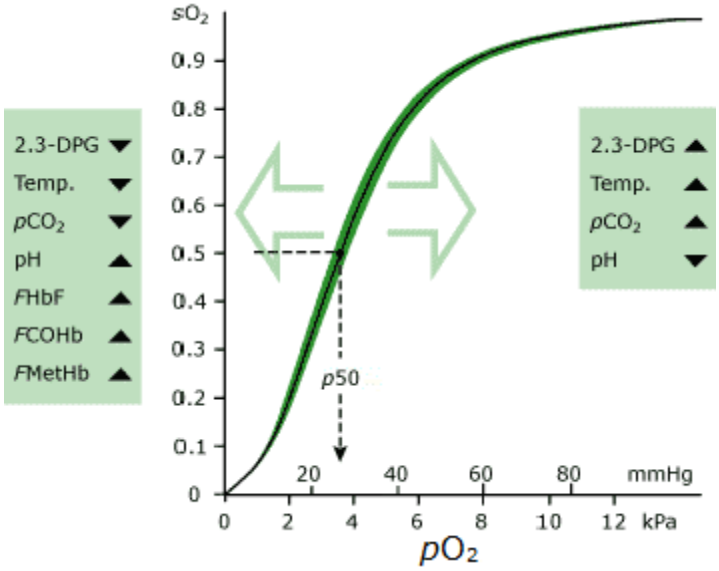


Fig. 2: oxygen dissociation curve (ODC) [21]

Oxygen saturation is the percentage of whole hemoglobin binding sites obtainable for binding to oxygen that is employed with oxygen. It is thus a degree of how much of the

oxygen-carrying capacity due to hemoglobin is being used, and is well-defined by the following equation [21]:

$$sO_2 = \frac{cO_2Hb}{cO_2Hb + cHHb} \times 100\% \quad \textbf{(equation 1)} \text{ [21]}$$

where cO_2Hb = oxyhemoglobin concentration in arterial blood

$cHHb$ = deoxyhemoglobin concentration in arterial blood

($cO_2Hb + cHHb$ = total hemoglobin concentration capable of binding oxygen)

It is vital to note that the denominator in this equation is not the concentration of total hemoglobin [21].

There are two classes of hemoglobin present in blood that are unable of binding oxygen and are not therefore comprised in the denominator. They are carboxyhemoglobin (COHb) and methemoglobin (MetHb), together called the dyshemoglobins because of their functional redundancy [21].

In health, COHb and MetHb together contain less than ~5% of total hemoglobin so that, generally, the concentration of total hemoglobin (*c*tHb) approximates to the sum of cO_2Hb and $cHHb$ [21].

However, there are pathologies - most remarkably carbon monoxide poisoning and methemoglobinemia - that are related to a noticeable growth in COHb or MetHb, and a resulting noticeable decrease in the oxygen-carrying capacity of blood, that is not reflected in sO_2 [21].

Likewise, decrease in *c*tHb (i.e. anemia) also decreases the oxygen-carrying capacity of blood, but causes no change in sO_2. Decrease in sO_2 only rises as a result of conditions (pulmonary and non-pulmonary) that cause decrease in pO_2 [21].

sO_2 (or SpO_2) within the (normal) reference range (95% to 98%) is thus no assurance that blood is well oxygenated, far less that tissues are effectively oxygenated [21].

13. Measurement of sO_2 by CO-Oximetry

Various modern blood gas analyzers have a combined CO-oximeter that allows direct measurement of sO_2. The basis of this measurement is on spectrophotometric analysis of the hemoglobin released from a sample of hemolyzed arterial blood [21].

The four-hemoglobin classes existing in blood (oxyhemoglobin, O_2Hb: deoxyhemoglobin, *HHb*: carboxyhemoglobin, *COHb*: and methemoglobin, *MetHb*) each have a typical light-absorption range [21].

Measurement of the quantity of light absorbed by the hemolyzed sample at several specific wavelengths allows precise determination of the concentration of each of the four-hemoglobin types. Concentration of O_2Hb and *HHb* allows sO_2 to be deduced (see equation 1 above) [21].

This method of sO_2 calculation allows simultaneous generation of further parameters [21]:

- **total hemoglobin, *ctHb*** *(cO2Hb + cHHb + cCOHb + cMetHb)*
- **fractionated carboxyhemoglobin, *FCOHb*** *(cCOHb / ctHb × 100)*
- **fractionated methemoglobin, *FMetHb*** *(cMetHb / ctHb × 100)*
- **fractionated oxyhemoglobin, *FO2Hb*** *(cO2Hb / ctHb × 100)*

14. Calculation of sO_2

Before the development of blood gas analyzers with combined CO-oximeters, sO_2 could only be produced during blood gas analysis by the measurement of pO_2.

Some blood gas analyzers in usage today do not have a combined CO-oximeter so that the production of measured sO_2 values during blood gas analysis lasts.

measurement of sO_2 from calculated pO_2 is based on the relationship between the two defined by the oxygen dissociation curve (ODC); the calculation is a mathematical description of the curve [21].

Here lies the potential deficiency of calculated sO_2, because the shape and position of the ODC is affected by features other than pO_2 and sO_2. The foremost significant of these are [21]:

- Temperature
- pH
- *p*CO2
- concentration of 2,3-diphosphoglycerate (2,3-DPG)
- dyshemoglobins concentration (carboxyhemoglobin, methemoglobin)

The standard (normal) ODC relates pO_2 and sO_2 in blood at standard circumstances (pH 7.4, pCO_2 40 mmHg, and temperature 37 °C). This standard curve also assumes normal concentrations of 2,3-DPG and dyshemoglobin (*COHb* and *MetHb*).

The curve can be shifted to the right (meaning lower sO_2 for a given pO_2) by any of the following [21]:

- Increased temperature > 37 °C
- Increased pCO_2 > 40 mmHg, 5.3 kPa
- Decreased pH < 7.4
- Increased 2,3-DPG

The curve is shifted to the left (meaning higher sO_2 for a given pO_2) by any of the following [21]:

- Decreased temperature < 37 °C
- Decreased *p*CO2 < 40 mmHg, 5.3 kPa
- Increased pH > 7.4
- Increased concentration of dyshemoglobin (*COHb* or *MetHb*)
- Decreased 2,3-DPG

Calculated sO_2 is based on interpolation of the ODC. Therefore, errors are unavoidably greater for hypoxemic arterial samples and all venous samples, because these are examining the steep part of the curve where pretty small errors in pO_2 measurement have noticeable effect on sO_2 [21].

15. Photoplethysmography (PPG)

The electro-optic technique of measuring the cardiovascular pulse wave, called photoplethysmography (PPG), is clinically used for non-invasive classification of physiological components by dynamic monitoring of tissue optical absorption. Non-invasive PPG technology has been utilized in an inclusive range of individual, home or public health monitoring. The submission of PPG has become one in every of the new subjects within the arenas of biomedical engineering lately [22].

A photoplethysmogram (PPG) is an optically gained plethysmogram that may be accustomed to sense blood volume variations within the microvascular bed of tissue. A PPG is usually gained by employing a pulse oximeter which lightens the skin and measures changes in light absorption. a traditional pulse oximeter monitors the perfusion of blood to the dermis and subcutaneous tissue of the skin [23].

With each cardiac cycle the heart pumps blood to the periphery. Although, this pressure pulse is damped by the time it reaches the skin, it is sufficient to distend the arteries and arterioles within the subcutaneous tissue. If the pulse oximeter is attached without compressing the skin, a pressure pulse also can be realized from the venous plexus, as a low secondary peak [23].

