


Development of Low-Cost and Portable Pulse Oximeter Device with Improved Accuracy and Accessibility

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Purpose: In a clinical setting, blood oxygen saturation is one of the most important vital sign indicators. A pulse oximeter is a device that measures the blood oxygen saturation and pulse rate of patients with various disorders. However, due to ethical concerns, commercially available pulse oximeters are limited in terms of calibration on critically sick patients, resulting in a significant error rate for measurement in the critical oxygen saturation range. The device's accessibility in developing countries' healthcare settings is also limited due to portability, cost implications, and a lack of recognized need. The purpose of this study was to develop a reliable, low-cost, and portable pulse oximeter device with improved accuracy in the critical oxygen saturation range.

Methods: The proposed device measures oxygen saturation and heart rate using the reflectance approach. The rechargeable battery and power supply from the smartphone were taken into account, and the calibration in critical oxygen saturation values was performed using Prosim 8 vital sign simulator, and by comparing with a standard pulse oximeter device over fifteen iterations.

Results: The device's prototype was successfully developed and tested. Oxygen saturation and heart rate readings were both accurate to 97.74% and 97.37%, respectively, compared with the simulator, and an accuracy of 98.54% for the measurement of blood oxygen saturation was obtained compared with the standard device.

Conclusion: The accuracy of oxygen measurement attained in this study is significant for measuring oxygen saturation for patients in critical care, anesthesia, pre-operative and post-operative surgery, and COVID-19 patients. The advancements made in this research have the potential to increase the accessibility of pulse oximeter in resource limited areas.

Keywords: blood oxygen saturation, pulse oximeter, accuracy, low-cost, portable, critical oxygen saturation range

Introduction

Health risks are on the rise these days, putting millions of people's lives in danger. Cardiovascular disorders are on the rise, with more than 8 million people dying each year as a result of hypertension. Acute respiratory infections, on the other hand, account for 142 per 1000 live births.¹ In these conditions, oxygen therapy is critical for patient care under proper monitoring of blood oxygen saturation.^{2,3} Patients in emergency situations, those under anesthesia, those in critical care, and those undergoing pre-operative and post-operative surgery all require oxygen saturation monitoring in order to avoid hypoxia.⁴⁻⁶

Pulse oximetry (PO) is a non-invasive technique for measuring peripheral oxygen saturation (SpO₂) that is based on the differential absorption of red and infrared light by oxygenated hemoglobin in a small tissue segment.⁷ In high-income countries' healthcare settings, PO is commonly used to monitor cardiovascular and respiratory system functionality and it has been designated the "fifth vital sign" in pediatrics.^{8,9}

While pulse oximetry is also a reliable and non-invasive method for identifying children with hypoxemia and monitoring patients during emergency, anesthesia, critical care, pre-operative, and post-operative procedures by measuring non-invasive peripheral oxygen saturation (SpO₂),^{5,6} it is rarely available outside of higher-level facilities in resource-constrained countries due to limited portability, cost implications, and a lack of perceived need among

policymakers.⁷ Pulse oximeters were designed to increase accuracy and performance while focusing on improving accessibility in low-resource settings, resulting in higher referral rates and, ultimately, better health outcomes. This is in part due to a greater emphasis on the necessity of improved access to pulse oximeters and oxygen therapy in Sub-Saharan Africa and Southeast Asia.^{10–12} According to the feasibility studies conducted recently, health workers in these settings can use these devices effectively,^{13,14} but usage still remains low.^{15,16} The current COVID-19 pandemic has posed significant challenges to these settings in terms of access to pulse oximeters because to its influence on lung functionality and the device's requirement to access blood oxygen saturation in order to administer oxygen therapy.¹⁷

