Pulse oximetry

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Abstract. An oximeter is a piece of medical equipment that is employed for the sole purpose of measuring the amount of oxygen that is present in the blood and can also be used to keep track of one's overall health. The optical principle serves as the primary foundation for the oximeter's detecting method, which allows it to determine the presence of oxygen in the blood. By using a method that is known as absorption, a particular color of light is shone on the blood. Next, spectral analysis is used to measure the absorption rate of oxygen in the blood after being exposed to various wavelengths of light. This allows one to calculate the concentration of oxygen in the blood and, ultimately, the blooding oxygen saturation. Pulse oximetry can be thought of as an example of a non-invasive biosensor because its operating principle is distinct from that of invasive biosensors. The measurement of pulse oximetry, as well as its development trend and the manner in which this gadget interfaces with a smartphone, will be the primary subject of this article.

Keywords: Pulse oximetry, blood saturation, signal characteristic and interference.

1. Introduction

Pulse oximetry, generally known as the fifth vital sign, is a rapid and non-invasive monitoring method utilized to assess oxygen saturation in the bloodstream. This technique involves the transmission of light at specific wavelengths through tissue, typically the fingernail bed. Therefore, this essay will first explain the importance of blood oxygen saturation, such as its critical role in medicine for surgery and treatment. The signal of the pulse oximeter is generated according to the pulse wave, which may be interfered with by motion, noise, and other factors in the measurement process. This paper will discuss the characteristics of the signal and the possible interference. The second part introduces the different modules of pulse oximetry, including LED driver circuits and connecting a photodiode to an amplifier. The future tendency is at the last part, pulse oximetry as a commonly used device to monitor people's health, the availability for reading the data is so important.

2. Measurement of blood saturation

2.1. Oxygen Saturation

One of the most important aspects of medical care is the measurement of oxygen saturation [1]. The regulation of oxygen levels within the human body is of great importance due to the potential for hypoxemia to have various acute deleterious effects on certain organ systems. The organs encompassed within this category are the brain, heart, and kidneys [2].

Hypoxemia is characterized by a diminished level of oxygen in the blood that falls below the standard range. Typically, a saturation value of oxygen less than ninety percent is categorized as hypoxemia, a medical disease that can occur as a result of several circumstances, including heart complications, sleep apnea, certain medications, and exposure to high altitudes [3]. The predominant manifestations of hypoxemia encompass headache, tachycardia, cough, dyspnea, wheezing, cognitive impairment, and cyanosis of the skin and mucous membranes. Additionally, Blood oxygen saturation (SaO2) is a critical parameter for assessing the preservation of the heart and brain during the perioperative phase [4].

A decrease in blood oxygen saturation levels suggests the presence of atrioventricular block or arrhythmia. Moreover, there is a potential for the individual to encounter a congenital cardiac condition, which could result in a consequential effect on the level of oxygen saturation inside the

bloodstream. Additionally, diminished heart performance can lead to a decrease in blood oxygen saturation levels. Hence, in the event of diminished blood oxygen saturation, a comprehensive examination ought to be conducted. The comprehensive evaluation of the cardiovascular system, especially the assessment of the heart, encompasses many diagnostic techniques such as electrocardiography. There is research indicates that children who have cyanotic congenital heart disease, which is related to oxygen saturation, need to consider the risk carried by low peripheral blood oxygen saturation (SpO2) during dental treatment. Therefore, we understand that measuring blood oxygen saturation is of great significance in medical diagnosis [5].

2.2. The Pulse Wave, Measurement Principle, and Characteristics of Signals

The pulse oximeter has greatly transformed contemporary medicine by being able to continuously and non-invasively keep an eye on the practical oxygen saturation of hemoglobin in arterial blood (SaO2) [6]. The oxygen saturation measurement is the determination of the ratio between hemoglobin molecules that have been currently connected to oxygen in relation to the number of hemoglobin molecules that are not bound. Hemoglobin is composed of four globular protein subunits at the molecular level. Every individual component is connected to a heme group. Every individual hemoglobin molecule possesses four heme-binding sites that are readily accessible for the purpose of binding oxygen. consequently, in the process of oxygen transportation within the bloodstream, hemoglobin exhibits the capacity to bind and transport a maximum of four oxygen molecules. The oxygen saturation formula shows that oxygen saturation is calculated by dividing the quantity of hemoglobin with oxygen by the total quantities of deoxygenated hemoglobin and oxygenated hemoglobin. Hemoglobin in its deoxygenated and oxygenated states has distinct light absorption properties at specific wavelengths, namely 660 nm and 940 nm, respectively. The light taken in by the pulse oximeter is subjected to analysis using a specialized algorithm, which results in the presentation of a saturation value. Pulse oximetry connects its functions with applications through the probs' infrared light, which the blood can adsorb. This device is positioned on the user's finger non-invasively. The process involves the utilization of light wavelengths to ascertain the proportion between the existing amounts of both oxygenated hemoglobin along with deoxygenated hemoglobin.