The variation in volume caused by the pressure pulse is noticed by revealing the skin with the light from a light-emitting diode (LED) and then calculating the quantity of light either transmitted or reflected to a photodiode. Each cardiac cycle looks as a peak, as seen in the figure. Since blood flow to the skin can be modulated by several other physiological systems, the PPG can also be used to monitor breathing, hypovolemia, and other circulatory conditions. Moreover, the form of the PPG waveform varies from subject to subject, and differs with the location and way in which the pulse oximeter is attached [23].

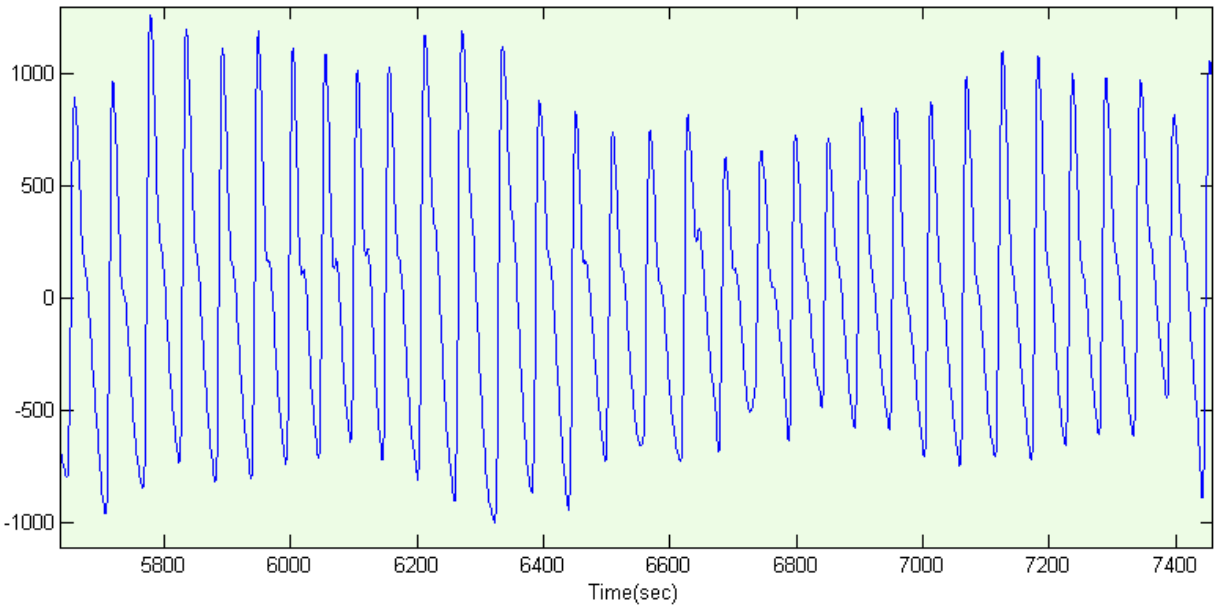


Fig 3: Representative PPG taken from an ear pulse oximeter (Variation in amplitude is from Respiratory Induced Variation.) [23]

The PPG derived from pulse oximeters is rarely displayed and is only generally used to determine heart rate. The PPG can be obtained from both transmissive absorption (at the fingertip) and reflection (on the forehead) [24].

The photoplethysmography (PPG) technique measures volumetric fluctuations of blood circulation, an important indicator of cardiovascular health. Recently, there is increase in the use of PPG technology as heart rate monitoring technique due to the easy way of

operation and its cost effectiveness. But there is still one major disadvantage of using PPG based monitoring which is, tracking the PPG signal in daily routine activity is inaccurate and high physical exercises. This is because PPG signals are very open to Motion Artifacts (MA) caused by hand movements. Moreover, alternative factors such as environmental noise may also affect the PPG signal acquisition, which consequently affect the estimation accuracy of the system [24].

15.1 PPG-Based Monitoring Devices

PPG devices mostly consist of light source and photodetector. Light source transmits light to tissues and then photodetector measures the reflected light from tissues. Reflected light is directly proportional to blood volume variation. For diagnosing cardiac arrhythmias (irregular heartbeats), PPG waves can be used. Mainly PPS sensors use IR – LED diode as source for measuring the flow of blood in body while green LED is used as source for calculating the absorption of oxygen in oxyhemoglobin (oxygenated blood) and deoxyhemoglobin. Wearable PPG sensors can only be placed at certain body locations such as the finger, earlobe and forehead [24].

15.2 Distinct Forms of PPG Sensors

PPG signals have two distinct forms, one is transmission mode and other is reflectance mode. Each mode has its own advantages and disadvantages. In transmission mode, light source as well as detector is separated by tissues. the photodetector is placed along the light source on the same side of the tissue to measure the reflected light. Both sensor types can provide non-invasive measurements. For transmission mode, the fingertip and earlobe are commonly used [24].

15.3 Wristband-Type PPG-Based Devices

Wristband type PPG based is widely used device and also preferred one. The reason behind this is, it is inexpensive, portable and easy to wear. But there are limitations also. This is placed on ulnar and arteries of wrist of patient instead of blood capillaries. For this method, nine axis MEMS sensor with green LED is used [24].

15.4 Forehead-Type PPG-Based Devices

Human head can also use for heart monitoring. Forehead is used, because the reflectance of optical signal from forehead is more powerful. Placement of PPG sensors on the human

forehead can alleviate the destructive effects of motion artifacts on the quality of the PPG signal specially during light physical activities [24].

15.5 Ear-Type PPG-Based Devices

Ear type PPG based device is frequently used for heart monitoring because it contains large blood supply. Moreover, earlobes are very less exposed to the effect of motion artifacts. From the past, magnetic ear clips and headphones have been used to obtain PPG signal. In this method, PPG sensor is places in ear and then earbuds are placed against the tragus to sense the light reflected from the subcutaneous blood vessels [24].

16. PPG Sensors

Photoplethysmography sensors measure change in blood volume even if they are designed in different types. Sensor emits light to tissue and photodiode measures intensity of non-absorbed light which is reflected from tissue. Mostly red and green colors prefer for LEDs and sometimes yellow. Longer wavelength light penetrates more deeply in tissues. However, infrared light is more susceptible to motion artifacts. Motion artifacts are usually caused by tile movement of tile PPG sensor over the tissue, skin deformation, blood flow dynamics, and ambient temperature. In addition, wearable devices could be equipped with accelerometers to capture the direction of motion to reduce movement artifacts, especially during intense physical activity [24].

16.1 Factors Affecting PPG Sensor Recordings

Several factors can affect PPG recordings. These factors are sensing, biological, and cardiovascular factors. Tissue variation generated by voluntary or involuntary movements can produce differences of inner tissues similar as muscle movement and dilation of tissues. The anatomy of individuals along with differences in organ sizes and number of fluids retained by tile tissues result in variation of the propagated light through the tissue. Physical activities as well as body movements can lead to the displacement of the sensor. Movement of sensor changes the light path and also modifies the signal. Applying the pressure on skin can control the magnitude of received signal [24].

17. PPG Signal

The PPG signal consist AC and DC components.AC component is given by cardiac synchronous blood variation while DC component by respiration, sympathetic nervous system activity which depends on the systolic and diastolic phases. Additionally, PPG can

be used to measure HRV (Heart rate variability), or the variations between heartbeat time intervals (Peak-to-Peak or P-P Interval). Features such as rise time, amplitude, and shape can predict vascular changes in the bloodstream. PPG signal can also be used for variation in heart rate (HRV) [24].

18. Some PPG Applications

The early detection of physiological parameters based on PPG signal gives great interest in research. This method can also be used for cardiovascular diseases such as vascular aging. This vascular aging is related to atherosclerosis, or hardening of the arteries. Since cardiovascular and respiratory system works together, PPG coveys the respiratory related information [24].

