KJMS 2022 VOL.4 (1): 62-71

KDU Journal of Multidisciplinary Studies (KJMS)

Volume 4. Issue 1 July 2022

DOI: http://doi.org/10.4038/kjms.v4i1.40

A RECHARGEABLE PULSE OXIMETER FOR REMOTE MONITORING OF MULTIPLE PATIENTS

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ABSTRACT

Pulse oximetry is a widely used medical respiratory method that is used to measure arterial blood oxygen saturation and pulse rate. Pulse oximeters enable measurements of the oxygen saturation in blood, which is an essential parameter in most clinical applications including diagnosis and rehabilitation. The demand for pulse oximeters is rapidly rising with the increasing occurrence of respiratory diseases and cardiovascular diseases. However, the existing pulse oximeters can only be used for a single patient, and multiple patient monitoring systems for patients in hospitals and home-based patients are not yet available in the current market. The existing devices also require manual patient data recording and frequent examinations of oxygen saturation levels. Also, most of the existing pulse oximeters are powered by batteries which will have to be periodically replaced. Hence, the main aim of this research is to develop a wireless wearable pulse oximeter for continuous patient monitoring by incorporating communication technologies such as the IoT technology- the Internet of Things. The proposed pulse oximeter will be a rechargeable one that allows Wi-Fi data transmission for temporary data storage. This is used for remote monitoring of multiple patients over a vast geographical area and it supports contact minimization to reduce transmissible diseases. An integrated alarming system is used to warn the doctor if the oxygen levels deplete abnormally, through a mobile application. The developed pulse oximeter has the ability to monitor 62 patients successfully, for a period of 2 days without charging. This non-invasive device will be developed in the future to support more patients, to increase the accuracy and the stability of the data displayed, and to minimize the time delay experienced during the transmission of data.

KEYWORDS: *Pulse Oximeter, Remote Monitoring, IOT- Internet of Things*

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1. INTRODUCTION

The oxygen saturation of the blood is required for different healthcare applications including diagnosis procedures and treatment processes. Hence, a special procedure known as Pulse Oximetry is used to measure the level of oxygen that is dissolved in the blood. It is an indirect, safe, cost-effective, and quick procedure that measures the arterial oxygen saturation of the blood as a percentage. The normal blood oxygen percentage value for a healthy individual lies between 95%-100%. But the SpO_2 value can drop below normal due to different health conditions including lung cancer, chronic obstructive pulmonary disease (COPD), heart failure, anaemia, asthma, pneumonia, etc., and when undergoing sedation during different surgical procedures as well. It is essential to monitor the blood oxygen levels and take necessary measures such as supplying artificial ventilation to supply the required levels of oxygen to the body. Hence, most clinical scenarios require data about the amount of oxygen carried by the blood for the diagnosis of diseases and to prescribe further medications. Pulse oximetry is widely used in healthcare applications by clinicians to ensure that a sufficient amount of oxygen is delivered into the bloodstream and to check the health condition of patients suffering from different diseases that affect the oxygen saturation in the blood. Moreover, pulse oximetry is a vital tool in measuring the oxygen saturation of blood during different clinical applications including examination of the effectiveness of certain drugs and medical procedures.

Pulse oximeters are major diagnostic tools employed for the process of pulse oximetry and most pulse oximeters provide measurements for multiple physiological parameters. A pulse oximeter is a non-invasive medical tool that gives results within a few seconds without drawing any blood samples and is tested in medical laboratories using different complex equipment. A conventional pulse oximeter gives two readings including blood oxygen saturation as a percentage and pulse rate in Beats Per Minute (BPM). Thus, depending on the application and the requirement, a pulse oximeter can be placed on the finger, earlobe, or around the leg of an infant, and accurate results can be obtained.