The reason for choosing infrared light is related to PPG (photoplethysmography). The SpO2 monitoring device under consideration has been developed utilizing the photoplethysmography (PPG) technique. The photoplethysmography (PPG) technique is a non-invasive approach used to quantify changes in blood volume within tissues of living organisms. The photoelectric receiver is responsible for capturing the reflected and transmitted components when a light beam with a designated wavelength interacts with the subject's fingertip. The light intensity experienced by the receiver is reduced due to the absorption and attenuation effects induced by the blood, muscle, as well as skin constituents of the person. At the receiver, the pulsatility of the light intensity reflects the pulsatility of the blood volume in the epidermis. The process of translating optical signals into electrical signals allows for the observation of blood volume fluctuations through the utilization of electronic devices [7]. Furthermore, The phenomenon in which the signal of light absorption changes over time is referred to as a photoplethysmogram [8]. The photoelectric receiver is responsible for capturing the reflected and transmitted components when a light beam with a designated wavelength interacts with the subject's fingertip. The light intensity experienced by the receiver is reduced due to the absorption and attenuation effects induced by the blood , muscle, as well as skin In Figure 1, oxygenated hemoglobin (HbO2) in blood absorbs more light at 800–1000 nm than hemoglobin (Hb) at 600–800 nm. Therefore, the application of red light (with wavelengths between 600 and 800 nm) and infrared light (with wavelengths between 800 and 1000 nm) facilitates the production of photoplethysmography (PPG) signals from hemoglobin (Hb) and oxygenated hemoglobin (HbO2) respectively. The determination of arterial oxygen saturation (SpO2) without the need for invasive procedures can be accomplished by analyzing the ratio of intensity of two photoplethysmography (PPG) signals.

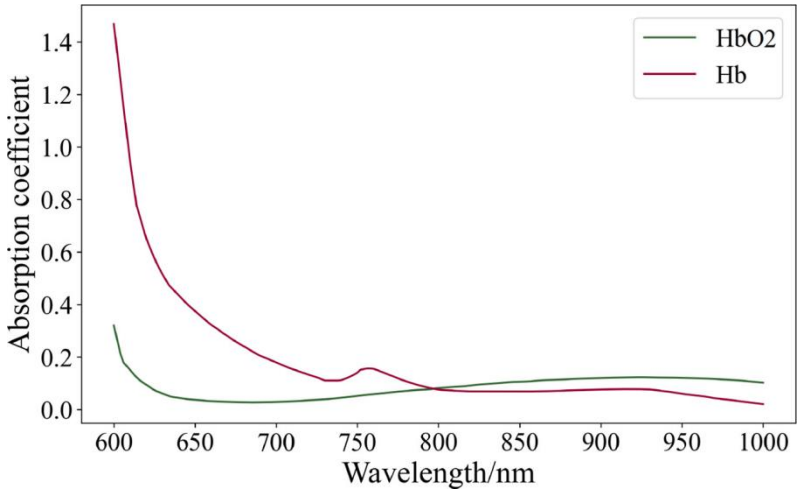


Figure 1. The absorption coefficient and wavelength diagram for Hb and HbO_2 [6]

However, the light sources applied on pulse oximetry to generate the signal are not only the infrared light but also the red and green light. Both of them have advantages and disadvantages. Red light is frequently employed over green light in transmissive pulse oximeters. The precision and degree of accuracy of several tests, including oxygen saturation and heart rate, could be improved by the application of red light. Red light penetrates deeper than green light because the human body absorbs little of it. Using green light to measure muscle saturation or total hemoglobin is limited. Furthermore, it has been observed that red light is less susceptible to the influence of dark skin tone or tattoos, hence minimizing any distortions in measurements conducted with green light. Nevertheless, it is commonly observed that consumer-grade devices predominantly consist of reflecting pulse oximeters that employ green light for the purpose of measuring photoplethysmography (PPG). The utilization of green light has numerous advantages. According to Verkruysse et al. (2008), it has been observed that green photoplethysmography (PPG) amplitudes exhibit the highest intensity within the spectrum of visible light. Furthermore, human tissues exhibit a high capacity for absorbing green light, so minimizing any potential interference from external sources and preserving the integrity of the measured signal.