19. Vascular Aging

Vascular aging is one of the factors which can be reason for the hardening of arteries. This is because of the change in peripheral pulse propagation. the presence of aging is barely visible in young subjects, but compared to older subjects, the systolic peak will be visibly steeper. This may lead to cardiovascular diseases. The amplitude of the PPG can show changes in blood volume. Therefore, by giving information about arterial compliance and arterial elastic properties. With increasing the hardness of arteries, the vessel thickness increases and the inner diameter reduces, which makes it harder for the cardiovascular system of the patient to work. Therefore, their resistance increases and capacitance decreases. Analyzing PPG signals also allows one to determine how well blood vessels adapt to their environment and more specifically, to the thickness of the blood in the cardiovascular system. As we age, we become more prone to arteriosclerosis, which contributes to increased arterial stiffness [24].

20. Respiration Rate and PPG:

Respiratory rate is one of the vital signs that are critical in determining if a subject is healthy and if he or she has illness. In resting, a person's respiratory rate is the number of breaths they take per minute. A healthy respiratory rate is one that is neither too high nor too low. Currently, nasal cannulas and chest bands are used to measure respiratory rates, but these methods may harm patients. There are three ways by which respiratory rate relates to PPG: 1) Flexibility of blood vessels affect the amplitude of pulse wave, 2) Variation in pulse envelope and 3) a decrease in intrathoracic pressure can lead to increasing venous return during inspiration. PPG can be good approach to determine respiration rates for obtaining information about respiration related things [24].

21. MATLAB Tasks

21.1 Representation of Data in Graphical Form Using MATLAB

To represent the data in graphical form, first we have to define each column of the data in matrix inside the MATLAB software.

Column 1	Time Vector
Column 2	PPG 670nm photoplethysmogram for 670nm wavelength - oxygenated O2HB
Column 3	PPG 808nm isosbestic point
Column 4	PPG 905nm deoxygenated haemoglobin - HHB
Column 5	PPG 980nm deoxygenated haemoglobin + water
Column 6	PPG 1310nm mainly water absorption

Chart 2: description table of data set

Here, data set consist of 6 columns. Column 1 is a time vector which is in millisecond. Column 2 to 6 are the 5 wavelengths of 670nm, 808nm, 905nm, 980nm respectively. PMD1 device has 16-bit AD converter i.e., resolution 65535 steps. Therefore, the output of transmission signals of raw data is between -32767 and +32767.

So, PPG data which is in ADC will be converted into voltage values i.e., measuring range 0 to 10Volts.

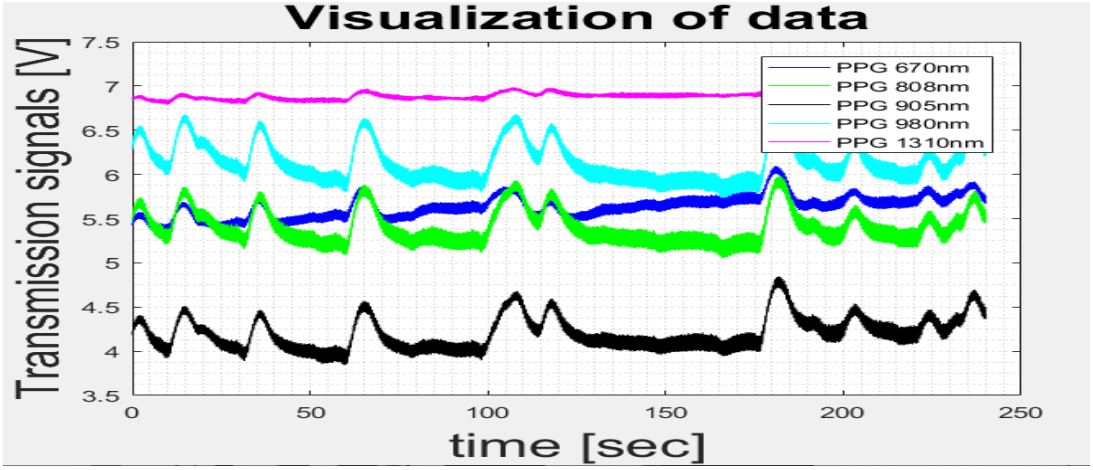


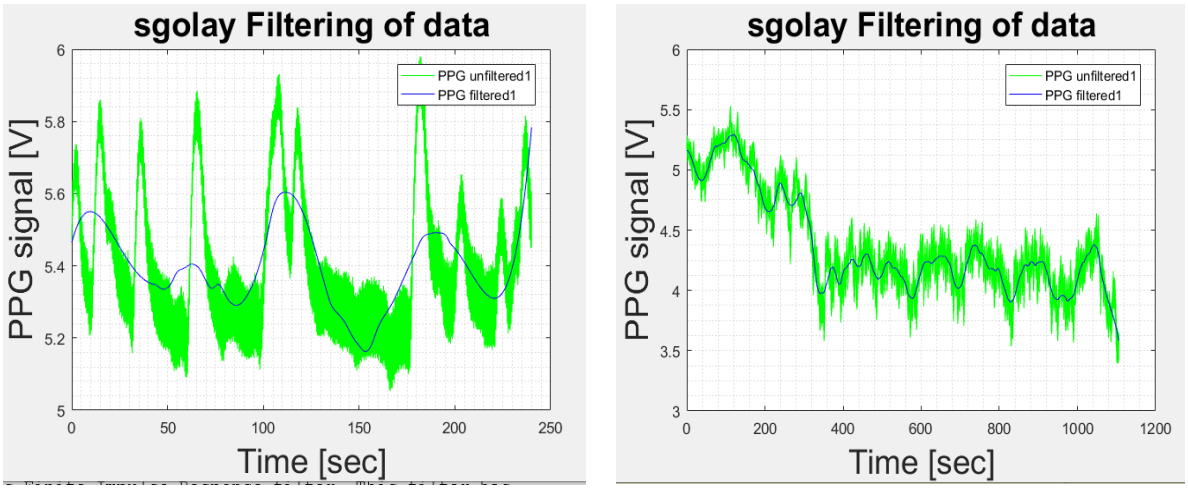
Fig. 5: Visualization of raw data

In the fig. visualization of raw data, the signals contain so much noise that it is difficult to analyze. For removing the noise from the signal, filter will be applied to the signal.

22. Savitzky Golay Filter

Savitzky Golay filter is a digital filter that can be applied to the digital data set to smooth out the data and it increases the precision of signal without any distortion [25].

Following figure shows the plot of data set after applying Savitzky Golay filter for wavelength of L808nm.



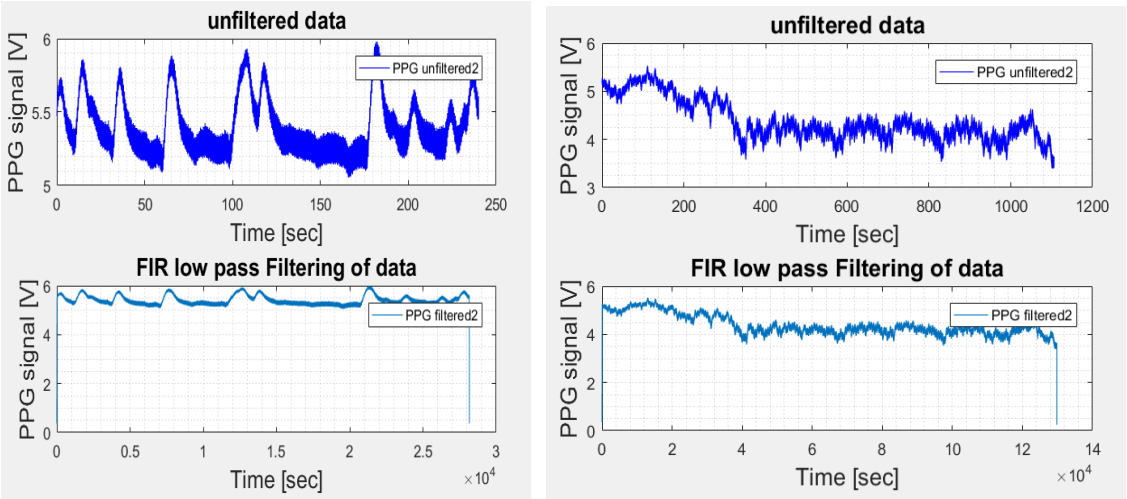
(a) (b)

Fig. 6: (a) Savitzky Golay filter applied on Infant_10_weeks_old. (b) Savitzky Golay filter applied on Hypoxia_volunteer

23. FIR Filter

FIR filter means Finite Impulse Response filter. This filter has response of finite duration. This settles down to zero after finite time interval [26].