Several advanced pulse oximeters have been recently developed. For instance, Huang et al¹⁸ developed a ring-type pulse oximeter with a multi-detector and obtained an SPO₂ correlation of 98.26% compared with a commercially available pulse oximeter without considering the measurement of oxygen saturation below 80%, the measurement of heart rate, and device accessibility in resource limited areas. In the same manner, Lin et al¹⁹ developed a wearable and wireless finger base-type pulse oximeter, focusing only on the measurement of oxygen saturation. Smartphone app pulse oximeters have also been developed with a wide range of accuracy, but the accessibility and reliability of these developments are limited.²⁰ In addition to these, in developing countries, the high initial cost, pulse oximeter probe fragility, and inadequate electricity supply are the main barriers to the access of pulse oximeter.²¹

In this study, a new prototype of a low-cost portable pulse oximeter device with better accuracy in the critical oxygen saturation region was developed, built, and tested. The device monitors blood oxygen saturation and heart rate via the right index finger and was built with a wide range of calibration compared to previous devices. It has multiple power supply options with increased durability to facilitate device accessibility in resource poor settings.

Materials and Methods

The block diagram of the proposed low-cost portable pulse oximeter device is shown in Figure 1. It is made up of two input sensors, a microcontroller, batteries, and a single output device. MAX30100 is used to monitor the heart rate and the oxygen saturation (SpO₂) in the blood. The MAX30100, shown in Figure 2, is an integrated pulse oximetry and heart rate sensor. It employs two light-emitting diodes (LEDs), a photodetector, improved optics, and low-noise signal processing to detect pulse oximetry and heart rate signals.²² Two LEDs in this sensor emit two wavelengths of light (red and infrared). The reflected light is then collected and processed to calculate two biomarkers, the pulse rate and the SpO₂. This sensor is connected to an Arduino nano microcontroller (Figure 3), which serves as the system's brain, through the I2C protocol. I2C is a popular serial communication technology that is used in embedded devices. Finally, a touch sensor is utilized to determine whether the patient has correctly placed his or her finger on the pulse sensor.

The measurement results will be shown on an OLED 124×64 display. It has a 1.8-inch screen. The pulse oximeter is powered by 3.7 V lithium-ion batteries with a capacity of 2000 mAh and also from a smartphone using USB OTG (on-the-Go). The energy in the batteries is sufficient to run the device continuously for approximately 13 hours, and they can be charged through the charger port. The power supply from the smartphone is used when the battery runs out and charging is not feasible. Figure 4 shows the wiring diagram for the low-cost portable pulse oximeter.

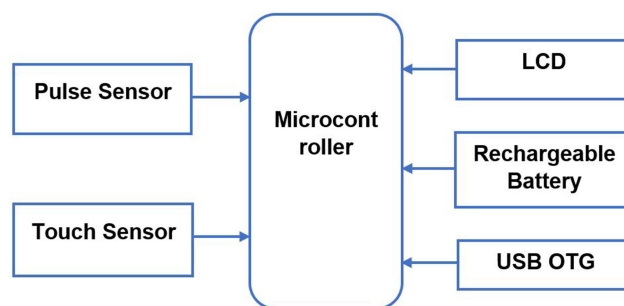


Figure 1 Block diagram of the proposed pulse oximeter device.

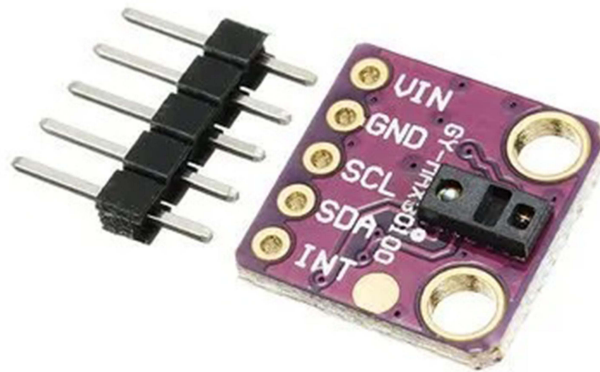


Figure 2 GY-MAX30100 pulse oximeter and heart rate sensor. Image reproduced with permission from Maxim Integrated.²²



Figure 3 Arduino nano microcontroller. Image reproduced with permission from Arduino.⁴⁵

The device's 3D design was developed using Automated Computer Aided Design (AutoCAD) software, as illustrated in [Figure 5](#), and the actual device body was produced using a 3D printer. The program code was written in C using an open-source Arduino sketch.