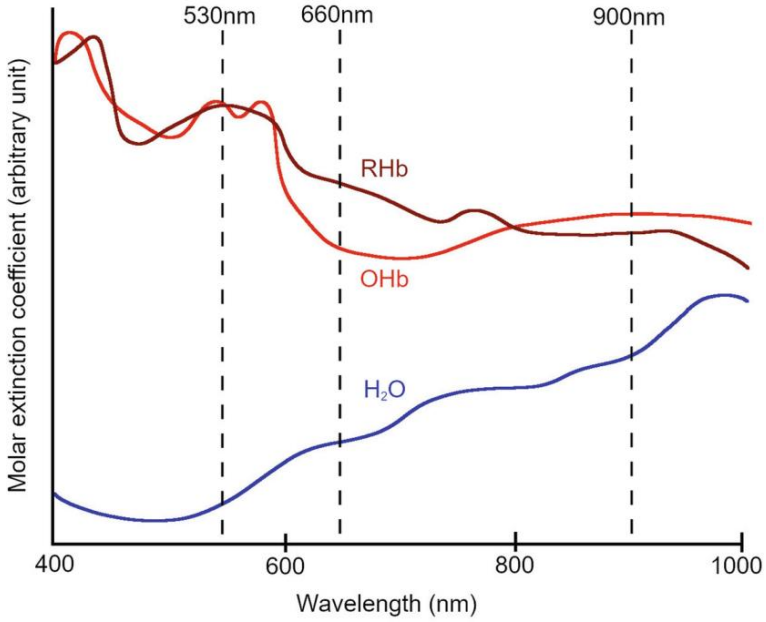


Figure 2. The wavelength and molar extinction coefficient diagram [7]

There is a case illustrating the combination of three light sources on pulse oximetry. The wavelengths of 530 nm, 660 nm, and 900 nm are usually associated with the green, red, and infrared light spectrums used in pulse oximetry devices. To be more specific, In Figure 2. it can be observed

that at a wavelength of 660 nm, the primary factor contributing to the absorption of light is the presence of reduced hemoglobin (RHb) in blood. In contrast, the absorption of light at wavelengths of 530 nm (green) and 900 nm (infrared) is mostly attributed to the presence of oxyhemoglobin (OHb), as it exhibits a greater molar extinction coefficient in comparison to reduced hemoglobin (RHb). The RHb represents deoxygenated hemoglobin, and the OHb represents oxygenated hemoglobin.

Transmissive pulse oximeters operate by detecting an absorption signal at a photodetector, which quantifies the amount of transmitted light that has traveled through a given material. The absorption signal features obtained from measuring the absorption signal of a fingertip are influenced by the differential light absorption properties of soft tissue, skeletal bones, and blood within the finger. The circulatory and respiratory systems induce changes in both the quantity and makeup of arterial blood through physiological mechanisms. Hence, the levels of the optical path length of the light and reduced hemoglobin (RHb), along with oxyhemoglobin, exhibit dynamic variations throughout time. The length of the light waves affects the PPG signal, which is the absorption.Compared to infrared light, red light is more sensitive to variations in oxygenation because decreased hemoglobin (RHb) has a higher molar extinction coefficient and absorbs less water. Water and either oxygenated or deoxygenated hemoglobin display similarities in their absorption of infrared light. Moreover, the utilization of infrared light results in a decrease in overall absorption as compared to red light. Hence, the use of infrared wavelength for measuring the PPG signal is more prevalent and offers greater stability compared to red light. Nevertheless, the estimation of SpO2 requires the utilization of both red and infrared light data.