FIR filter applied to datasets of wavelength 808nm.



(a) (b)

Fig. 7: (a) Filtered and unfiltered data plot for Infant_10_weeks_old (b) Filtered and unfiltered data plot for Hypoxia volunteer

24. Heart Rate in bpm and Hz

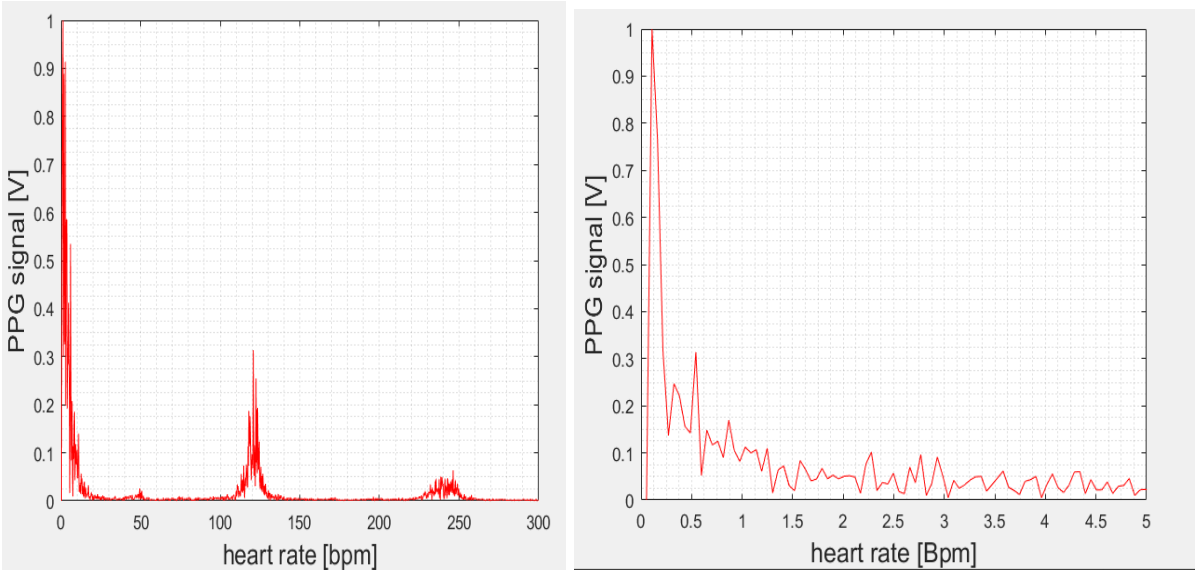


Fig. 8: (a) Heart rate plot for Infant_10_weeks_old (b) Heart rate plot for Hypoxia volunteer

In the figure above, shows the plot of heart rate of data set. Generally, the heart rate of 10 weeks old baby is between 80 to 130 bpm. From the graph, the heart rate is around 130 bpm which is correct.

The following figure shows the graph of heart rate in Hz.

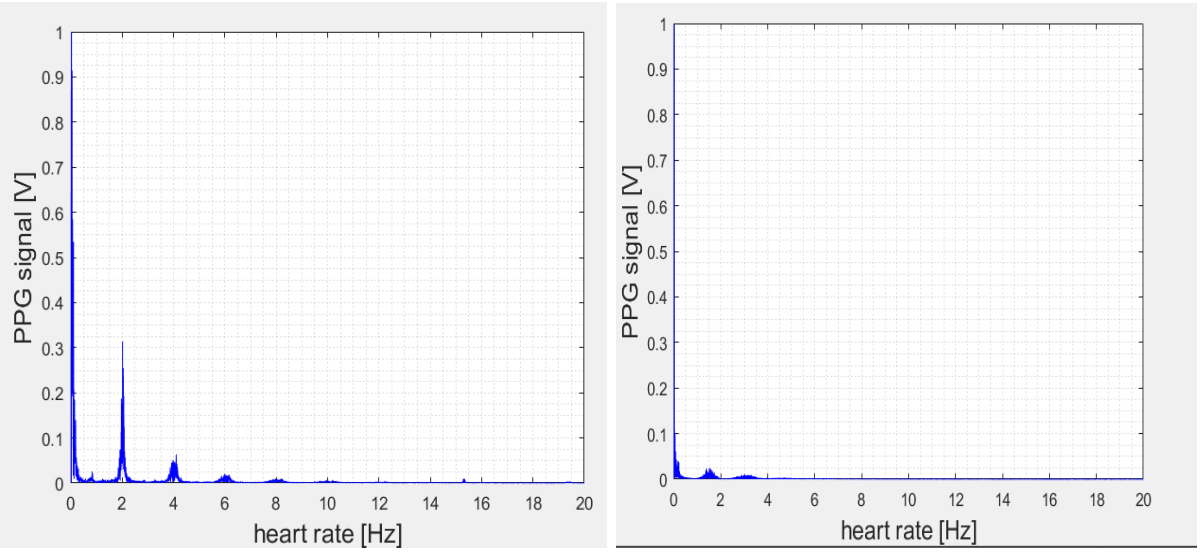


Fig. 9: (a) Heart rate in Hz for Infant_10_weeks_old (b) Heart rate in Hz for Hypoxia volunteer

From the fig. Heart rate in Hz, we can observe that the heart rate of the infant at the age of 2 weeks is higher as compared to the 10 weeks.

25. First Derivative and Second Derivative:

The first method for calculating the derivative is two-point central method i.e., diff-function which is inbuilt in MATLAB.

The second method for calculating derivative is FIR filter. First, we have to build the FIR filter which includes some coefficients like frequency vector, gain vector.

The following filter shows the subplot of 3 different plots.