Results

The block diagram, electronic components, the wiring diagram, and the 3D design of the proposed low-cost portable pulse oximeter (ie, [Figures 1–5](#)) were successfully assembled, and the prototype is constructed as shown in [Figure 6](#). The online resource 1 shows a demonstration of the low-cost portable pulse oximeter's operation. The prototype was tested using a ProSim 8 vital signs simulator from Fluke Biomedical and by comparing it with a standard pulse oximeter device to check its accuracy by taking fifteen iterations as shown in [Table 1](#). Pulse rate, and SpO₂ at different levels were given using the simulator through the artificial finger placed on the prototype, and the measurement by the developed device was compared against the given parameters. The percentage errors for the measurement of SPO₂ and HR were computed using Equation 1–3.²³

$$\% \text{ Error SPO}_2 = \left(\frac{\Delta \text{SPO}_2 (\%)}{\text{Simulator SPO}_2 (\%)} \right) \times 100\% \quad (1)$$

$$\% \text{ Error HR} = \left(\frac{\Delta \text{HR}}{\text{Simulator HR}} \right) \times 100\% \quad (2)$$

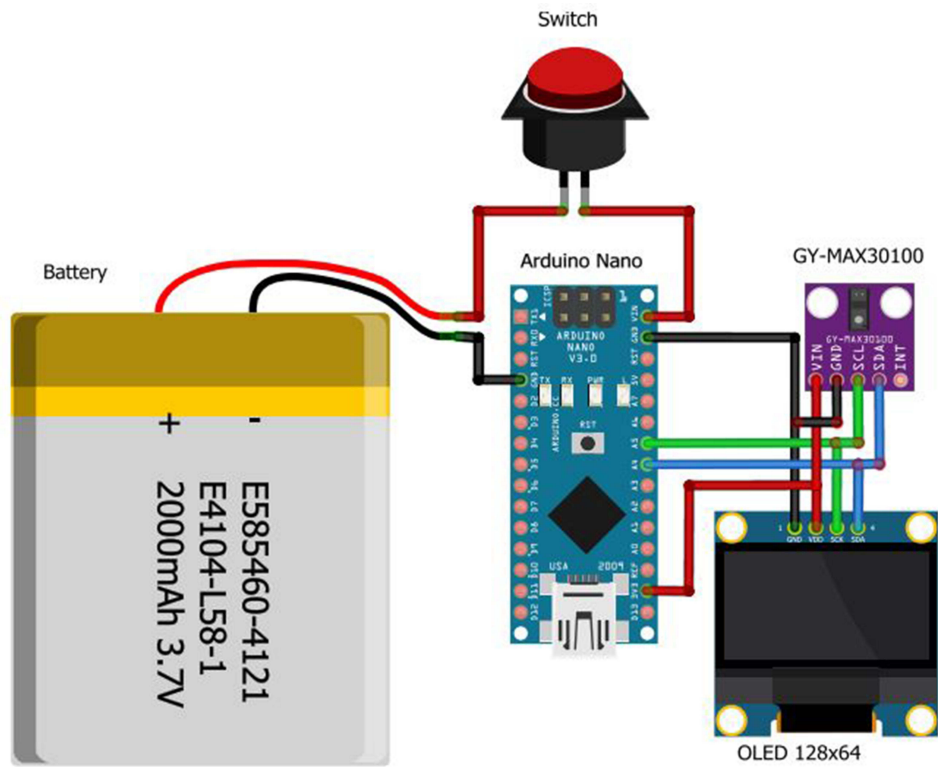


Figure 4 The wiring diagram of the proposed pulse oximeter device.