The pulse oximeter reading, which gives the arterial blood oxygen saturation, is determined using the principles of light absorption characteristics in blood. Pulse oximeters contain a sensor that includes two light sources that are two light-emitting diodes and a photodetector to measure the absorption. The two light-emitting diodes consist of two separate wavelengths. The two LEDs emit the light of wavelength 660nm for the red light and infrared light of 940nm wavelength. Thus, when the light passes through the blood in the finger, the absorption of the emitted light will be different for oxygenated blood and deoxygenated blood. Pulse oximeters calculate the light absorption difference between haemoglobin (Hb) and oxyhemoglobin (HbO2), where oxyhemoglobin absorbs more infrared light of 660 nm wavelength and lesser red light of 940 nm wavelength than Hb. Thus, Deoxyhemoglobin absorbs more red light, and infrared is absorbed highly by oxygenated hemoglobin. The ratio of absorption is measured between two points and is compared with reference values. (John Hopkins Medicine, 2019) Hence the amount of oxygen saturation in the blood can be determined (Nitzan, Romem and Koppel, 2014).

There are two main methods of pulse oximetry. (Figure 1)

1. Reflective mode
2. Transmissive mode

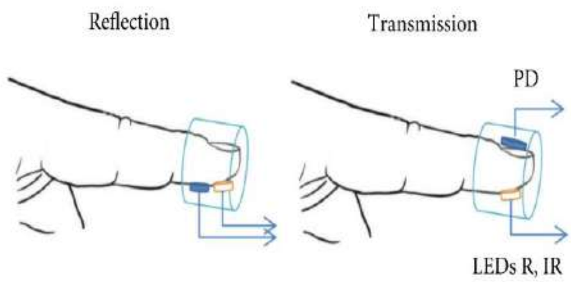

Figure 1. Refractive mode and transmissive mode of pulse oximetry. Source: (Fine and Kaminsky, 2019)

Depending on the measurement site and the application, either the transmissive or the reflective mode can be used (Lee, Ko and Lee, 2016). In the Reflective method, the light sources and the photodetector is placed on the same side. In contrast, in the transmissive mode, the sensor containing two light sources is situated on a side, and in a separate site opposite that, the photodetector is placed. The light emitted from the red and infrared LEDs passes through the fingertip and by using the photodetector on the opposite side, the transmitted light is captured for measurement. The transmissive mode is the most widely used method in pulse oximeters due to its higher accuracy and high stability (Lee, Ko and Lee, 2016). But, since the measurement is placed between the light source sensor and the photodetector, only thin measurement sites can be measured effectively. But in the reflective mode, since the light sources and the detector are on the same side, a thin site is not compulsory for accurate results as the thickness and the size will not be limiting factors for the measurement.

2. LITERATURE REVIEW

Pulse oximeters are non-invasive detectors that are used to assess the oxygen saturation levels of an individual's blood peripherally. The accuracy of a conventional pulse oximeter is 2-4% (Webster, 1997). Usually, the blood oxygen level lies between 95%-100% for a healthy individual (McCallum, 2020) This can be lowered due to different abnormalities in the body. Especially the uprising Covid-19 pandemic has led to an increase in the demand for pulse oximeters and thereby for the supply of pulse oximeters since this respiratory disease leads to the deterioration of the lungs and causes a decrease in the blood oxygen levels. Therefore, detection of the oxygen levels can indicate the severity of the disease. (Gotter, 2017)

The most widely used pulse oximeter is the finger-tip oximeter which is lightweight and compact. Pulse oximeters are predominantly used in hospitals, with a 36.5% market share. However, pulse oximeters used for homecare settings, have risen in number and they had the fastest-growing market in 2021 especially due to the prevailing pandemic. (Health, C. for D. and R., 2021). The accuracy of the pulse oximetry readings is a highly important parameter when using the device. The accuracy of the readings obtained by the pulse oximeters can be reduced due to different reasons. Some of them include anemia, hyperpigmentation, low perfusion, electromagnetic interference, reduced body temperature, low blood pressure, and the presence of nail polish on fingernails. (Feiner, Severinghaus and Bickler, 2007)