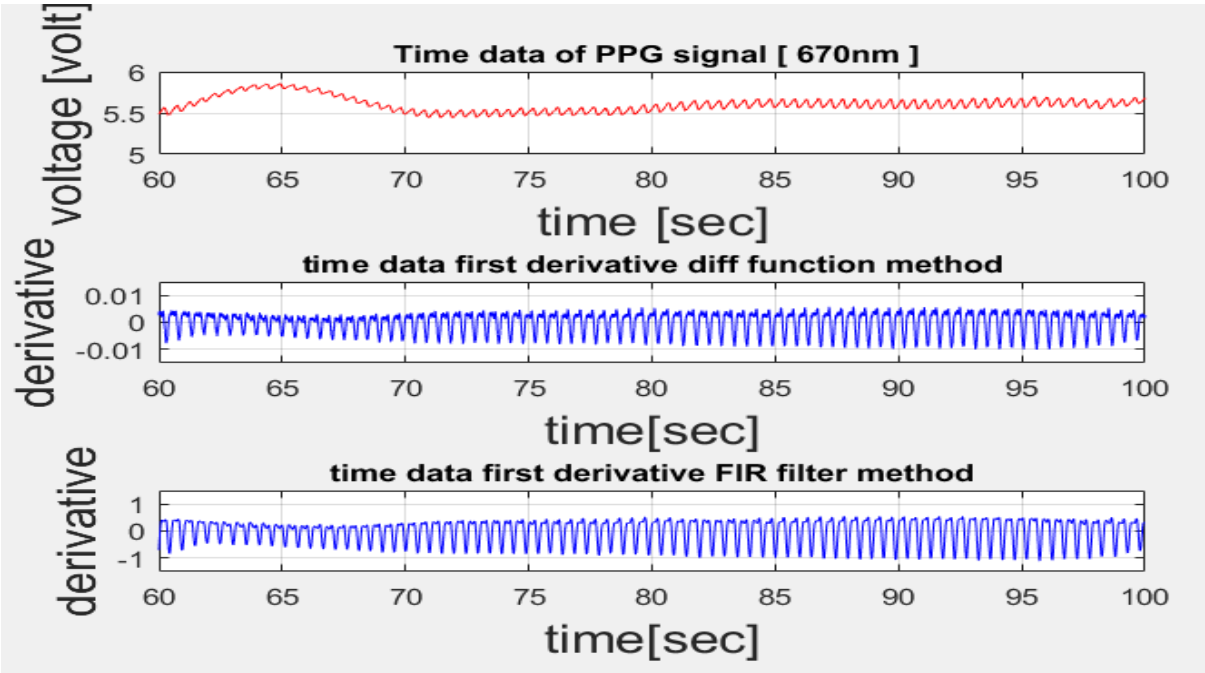


Fig. 10: Time data and first derivative for Infant_10_weeks_old

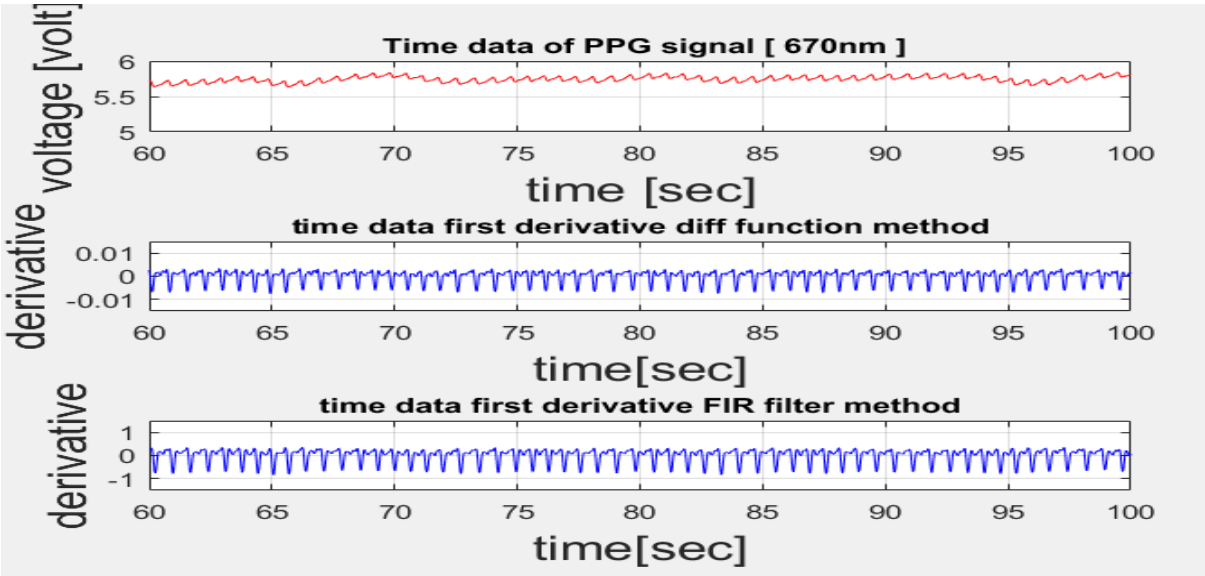


Fig. 11: Time data and first derivative for hypoxia volunteer

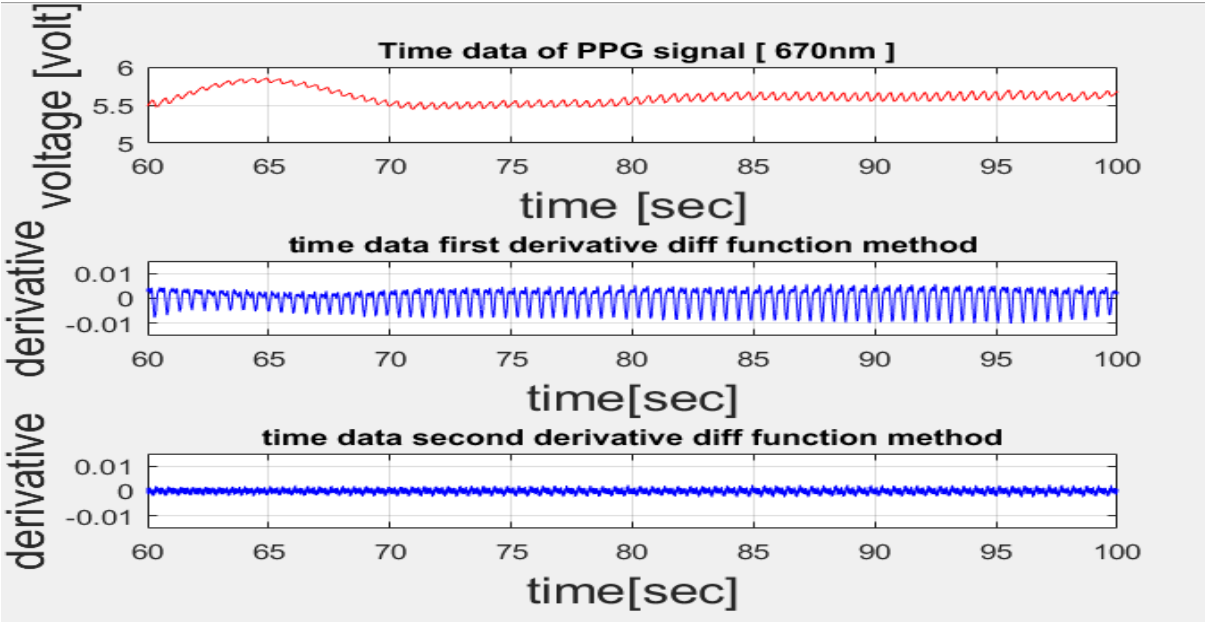


Fig. 12: Second derivative for Infant_10_weeks_old

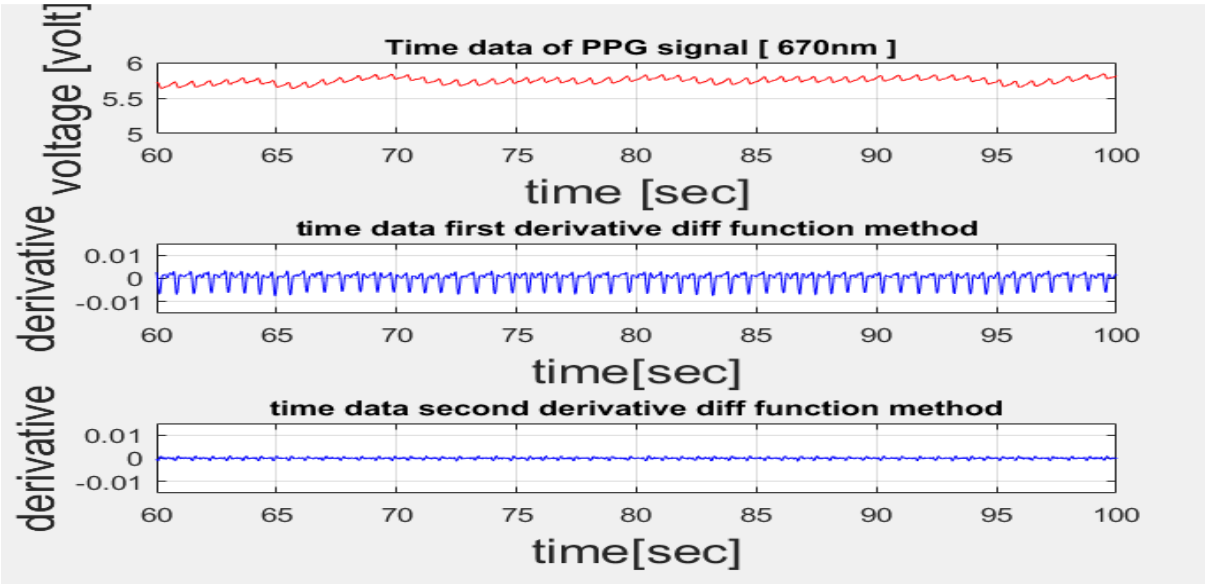


Fig. 13: Second derivative for hypoxia volunteer

26. Data Analysis in Time – Frequency Range (STFFT):

Short – Time Fourier Transform is a Fourier transform sequence applied on windowed signal. It