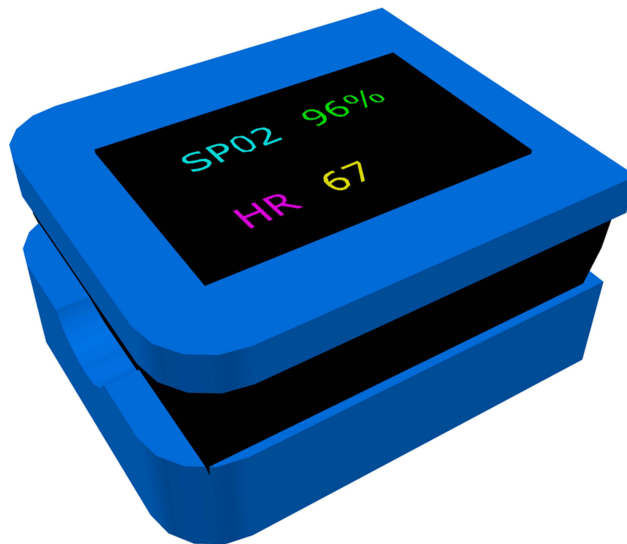


Figure 5 3D design of the proposed pulse oximeter device designed on AutoCAD software.

$$\% \text{ Error } SPO2 = \left(\frac{\Delta SPO2 (\%)}{\text{Standard Pulse oximeter } SPO2 (\%)} \right) \times 100\% \tag{3}$$

Based on the percentage error calculation, the average accuracy for measuring SPO2 and heart rate was 97.74% and 97.37%, respectively, on the simulator, while an average accuracy of 98.54% was obtained for SPO2 measurement when compared with the standard pulse oximeter device. Figure 7 depicts the calibration curve for SPO2 measurement using the simulator, whereas Figure 8 depicts the calibration curve for heart rate measurement. In addition to the accuracy test,

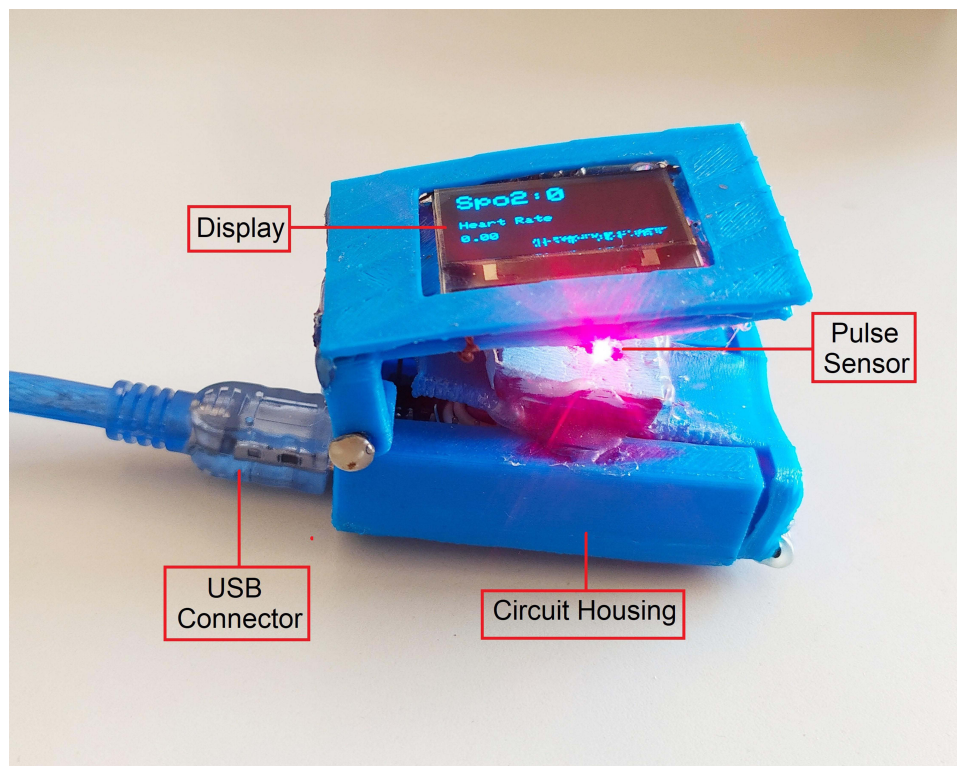


Figure 6 Final prototype of the proposed pulse oximeter device.

the device's cost effectiveness was assessed by estimating the cost of materials used to construct the prototype, which came to \$13.24.