With the advent of oxygen saturation detectors in the 1980s, bedside pulse oximeters that converted the pulse patterns and the infrared light and red-light absorption values into SpO_2 values were developed. These devices had great inaccuracies unless the sensors were perfectly calibrated. These limitations were overcome with the advancements of modern technology. However, exclusion of motion artifacts is still not successfully achieved (Welch, 2005). With advancements in innovative technology, the sensitivity of the device was increased, and wearable sensors were developed so that these machines became portable. The power consumption was lowered, and the range of applications was expanded. Latest pulse oximeters are able to monitor sportsmen, and sleep apnea and even aid the rehabilitation of patients. (Milner and Mathews, 2012) Different improvements have been made to the existing pulse oximeters to enhance accuracy, reduce motion artifacts, pair them with mobile phones, and aid sports and sleep monitoring. Moreover, wireless data transmission technologies are incorporated into the new and emerging pulse oximeters, which enable the transmission of obtained data remotely in real-time. (Hornberger et al., 2000)

The existing pulse oximeters can accurately measure the SPO_2 levels and the heart rate. However, most oximeters operate with two 1.5V AAA batteries which have to be periodically replaced. This is an added cost to the user and it is inconvenient too. Apart from this, the existing pulse oximeters obtain readings from a single patient. Multiple patient monitoring would not be possible using the existing pulse oximeters. In a hospital setting, where data from numerous patients would have to be constantly monitored, it is inconvenient to check the oxygen saturation levels and blood pressure values of all patients frequently. If these variables are not frequently observed, it would be difficult to detect the abnormalities using the existing pulse oximeters. Also, manual recording of vital patient parameters increases the contact with a patient. This can increase the spread of infections in a hospital setting, from the patient to the health workers including nurses and doctors. (Welch, 2005)

It is also a commonly known fact that these pulse oximeters are slow in measuring and displaying their readings. Most common pulse oximeters take around 15 seconds to provide reliable SpO2 and Heart rate readings. This time delay is large enough to be noticeable and will be unsuitable when continuous monitoring of vital parameters is performed (FierceHealthcare, n.d.), (Greenhalgh et al., 2021).

The prevailing pandemic has brought about social distancing practices and quarantine measures. In Sri Lanka, around 10 Covid patients are assigned to one doctor to be monitored. However, it will be a strenuous task to observe multiple patients from different locations around the country throughout the day. The blood oxygen levels of Covid patients are subjected to constant fluctuations and if it drops to dangerously low levels, the life of the patient will be at stake. Thus, it is important to detect low blood oxygen levels in quarantined patients with a minimal time delay. (Watson, 2019) For patients who are crippled and are unable to move and especially for old patients, leaving their residence for regular hospital checkups would be inconvenient. The oxygen levels of old and diseased patients are also subjected to constant variations. Thus, it is vital that the oxygen levels and heart rates of these groups be monitored, and abnormalities should be detected immediately for further medications. However, existing telemetry systems fail to achieve this. (Hannhart et al., 1991).

3. METHODOLOGY

This project aimed to develop a wireless and rechargeable pulse oximeter that can be used for remote monitoring of multiple patients simultaneously in real-time. This system was designed to measure the blood oxygen levels of all individuals. This would be highly useful for monitoring multiple patients in hospital wards and Intensive Care Units (ICU), patients who are quarantined at home, elderly patients, and individuals who are crippled, or bedridden. This system is comprised of 3 main parts: (Figure 2)

1) The patients' end: The wearable pulse oximeter is clipped to the patients' fingertips for the patients to view their oxygen saturation levels and to collect data from patients. A wireless data transmission unit is incorporated into the patients' end to send data.

2)The database: It enables temporarily storing and comparing the obtained data with the threshold SpO2 and heart rate values. Patients' SpO2 values and their heart rate readings will be uploaded to the database remotely in real-time. This was built using Firebase.

3) The doctor's end: A mobile application to view the readings of the patients simultaneously. This was designed using Android Studio.