provides time localized frequency information. In this Fourier transform, long time signal is divided into short time signal with equal length and then Fourier transform is applied on each separate part [28].

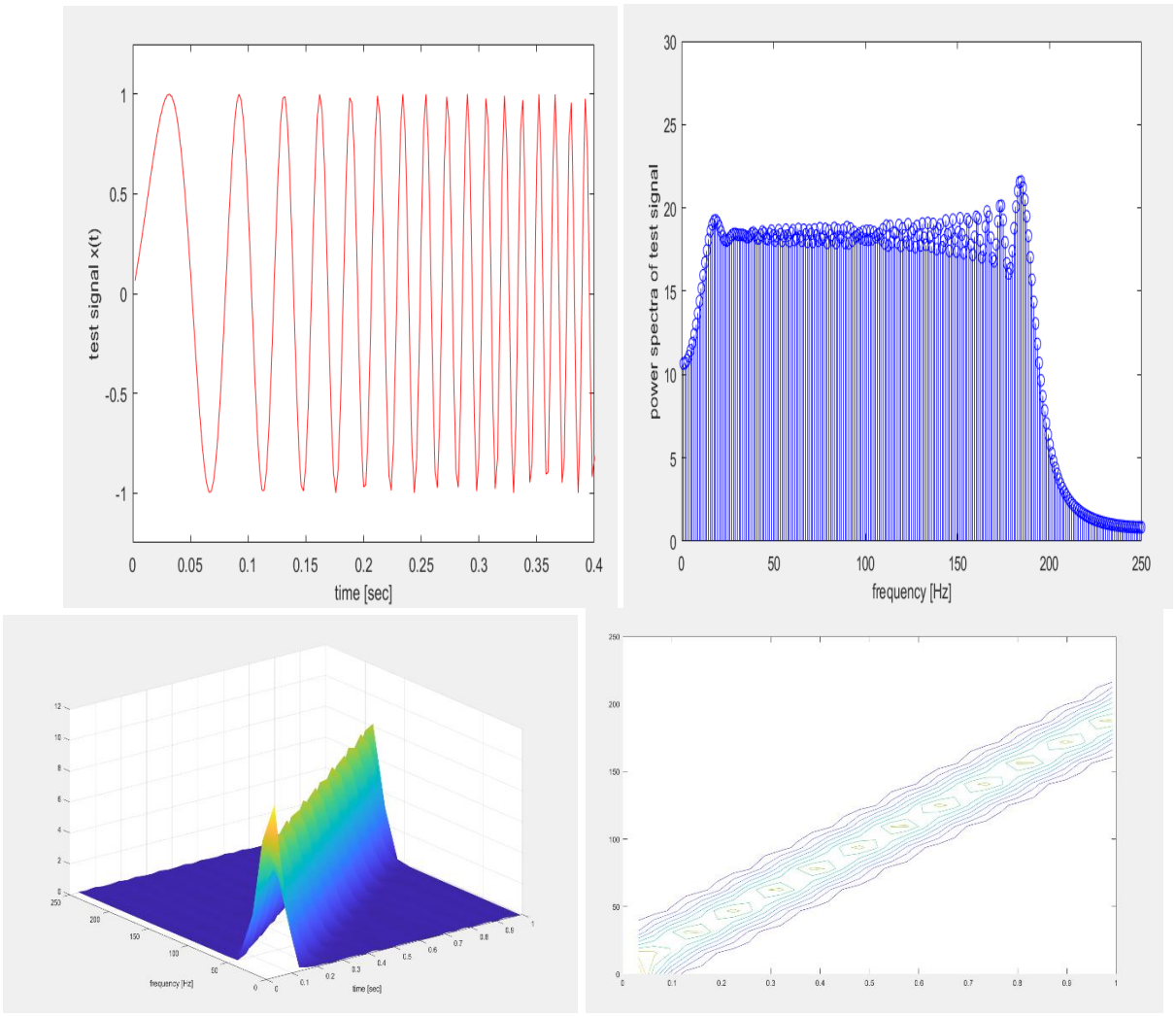


Fig. 14: Time and frequency characteristics

27. AC/DC Ratio of Two Wavelengths:

We have the wavelengths in the range of -32767 to +32767. We have to convert the output of the device in voltage form. ADC is Analog to digital converter which converts the analog signal into digital signal.