The formation of the absorbance signal comprises three distinct components, namely the direct current (DC), the low-frequency alternating current (LF-AC), and the high-frequency alternating current (HF-AC) components, as seen in Figure 3. The absence of any pulsing or time-varying elements characterizes the direct current (DC) component, which denotes the absorption of light in a stationary medium. On the other hand, the low-frequency alternating current (LF-AC) and high-frequency alternating current (HF-AC) exhibit temporal variations. The LF-AC component is tasked with transmitting information pertaining to changes in blood volume, which may occur due to fluctuations in respiration, temperature regulation, autonomic nervous system activity, and hemoglobin concentration. As the core of the photoplethysmography (PPG) signal, the high-frequency alternating current (HF-AC) component predominantly denotes the pulsatile nature of the arteries.

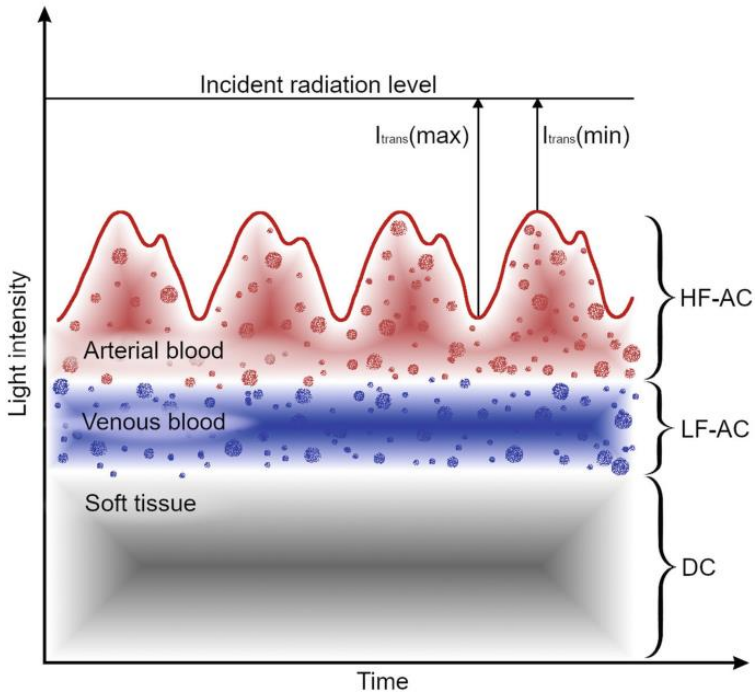


Figure 3. Photoplethysmography signal [7]

2.3. The limitations and Interference on Measurement of Oxygen Saturation

It is crucial to acknowledge the inherent limits of pulse oximetry in diverse clinical scenarios in order to interpret the obtained results accurately. Even minor movements can result in the occurrence of motion artifacts [9]. Examples of minor bodily actions encompass the act of engaging in keyboard typing with a wrist-mounted sensor, as well as the act of respiration with a shoulder-mounted sensor. Motion artifacts have the capacity to undermine the integrity of the signal through several mechanisms. Baseline drift can be induced by these factors and can have an impact on the signal's shape. The main cause of motion artifacts is changes in the tissue's distance from the probe brought on by movement. This phenomenon causes changes in the amount of light that is reflected and diffused by the tissue, as well as the amount of light that is absorbed within the tissue. Apart from extracorporeal motion, there exist alternative causes of spurious alternating signals. When the amplitude of incident light is increased in order to detect an alternating current (AC) signal, the accompanying result is the amplification of both artifactual signal and noise. While contemporary pulse oximeters are equipped with sophisticated algorithms that effectively differentiate between noise and signal, and consequently only accept signals that meet a specific signal-to-noise ratio, there are instances where this noise might be erroneously processed and displayed as a valid signal. Moreover, skin pigmentation is likely to influence the signals that result in detection failures, which can be classified as a limitation.

3. Different Parts of Non-invasive Oxygen Oximetry and Current Development Trend of Oxygen Oximetry

3.1. Different Parts of Non-invasive Oxygen Oximetry

3.1.1. LED driver circuits

A current control technique called pulse width modulation (PWM) makes it possible to regulate heater heat output, motor speed, and other related applications in a way that is both energy-efficient and typically quieter. Pulse Width Modulation (PWM) operates through the generation of pulsating direct current (DC) and the manipulation of the duration of each pulse in order to regulate the magnitude of current directed toward a specific device, such as an LED. Voltage-controlled current source is shown as Fig.4. Pulse Width Modulation (PWM) is a digital signal modulation technique characterized by its binary nature, wherein it operates in two distinct states: the "on" state and the "off" state. The luminosity of the LED will increase proportionally with the duration of each pulse. The LED remains continuously illuminated due to the tiny delay between pulses. In other words, Light-emitting diodes (LEDs) have the capability to alternate between an activated and deactivated state rapidly, and are not often maintained in an illuminated state continuously. PWM systems typically encompass multiple parameters that require tuning, and it is worth mentioning that the pulse width offset D has a formula of $D=100\%*(V_{REF+} -V_{REF})/(V_{max}-V_{min})$.