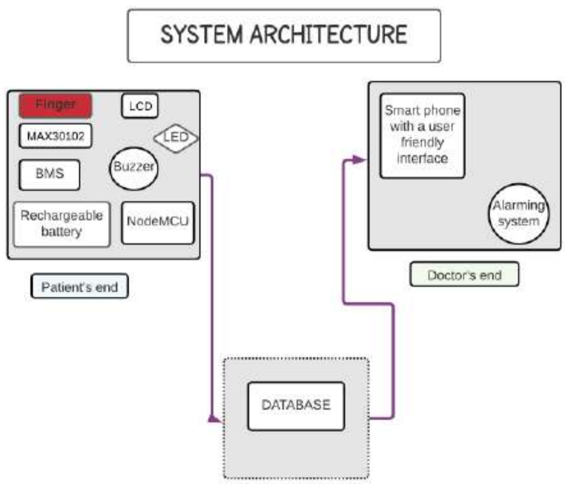

Figure 2. System Architecture Source: Author

This wearable IoT device is integrated with a Node MCU for data transmission through Wi-Fi. This allows data transmission over a large distance, irrespective of the geographical location. Data from multiple patients (in a hospital ward or home-based patients) can be collected and transmitted through a Node MCU to the central database. A Mosquito MQTT was used for high-speed data collection to minimize time delay. The data is transmitted to the central database that collects data at a slower speed. The use of MQTT is to prevent the loss of patient data (Eclipse Mosquitto, 2018).

This will temporarily store the real-time data. A threshold is set so that if the SpO_2 value falls below 95%, a notification will be sent through the mobile application at the doctor's end. This mobile application can be used by doctors or the clinical staff to monitor patients. If the SpO_2 level drops below 95%, an alarm will notify the doctor along with the patient's details. This will eliminate the need for continuous monitoring and periodic check-ups of the patients since the patient will only have to be observed when the alarm indicates abnormal oxygen levels. This will allow the doctor to take corrective measures at the right time. Thus, this will be an efficient system and will minimize time delay.

This pulse oximeter has a competitive advantage over those that currently exist in the market since most are not rechargeable. They will require the replacement of batteries after some time. Replacing the conventional batteries with rechargeable batteries will be a cost-effective solution since new batteries do not need to be frequently purchased. By including a Battery Management System (BMS), rechargeable batteries, and a charging port, the system can be integrated with a recharging mechanism.

This will be integrated with an LCD to display the real-time SpO2 and pulse rate readings to the patient. The proposed pulse oximeter will be provided as a kit with a central monitoring system, and the number of pulse oximeters per kit can be adjusted.

A. Components

The hardware components used for the pulse oximeter are:

1) Data acquisition module: MAX30102 pulse oximetry sensor- the biosensor that measures heart rate and the SpO_2 levels simultaneously. This contains a red light and an IR module, photodetectors, optical components, and a noise-cancelling electronic circuit. This also represses ambient light to increase the accuracy of the reading.

2) NodeMCU: An open-source firmware for ESP8266 Wi-Fi module. This is the IoT platform that enables the pulse oximeter to be connected to Wi-Fi for wireless data transmission for remote patient monitoring.

3) BMS Board along with the Tp4056 charging module: This allows the rechargeable battery to be safely connected to the circuit by controlling the operating voltage so that it will only operate within safe limits.

4) OLED 0.91" 128X32 12C Display: This will provide real-time readings of SpO2 and heart rate (in BPM) to the patient. This enables the pulse oximeter to be used as a standalone device for home users.

5) Rechargeable battery: A 18650 Lithium-ion rechargeable battery is used. This will allow the pulse oximeter to be recharged and reused, without replacing the battery.

6) Charging cable: To recharge the pulse oximeter by connecting it to a power supply.

7) Buzzer: Makes a beeping noise when the oxygen saturation falls below the threshold. This can be used as an alarm for the patient.

8) Light Emitting Diode: Used to notify the patient of low oxygen levels.