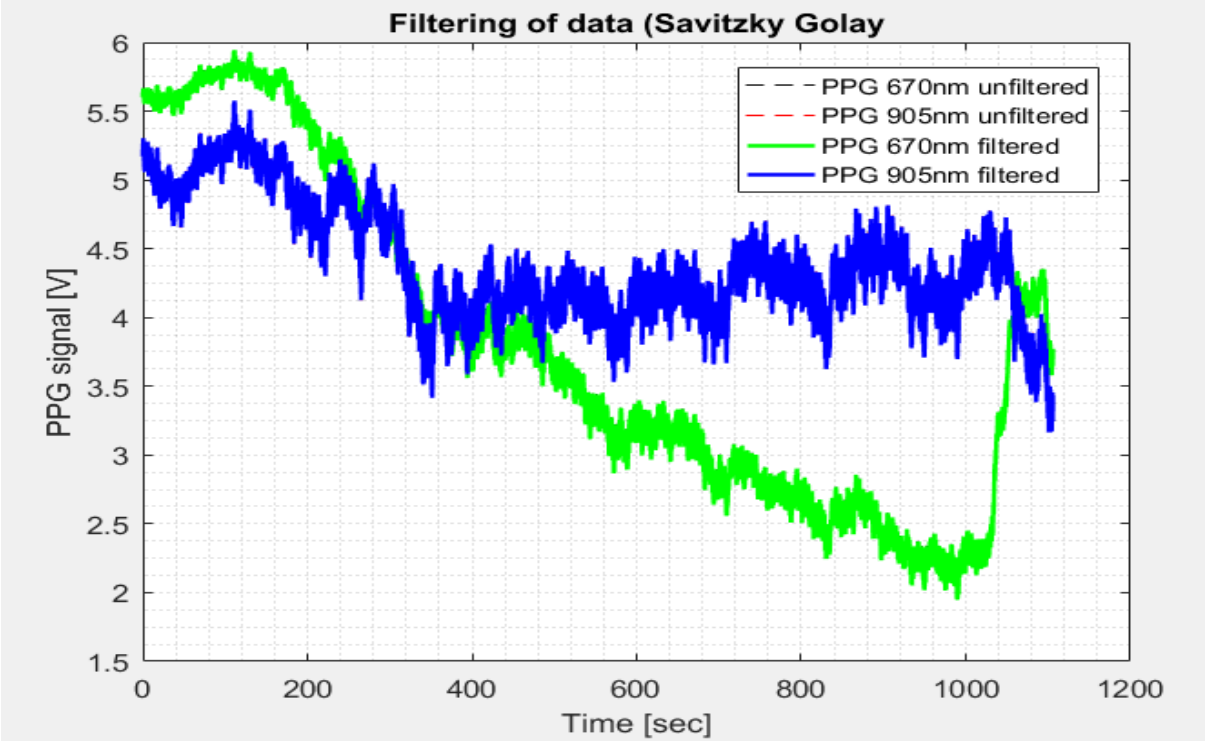
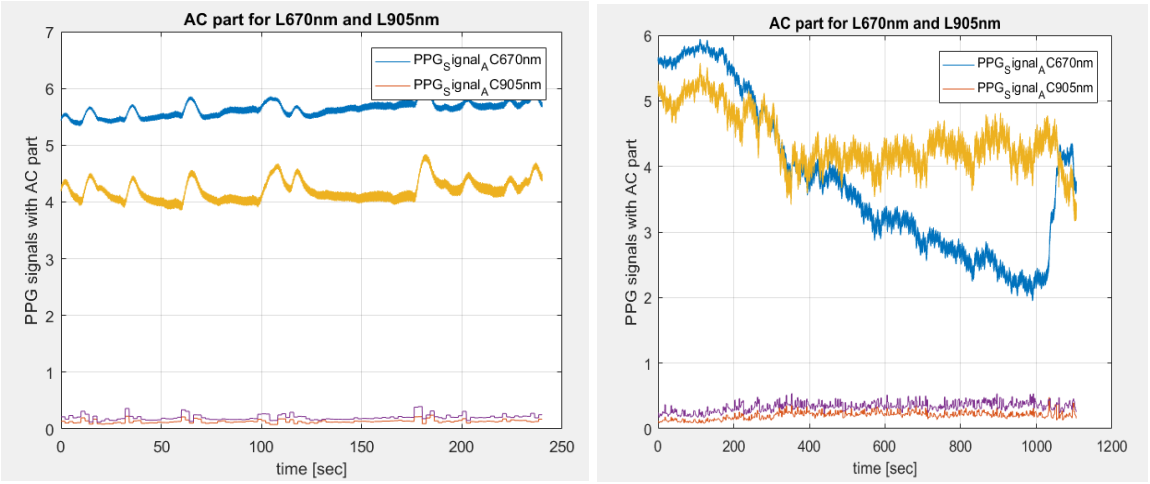
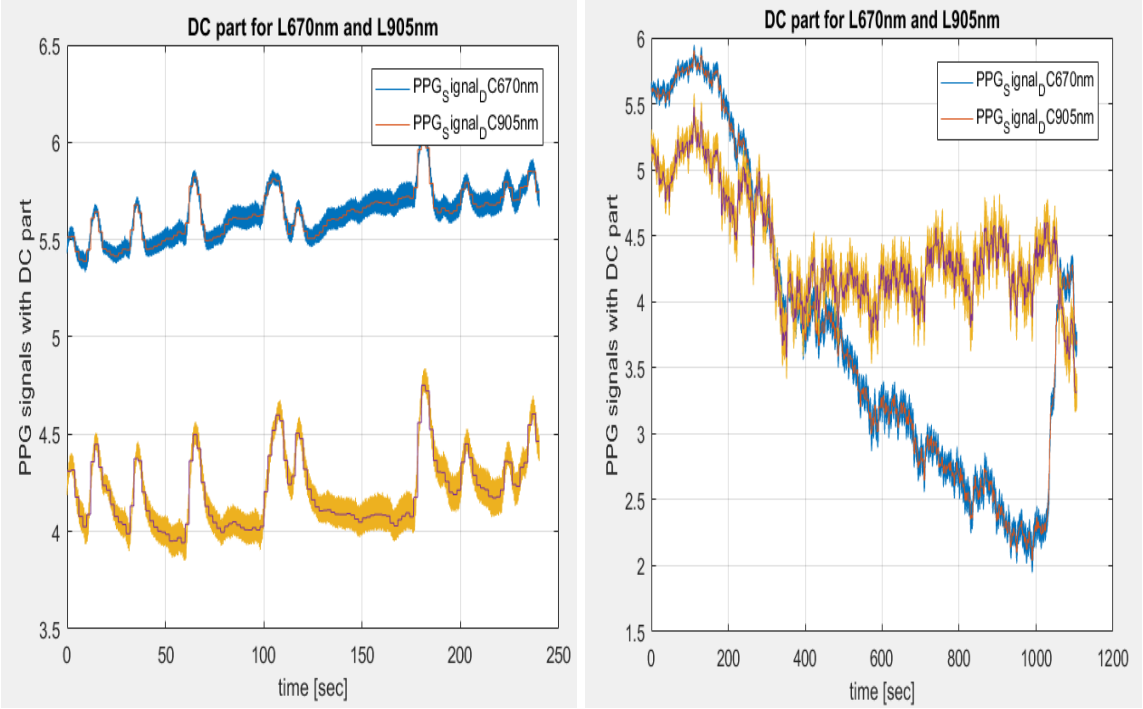


Fig. 15: (a) Filtered and unfiltered signals of wavelength 670nm and 905nm for Infant_10_weeks_old. (b) Filtered and unfiltered signals of wavelength 670nm and 905nm for Hypoxia volunteer

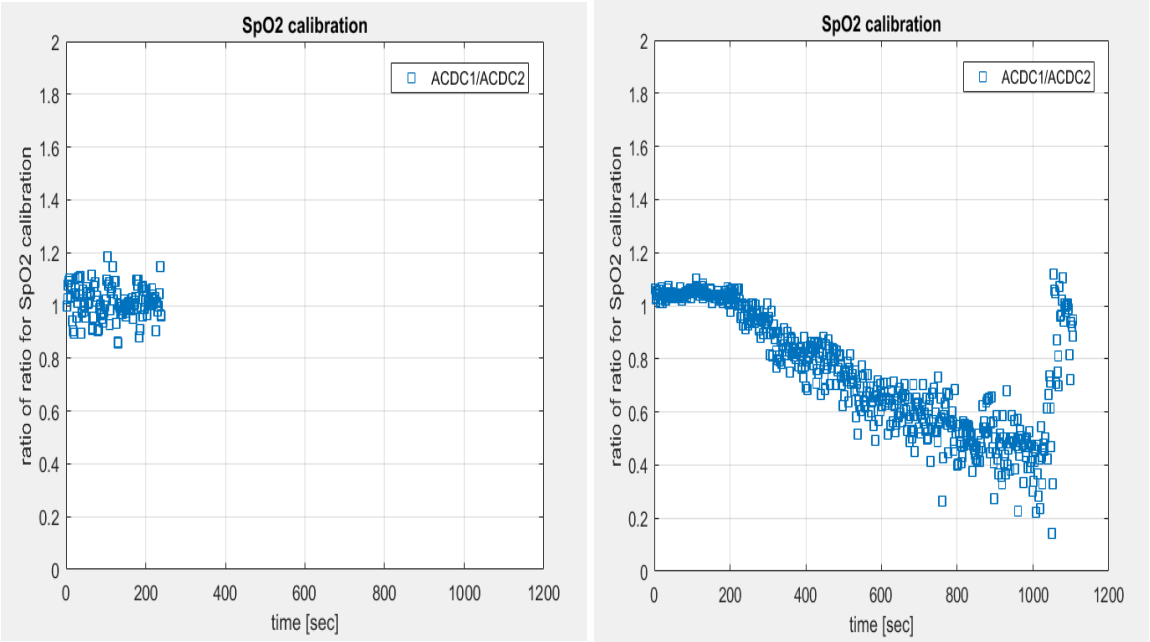
After calculating the AC and DC part separately for two different wavelengths L670nm and L905nm, ration of AC and DC values for each wavelength is done. After ratio of ratios is taken for SpO2 calibration. The following figures shows the AC calculation, DC calculation and SpO2 calibration for Hypoxia volunteer dataset. The oxygen saturation at the starting is grater as compare to the end.