Discussion

The measurement of blood oxygen saturation is becoming a standard screening tool in clinical settings in order to determine the respiratory system's performance.^{24,25} The pulse oximeter is essential in emergency medicine, critical care, anesthetic delivery, and pre-operative and post-operative surgery to appropriately monitor the status of patients for remedial action to reduce mortality and morbidity.^{4,5,26,27} The use of pulse oximeters is especially critical at all levels of health care facilities for monitoring COVID-19 patients since it produces silent hypoxia without shortness of breath²⁸ which results in lung injury, additional problems, and death.^{29,30} Detection of this silent hypoxia in COVID-19 patients at an early stage is therefore of significant importance to prevent morbidity and mortality in these patients.^{31,32}

The development of pulse oximeters for enhanced accessibility and accuracy should take into account their practical constraints such as calibration of measurement accuracy in the critical oxygen saturation range, portability, power requirement, and cost.^{33–36} Measurement inaccuracy is expected with commercially available pulse oximeters for critically ill patients due to ethical issues about calibrating the device on ill patients, resulting in substantial deviations in measurement,³⁷ despite the significance of accurately monitoring the blood oxygen saturation of critically ill patients receiving oxygen therapy.^{26,38–40}

In this study, a low-cost portable pulse oximeter with improved accuracy and accessibility was developed. In comparison to recently developed pulse oximeters such as the ring type wearable pulse oximeter, which has an SPO2 measurement accuracy of 98.26%¹⁸ and the deluxe hand-held pulse oximeter, which has an SPO2 average measurement accuracy of 97.67%,⁴¹ our device has a better SPO2 measurement accuracy of 98.54%. Taking the power issue into account, the deluxe handheld pulse oximeter uses non-rechargeable AA batteries,⁴¹ which are not affordable in resource poor settings. But in our device, we have used a rechargeable battery and an option to power the device from a smartphone.

Apart from the inclusion of multiple power supply options, the developed prototype has the advantage of low power consumption and good results in low peripheral perfusion situations, which is comparable to existing reflective type pulse

Table 1 Evaluation of Our Device with Vital Sign Simulator and Standard Pulse Oximeter Device

Iteration Number	Test on Prosim 8 Vital Sign Simulator						Comparison with Standard Device		
	SPO2 Test			Heart Rate Test			SPO2 Test		
	Values from the Simulator	Measurement by Our Prototype	% Error	Values from the Simulator	Measurement by Our Prototype	% Error	Measurement by Standard Pulse Oximeter	Measurement by Our Prototype	% Error
1	70	67	4.29	120	123	2.50	68	67	1.47
2	72	69	4.17	115	117	1.74	70	69	1.43
3	74	71	4.07	110	113	2.73	73	71	2.74
4	76	74	2.63	105	107	1.90	75	74	1.33
5	78	76	2.56	100	103	3.00	77	76	1.30
6	80	78	2.5	95	98	3.16	79	78	1.27
7	81	79	2.47	90	92	2.22	80	79	1.25
8	83	81	2.41	85	86	1.18	83	81	2.41
9	85	83	2.35	80	80	0.00	84	83	1.19
10	88	86	2.27	75	76	1.33	88	86	2.27
11	90	89	1.11	70	71	1.43	90	89	1.11
12	93	92	1.08	65	66	1.54	93	92	1.08
13	95	96	1.05	60	62	3.33	96	96	0.00
14	97	97	0	55	52	5.45	98	97	1.02
15	99	98	1.01	50	46	8.00	100	98	2.00
Average % Error			2.26			2.63			1.46

oximeters.^{42,43} The device is inexpensive (\$13.24) when compared to commercially available finger pulse oximeters, which cost \$20 - \$50 without import and taxation costs,²¹ and handheld pulse oximeters, which can cost up to \$266.⁴¹ The obtained average accuracy of oxygen saturation measurement and heart rate measurements are in the recommended accuracy range for finger pulse oximeters, such as ±3% for oxygen saturation and ±3 bpm for heart rate,⁴⁴ and this could be further improved by proper attenuation of the ambient light.