The developed system was initially simulated in a virtual environment, using the proteus software. Replacements were used for the libraries of the sensor and the NodeMCU since they were not available in the platform used. (Figure 3)

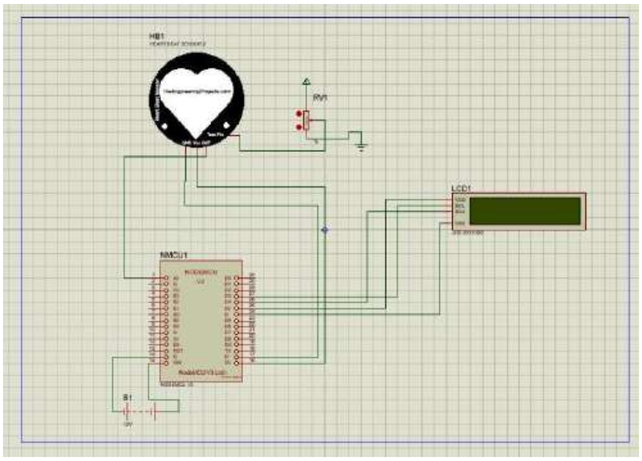

Figure 3. Schematic Diagram Source: Author

The circuit was successfully implemented on a breadboard where the connections were established. (Figure 4).

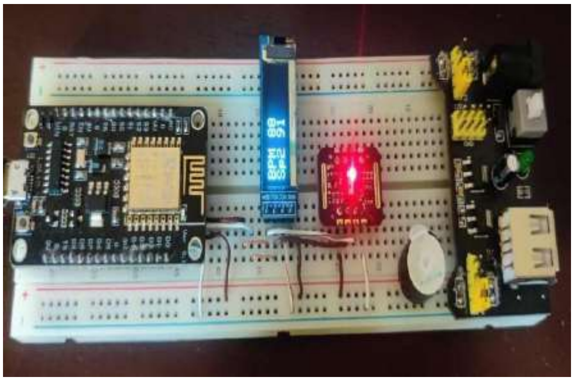

Figure 4. Connections of the pulse oximeter on breadboard Source: Author

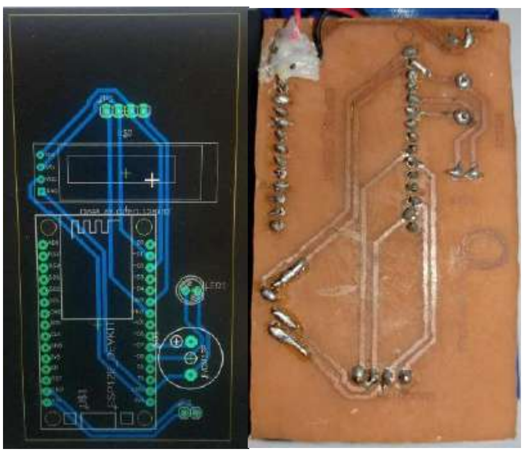

Figure 5. PCB design and development Source: Author

A PCB was developed for the wireless pulse oximeter. This was designed using the Autodesk EAGLE software. The PCB was manually printed on a copper board as shown in Figure 5. Following the PCB design, the final connections were established. (Figure 5)

The components of the charging circuit were the Battery Management system, a Tp4056 charging module, a rechargeable battery, and a charging cable. The charging module contains a micro USB interface, for the charging cable to be connected when needed. This also acts as a safe charging interface. The BMS board was included to make sure the rechargeable battery ran within the designated safe operated voltage. The red light on the charging module serves as an indicator of the battery level. The device can be used for roughly 2 days after fully charging it.

The code for displaying the heart rate and SpO2 values were implemented using Arduino IDE. This is an open-source platform that is based on C++. Libraries such as SpO2, Heart rate sensors, LCD, and Node MCU were used. Using a loop, stored data values will be removed from the system. To detect if the finger has been positioned accurately on the sensor, an intensity threshold is set up. The intensity increases as the finger approaches the sensor. If this value is less than 7000, this indicates that the finger is distal so the outputs will be displayed as zero. Once the finger is detected, the algorithm will calculate the heart rate and display it. When the device is switched on, the display will be initialized and the connections with the database will be established.