(a1) (a2)



(b1) (b2)



(c1) (c2)

Fig. 16: (a1) AC calculation (b1) DC calculation (c1) SpO_2 calibration for Infant_10_weeks_old. (a2) AC calculation (b2) DC calculation (c2) SpO_2 calibration for Hypoxia volunteer.

28. Spectrogram

Spectrogram is a visual representation of signal spectrum which is in frequency domain. It displays the strength of signal over time which varies with the frequencies. Spectrogram is represented with the colormap [27].

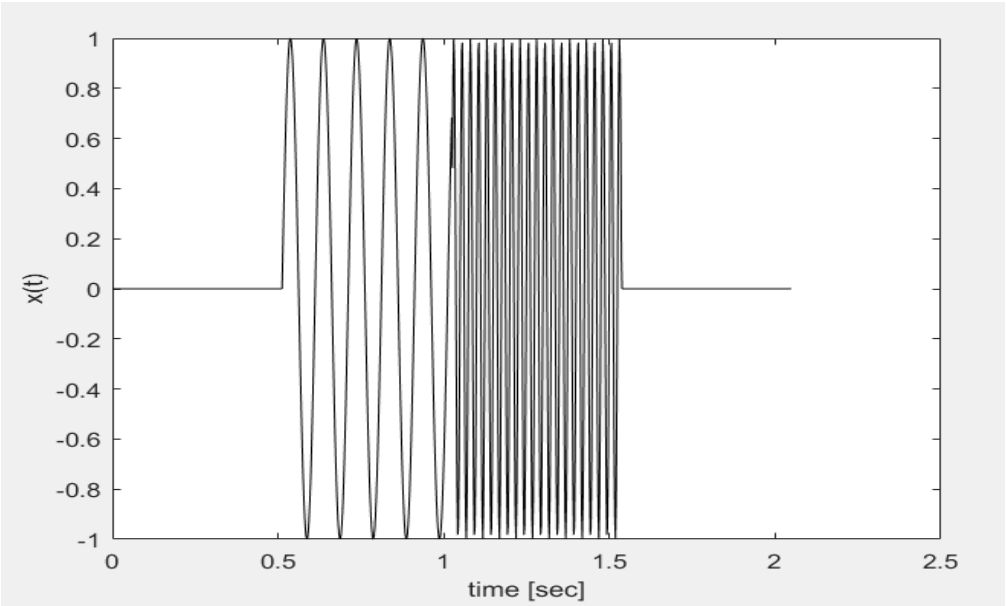


Fig. 17

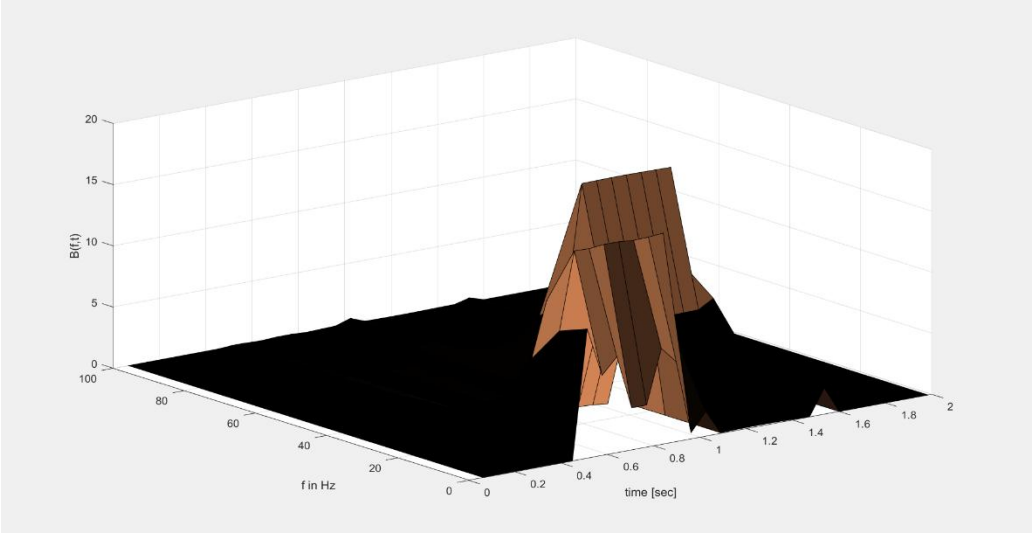


Fig. 18: Spectrogram

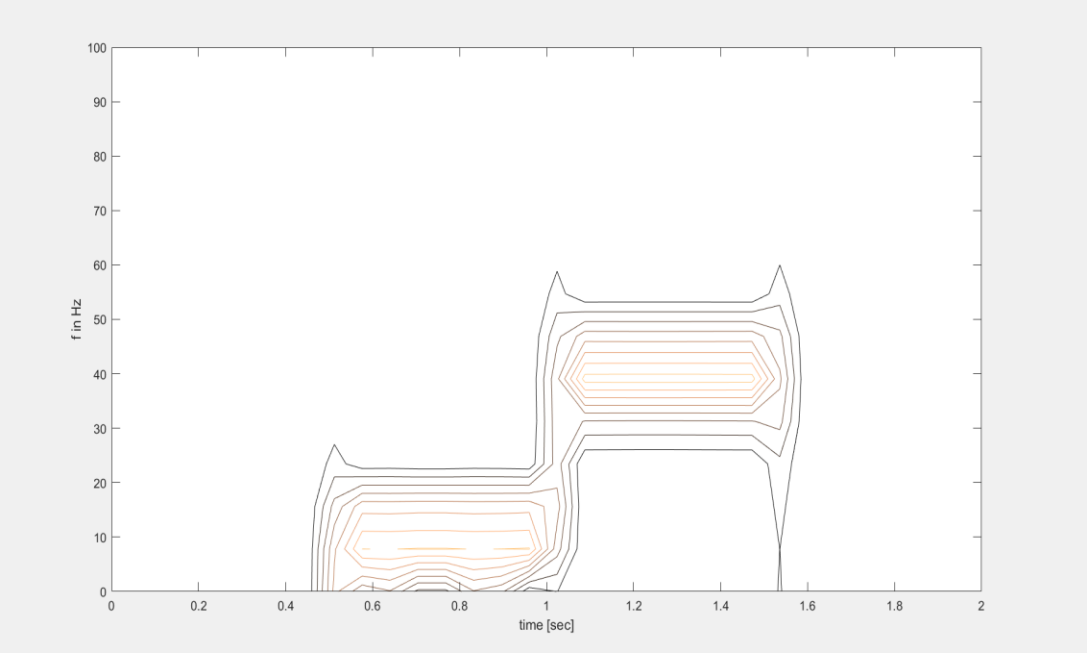


Fig. 19: Contour

29. Conclusion

This report was all about the analysis on different data sets collected by healthy and unhealthy patients which faces the problems such as hypoxia, diabetes and also infants by using pulse oximeter. All the data processing is done using MATLAB software tool. After processing on data sets, we found that heart rate is different for each different problem. By observing the heart rate, we will come to know the health of a person which is nowadays much more important.

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