Conclusion

The accuracy of oxygen measurement achieved in this study is significant for measuring oxygen saturation of patients in critical care, under anesthesia, pre-operative and post-operative surgery, and patients with COVID-19 due to the requirement for measurement accuracy for these patients. The device’s accuracy, durability, portability, and low cost

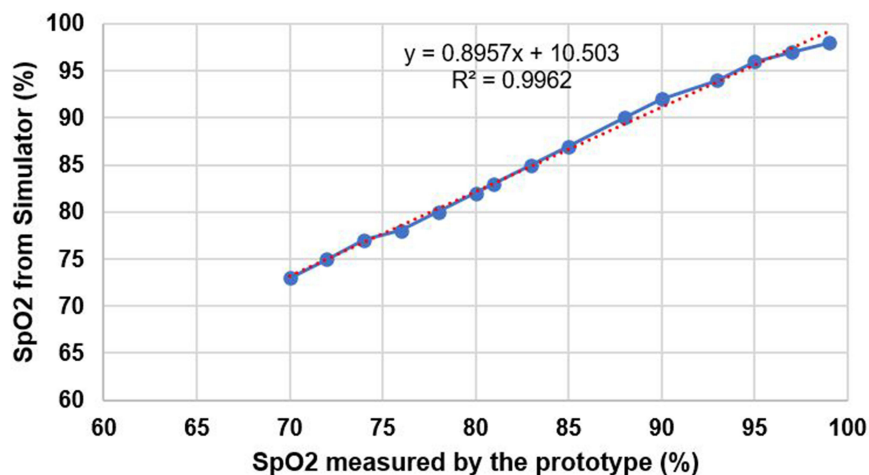


Figure 7 Calibration curve of SPO2 measurement.

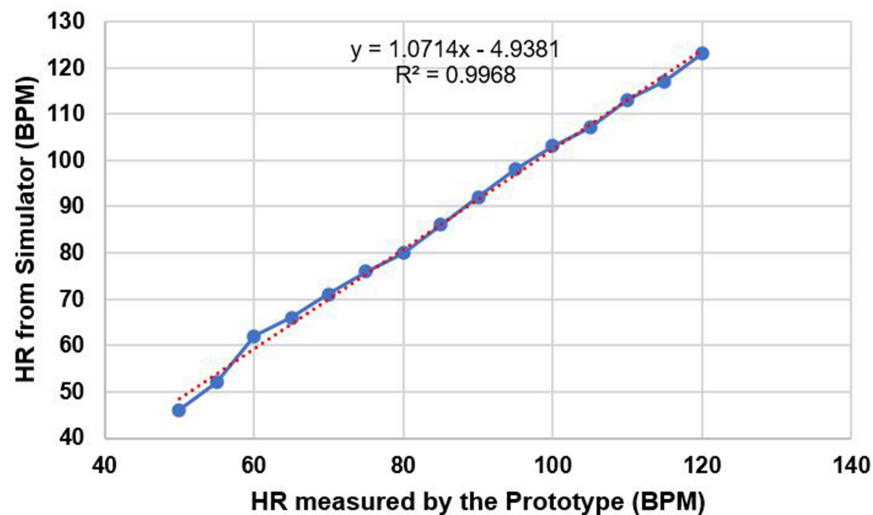


Figure 8 Calibration curve of heart rate measurement.

will make it more accessible to patients, thereby improving their lives by lowering mortality and morbidity. The developed pilot prototype is intended to be a trustworthy tool for patient monitoring in a clinical setting with enhanced finger attachment and ambient light prevention during measurement.

Abbreviations

AutoCAD, automated computer aided design; BPM, breaths per minute; 3D, three dimensional; HR, heart rate; LED, light emitting diodes; LCD, liquid crystal display; OLED, organic light emitting diode; OTG, On-The-Go; PO, pulse oximeter; SPO₂, spot oxygen saturation; USB, universal serial bus.

Ethical Approval

This study does not involve human subjects. No ethical approval is required.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors have no relevant financial or non-financial interests to disclose in this work.

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