The mobile application was designed and developed using Android Studio. The front-end and the backend of the application were implemented using the programming language Java. A system-generated ID will be used to identify the heart rate and oxygen saturation readings from each patient. This will allow the backend to identify the value and update itself.

The database of the system was developed using Firebase. The reference ID represents the unique patient code that is used for the identification of the patient. This is generated by the system. The heart rate and SpO2 values that are displayed will be changed when the database is updated. The values that are updated in the database will be derived by the listener function and will be stored in the heart rate and SpO2 variables. This will be fed into the UI of the mobile application.

The housing of the system was designed using the SolidWorks software. This was manufactured by 3D printing using plastic as the raw material for the final product. (Figure 6).

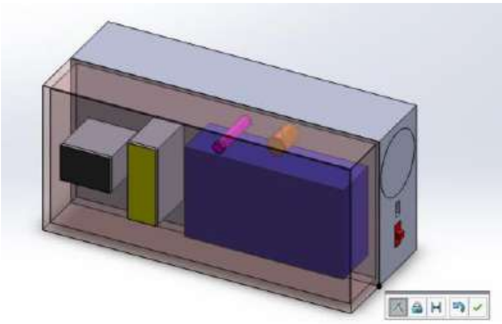

Figure 6. System Design in 3 Dimensions using SOLIDWORKS. Source: Author

4. RESULTS

The device captures data from the sensor and allows the user to view it. This will be simultaneously uploaded to the cloud. The cloud will send the data to the database using the NodeMCU module. This will require the WIFI username and password through which the NodeMCU connects to the internet. Using the host and the authentication key of the firebase, the device will identify the database. The database of the system was designed using Firebase to temporarily store data from multiple patients. (Figure 7). This was linked to the mobile application to display the readings.

Figure 7. The database that was developed using Firebase Source: Author

The mobile application was designed in a simple, yet user-friendly manner. The initial interface displayed data for multiple patients. (Figure 8) The system allows new patients to be added via the application, where a unique patient ID, Patient Name, Age, Gender, and Device number can be defined.

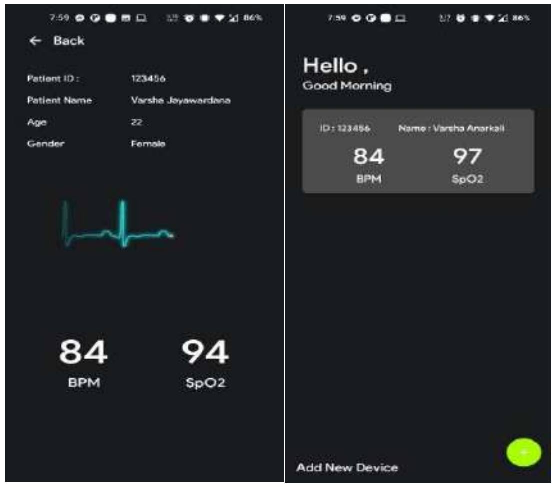

Figure 8. UI of the mobile application Source: Author

The doctor can view the heart rate as a BPM value and oxygen saturation (SpO_2) as a percentage for a single patient by selecting the desired patient. The alarming system was implanted by setting a threshold. If the SpO2 value drops below 90%, the mobile application notifies the doctor through a sound. The product was given the name 'Oxycare' for commercial purposes. (Figure 9)

Figure 9. Final product with the complete housing Source: Author

5. DISCUSSION

The main aim of this research was to develop a wearable, WI-FI-enabled pulse oximeter that could be used for remote patient monitoring. Long-distance data transmission is a major advantage of the designed device. This was done by integrating a NodeMCU, which was able to transmit the heart rate and oxygen saturation data to a database and then to a mobile application on the doctor's end. Previous research articles discussed pulse oximeters which had the ability to transmit data over a long distance. All these devices had the ability to transmit data within a range of 50± 5m. The device designed through this study will allow transmission of data across 350 ± 10 m distance when using a PCB antenna (Benchoff, 2014). The database of the novel pulse oximeter was developed on an online platform called Firebase. While the existing oximeters are able to transmit data within a household, "Oxycare" has the ability to transmit data across cities. This allows patients from remote locations to be monitored by doctors from cities, despite the geographical barriers. Optimizing the network settings would allow data transmission across countries, which would be implemented in the future.