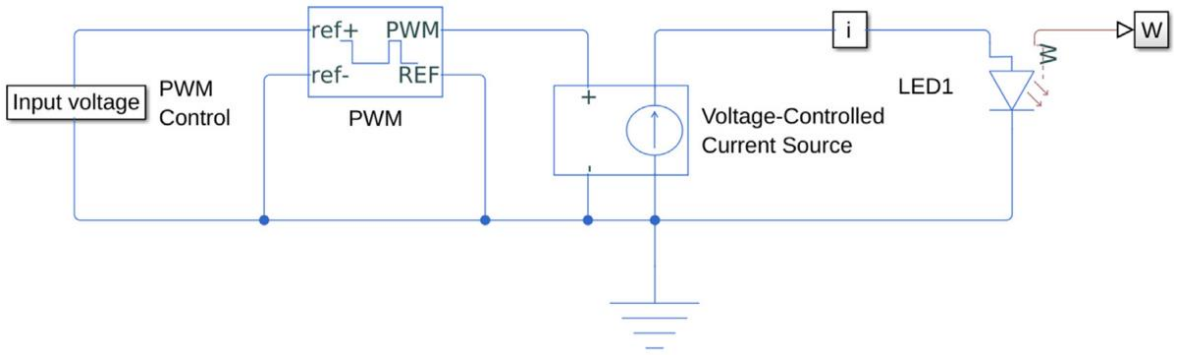


Figure 4. Voltage-controlled current source [8]

3.1.2. Connecting a photodiode to an amplifier

An output voltage is created by amplifying the reverse-current-based current coming from the photodiode using a trans-impedance amplifier. Fig 5 shows the trans-impedance amplifier. A form of amplifier called an operational amplifier uses a single power supply rail to power itself, with Vcc standing for voltage supply and being equal to 3.3 V. The multiplicity of the resistor R1 demonstrates proportionality in the output voltage of the amplifier, and the current is produced by the photodiode. The capacitor C1 is utilized to impart low-pass filter characteristics.

The addition of resistors R2 and R3 to the circuit creates a divider circuit that ensures that the operational amplifier's output voltage stays above the required low output voltage even when there is only a tiny amount of dark current flowing through the photodiode. The photodiode detects the irradiance, which is expressed in milliwatts per square centimeter, emitted by an LED. The pulse width modulation (PWM) frequency and duty cycle for the LED are 1 kHz and 30%, respectively. An illuminance percentage of 2% and a radiant power of 1 mW are used to calculate the determined simulated irradiance. The current of the photodiode is measured to be 5 mA. The trans-impedance amplifier is responsible for converting the electrical current produced by the photodiode into a corresponding voltage signal, which can then be subjected to filtering and subsequent processing.