The second aim of this research was to develop a multiple-patient monitoring system. Referring to the existing literature, all of the devices focused on monitoring a single patient at one time. However, "Oxycare" allows multiple patient monitoring, and up to 60 patients could be added to the database as the mobile application was developed to enroll a maximum number of 60 patients. This would mean that multiple patients from different locations could be monitored at one central clinical point, and the doctor can observe the patient data from different locations at any time of the day. This system did not allow the 63rd patient to be added, due to the limitations in data processing capacities of the software used. Further optimization of this software would allow more patients to be monitored simultaneously, which would be a part of the future works of this research. The time delay of this system was only 0.2±0.1s, and this may be due to the network lag. Another possible reason for this could be the slow uptake of data by the database; the Firebase cannot store data at the speed that data is transmitted from the system. This could lead to minor losses in data. However, by incorporating a Mosquito MQTT, it would collect and store data before it reaches the Firebase, so data can be transmitted at a slower pace to it. This would avoid the potential loss of data.

The final goal of this research was to develop a rechargeable pulse oximeter. The rechargeable battery had a battery life of 2 hours as the battery that was used for the pulse oximeter was low in capacity. This would mean that the cost of battery replacement would be cut down. If a battery with a battery life of 3 to 5 days was included, the device would be bulky and uncomfortable for the patients. Thus, the battery that is currently being used is the one that can provide the maximum battery life with minimum inconvenience. To make the device more compact and lighter-weighted and to include a battery percentage indicator will be advancements in the "Oxycare" pulse oximeter in the future.

While factors like remote and continuous monitoring, long-distance data transmission, and rechargeability were given prominence, the accuracy of the data collected appeared to be compromised. By comparing the developed device with a device in the current market, the accuracy was validated. The readings obtained using the two devices appeared to be similar for most of the instances. However, fluctuations in the data values were observed, which gave unstable readings on rare occasions. This was due to the ambient light interfering with the Red light/IR sensor. In the future, the algorithm will be developed to cut down the effect of ambient light and the device will be optimized by placing the sensor internally.

6. CONCLUSION

Health care sectors had to take a huge blow due to the Covid-19 pandemic, which led to a demand for new technological medical devices. The development of a wireless pulse oximeter for remote patient monitoring can facilitate monitoring of blood oxygen saturation (SpO_2) and heart rate in Covid patients from a safe distance in this time of health disaster.

Not only Covid patients but bed-ridden and crippled patients at homes and healthcare facilities can also be easily monitored through the newly developed Oxycare pulse oximeter. The advancement which can monitor the SpO2 and heart rate values of several patients simultaneously over a wireless mobile platform proved to be highly useful and convenient. The use of Wi-Fi technology for long-range data transmission has opened a new door in telemedicine for pulse oximetry, enabling the safest and most efficient non-invasive monitoring of SpO_2 and heart rate. The rechargeable battery of the novel pulse oximeter added a competitive advantage over existing pulse oximeters which will be convenient for long-term use. In the future, this device will be developed to enhance the number of patients that can be added to the system. Furthermore, this system would be optimized to minimize the time delay in data transmission. The development of the mobile application to access the real-time data values and the warning notifications, and the compact and portable nature of the device have made the “Oxycare” pulse oximeter a better alternative to the conventional pulse oximeters.

7. ACKNOWLEDGEMENTS

The authors would like to thank the panel of lecturers of Biomedical Engineering in the Department of Electrical, Electronic and Telecommunication Engineering of the Faculty of Engineering of General Sir John Kotelawala Defence University, for the valuable guidance and feedback provided. The authors would also like to extend their sincere gratitude to Mr. PARD Dharmarathne and Mr. IAMP Ileperuma for the support extended to complete the project.

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