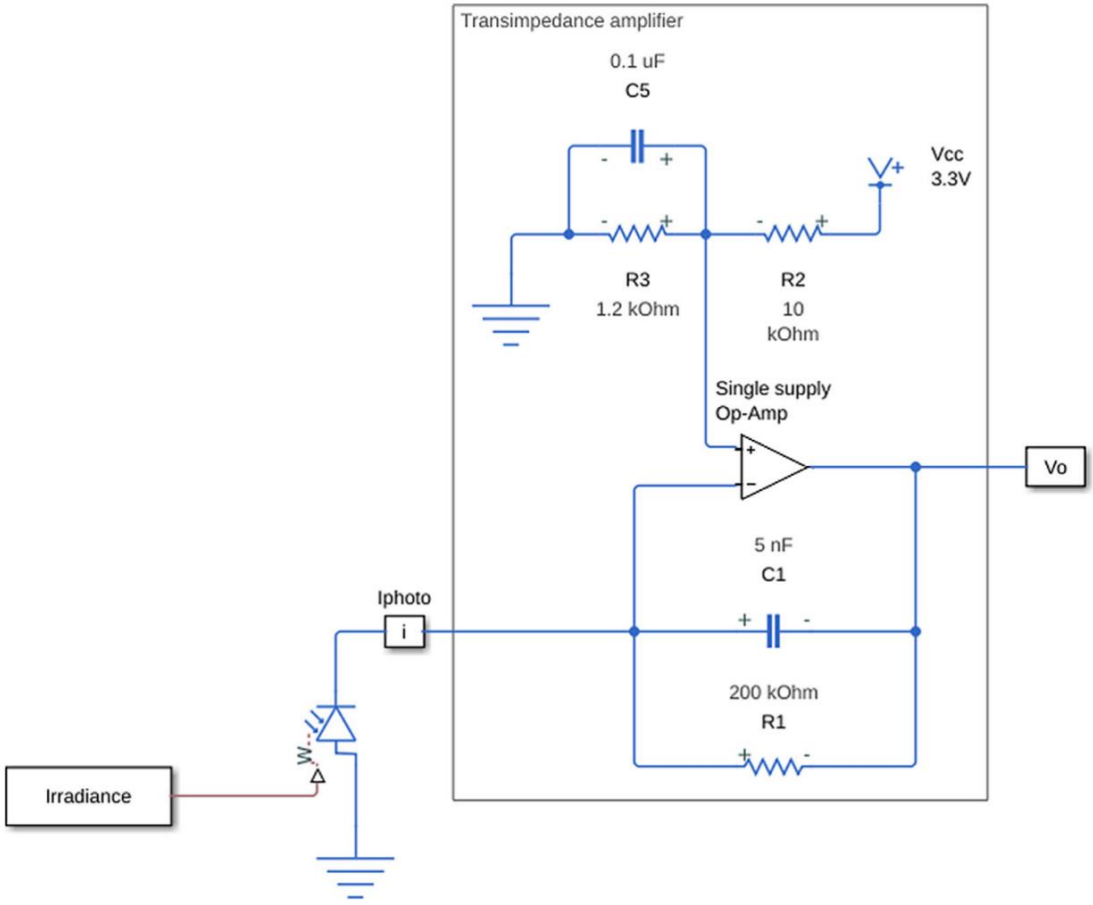


Figure 5. Transimpedance amplifier [8]

3.2. Current Development Trend of Oxygen Oximetry

3.2.1. Connect with smartphone

Because of technological improvements like smartphones and smartwatches, the accuracy of vital signs tracked by these devices has increased. The investigation obtained from smartphone measurements was conducted prospectively at a tertiary healthcare center. A comparative analysis was conducted to assess the oxygen saturation and heart rate values obtained from smartphone measurements in hypotensive patients who sought medical attention at the emergency department

(ED) along with and underwent arterial blood gas evaluation. These measurements were compared with those obtained from a vital signs monitor (VSM) upon admission to the ED, as well as the oxygen saturation values obtained from a blood gas analyzer (BGA). The study was conducted by Prof. Sehit , and it contained a sample size of 200 participants, consisting of 117 female individuals and 83 male individuals [10]. The patient was positioned in a supine posture, and their blood pressure was assessed on three occasions, with each measurement taken at 3-minute intervals. When the mean arterial pressure was less than 65 mmHg, the systolic blood pressure was less than 90 mmHg, or there was a drop of 40 mmHg, hypotension was diagnosed. The data was gathered utilizing a smartphone and VSM, while concurrently procuring an arterial blood gas sample. It was discovered that the intra-class correlation coefficients for the saturation values measured by the smartphone in relation to the blood gas analyzer and vital signs monitor were 0.957 and 0.949, respectively, after comparing the saturation values obtained from the vital signs monitor, smartphone, and blood gas analyzer. These high correlation coefficients suggest a strong level of agreement between the measurements. This study shows that smartphones possess the ability to effectively detect heart rate as well as saturation levels of hypotensive patients, so allowing them to assess crucial physiological indicators without dependence on alternative medical instruments. This intervention enhances the quality of life for patients and offers timely and precise health information to healthcare professionals.

3.2.2. Comparison of transmittance and reflectance pulse oximetry

Currently, the pulse oximeters commonly utilized in critical care and emergency department environments exclusively use transmitted light. Reflectance oximeters, which employ the detection of light "back-scatter" from light-emitting diodes (LEDs) positioned adjacent to detectors, are currently being utilized in the fields of anaesthesia and obstetrics. In anaesthesia, these oximeters are employed to monitor oxygen saturation levels in patients, while in obstetrics, they are utilized by placing a probe on the fetal presenting part to assess oxygenation. Further, the application of reflection oximetry of retinal blood has been investigated as a means of assessing brain oxygenation. To this end, a device has been created by integrating a reflectance oximeter with a laser Doppler flowmeter, enabling the continuous measurement of both saturation and perfusion. However, the adoption of reflectance pulse oximetry probes positioned on the forehead has the potential to enhance the effectiveness of monitoring patients with poor perfusion, as compared to the conventional transmittance probes placed on the finger, toe, or earlobe. The research was conducted by Wax, David B., and it aims to compare the behavior between these two different pulse oximetry through vascular surgery. During the vascular surgery procedure performed under general anesthesia, patients diagnosed with peripheral vascular disease were subjected to monitoring using two different types of probes: a transmittance earlobe probe and a reflectance forehead probe. Continuous recording of SpO2 was performed using two probes, and analysis of gas samples of arterial blood was conducted when there was a clinical indication to do so. Bland-Altman analysis was employed to compare the average values obtained from both probes for every individual minute. A cohort of twenty individuals was selected, resulting in a dataset including 3993 pairs of data averaged across one-minute intervals. Both probes did not fail to report a value for a duration exceeding one minute. The Bland-Altman figure illustrated the range of agreement between the probes, with limits of agreement ranging from -4.0% to +2.6%. From this research, it is noticed that The recently evaluated reflectance forehead Spo2 probe demonstrates satisfactory concordance with the previously used transmittance probe positioned on the earlobe for the goal of pulse oximetry in patients undergoing vascular surgery, particularly within the customary limits of Spo2.

4. Summary

Most oxygen blood saturation measurements use non-invasive biosensor pulse oximetry. Blood saturation can reflect the patient's health condition, so it acts as an important index before treatment. The device works according to the different wavelengths that will be absorbed in deoxygenated and oxygenated hemoglobin. The absorption from light sources plays an inversely proportional

relationship with blood saturation. However, the data from pulse oximetry contains uncertainty. One of the non-negligible interferences is named motion interference. With the development of science and technology, non-invasive pulse oximetry aims to connect with a smartphone, through the experiment of comparison of measured values from signs monitor, smartphone, and blood gas analyzer to obtain the result of the values have excellent agreement between them. This development contributes a great help for patients, especially hypotensive patients. This technology gives them the chance to detect vital parameters before medical help.

References

[1] Torp K D, Modi P, Pollard E J, et al. Pulse Oximetry. Treasure Island (FL): Stat Pearls Publishing, 2023.

[2] Hafen B B, Sharma S. Oxygen Saturation. Treasure Island (FL): StatPearls Publishing, 2023.

[3] Dutta S S, Hendson E. "What is oxygen saturation" News Medical Life Science, 25 Feb, 2021.

[4] Ye Lincai, Qiu Lisheng, Feng Bei, et al. Role of blood oxygen saturation during post-natal human cardiomyocyte cell cycle activities. JACC: Basic to Translational Science, 2020, 5 (5): 447 - 460.

[5] Dutra R M F, Neves I L I, Neves R S, et al. Peripheral oxygen saturation, heart rate, and blood pressure during dental treatment of children with cyanotic congenital heart disease. Clinics, 2014, 69 (5): 314 - 318.

[6] Edward D. Chan, Michael M. Chan, Mallory M. Chan. Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations. Respiratory Medicine, 2013, 107 (6): 789 - 799.

[7] Sun Guiling, Ren Xiangnan, Wang Zhihong, et al. Adaptive low-power wrist SpO2 monitoring system design using a multi-filtering scheme. Biomedical Signal Processing and Control, 2023, 81: 104432.

[8] Leppänen T, Kainulainen S, Korkalainen H, et al. Pulse Oximetry: The Working Principle, Signal Formation, and Applications. Advances in Experimental Medicine and Biology, 2022, 1384: 205 - 218.

[9] Bolic M. Chapter 6 - Devices based on photoplethysmogram and pulse oximetry. Pervasive Cardiovascular and Respiratory Monitoring Devices, Academic Press, 2023: 201 - 244.

[10] Totuk A, Bayramoglu B, Tayfur I. Reliability of smartphone measurements of peripheral oxygen saturation and heart rate in hypotensive patients' measurement of vital signs with smartphones. Heliyon, 2023, 9 (2): e13145.