JPPIPA 9(11) (2023)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Development of Optical Sensor Technology for Non-Invasive Hemoglobin Measurement

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Received: September 27, 2023
Revised: October 10, 2023
Accepted: November 25, 2023
Published: November 30, 2023

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DOI: 10.29303/jppipa.v9i11.5610

Abstract: This research focuses on the development of hardware and software required to implement optical sensor technology. The optical sensor used is the MAX30102, equipped with infrared (IR) and red-light sources along with a receiver. The signals generated by the sensor are processed by NodeMCU and displayed on the OLED. The calibration results indicate the relationship between hemoglobin obtained using the invasive method and the output of the MAX30102 sensor, which is in the form of wavelength. It has the equation $y = 0.0164x - 13.478$ with an R^2 value of 0.9114. This equation is utilized to program the NodeMCU through the Arduino IDE. Validation and clinical trials have been conducted to evaluate its accuracy and applicability in clinical contexts. The results show that the non-invasive device has an average standard deviation of 0.32, indicating consistent measurement values. The non-invasive device demonstrates an average accuracy of 99.24%, signifying high precision and similarity to invasive methods. This suggests that the device holds potential as an innovative solution for Hemoglobin measurement.

Keywords: Calibration; Hemoglobin; Non-Invasive; Optical Sensor.

Introduction

Hemoglobin measurement is a crucial clinical parameter in the medical field (Taneri et al., 2020). Hemoglobin is a protein in red blood cells that plays a major role in transport. Oxygen from the lungs is transported throughout the body and carries back carbon dioxide from the rest of the body to the lungs for excretion (Akinbosede et al., 2022). Disturbances in hemoglobin levels can indicate various health conditions, including anemia, polycythemia, and other hematological disorders (Adegoke et al., 2022). Conventional methods for measuring hemoglobin levels typically require invasive blood sampling (Hsu et al., 2016). This can cause discomfort to the patient and has a risk of infection (Pinto et al., 2020). Therefore, the development of non-invasive methods for hemoglobin measurement has become an increasingly important research focus in the quest to enhance health monitoring (Ryan et al., 2016; Garrett et al., 2021; Wittenmeier et al., 2021). This research not only can provide a better alternative for patients but also has the potential to improve efficiency in the measurement process, reduce the time needed to obtain vital information, and optimize the overall quality of medical care.

One potential approach is the use of sensor technology (Hasan et al., 2021). A sensor is a device used to detect or measure changes in the physical or chemical environment and convert them into signals that can be interpreted or used for specific purposes (Diharja et al., 2022; Lensoni et al., 2023). Sensors are employed in various fields, including electronics, industry, medicine, automotive, and more (Hidayat & Yulianti, 2021). Examples of sensors include temperature sensors, motion sensors, pressure sensors, and optical sensors (Hong et al., 2021). Optical sensors utilize light or electromagnetic waves to detect and measure characteristics or changes in the environment, producing output that can be used for monitoring or measuring a condition or object (Holovatyy et al., 2020).

How to Cite:
Muthmainnah, Arabani, F. Z., Tazi, I., Chamidah, N., Sasmitaninghidayah, W., & Tirono, M. (2023). Development of Optical Sensor Technology for Non-Invasive Hemoglobin Measurement. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 10252–10258. https://doi.org/10.29303/jppipa.v9i11.5610

In this context, optical sensors leverage the optical properties of blood interacting with light waves to measure blood components, including hemoglobin (Chen et al., 2022). This technology can offer significant advantages in non-invasive hemoglobin measurement, reducing the risk of infection and improving patient comfort.

The development and evaluation of invasive hemoglobin measurement tools have become increasingly critical in efforts to enhance the quality of patient care. Several studies have reported the development of non-invasive hemoglobin measurement tools. Dervieux et al (2020), utilized spectrophotometry with a wavelength range of 230-1000 nm to obtain hemoglobin spectra. The results showed a CO2Hb spectrum closely resembling the HHb spectrum (Dervieux et al., 2020). The Radical-7 Pulse CO-Oximeter was used to monitor SpHb levels at a frequency of 0.5 Hz. The data were recorded and could be modeled with kernel regression (Man et al., 2022). Photodiodes with varying wavelengths were used to measure hemoglobin levels. The device was equipped with a photodetector integrated into the voltage source. Wavelengths that exhibited strong hemoglobin absorption were 670 nm, 810 nm, and 950 nm (Pinto et al., 2020). Non-invasive hemoglobin measurement tools have also been developed through imaging of the arteries in the eye (Farook et al., 2023).

Although the concept of hemoglobin measurement based on optical sensor technology has been developed (Chambouleyron et al., 2021), it is crucial to understand that calibration and validation are critical aspects to ensure the reliability and accuracy of the device. The calibration process ensures an accurate relationship between the sensor output and the true values, while validation confirms the reliability and accuracy of the device in real-world usage conditions (Prasetyo et al., 2021). Prioritizing meticulous calibration and validation processes, optical sensor technology can become more reliable, providing consistent results and making a more significant contribution to the development of its clinical applications (Man et al., 2022). Furthermore, further exploration of the potential of optical sensor technology in various clinical applications, such as patient monitoring, early disease diagnosis, and monitoring in emergency medical situations, is a crucial step to optimize its benefits in everyday medical practice (Adegoke et al., 2022; Gonnade et al., 2017; Ryan et al., 2016).

Based on the provided information, the objective of this research is to develop optical technology for non-invasive hemoglobin measurement. Several critical aspects to be discussed include sensor design, sample collection techniques, measurement calibration, measurement validation, and integration with broader healthcare monitoring systems. This research aims to contribute to the early detection of hemoglobin changes that may indicate health issues and provide in-depth insights into the potential of optical sensor technology in enhancing non-invasive hemoglobin measurement. It is expected to play a significant role in the development of innovative optical sensor technology for non-invasive hemoglobin measurement, ultimately improving the quality of healthcare monitoring and patient diagnosis, with broad applications in safer and better medical care.

Method

Tool design

This research is categorized as research and development. The flowchart in this study is shown in Figure 1. The tools used in this study include the MAX30102 sensor, NodeMCU ESP8266, breadboard, switch, OLED display, battery, project box, and an invasive hemoglobin measurement device. The MAX30102 sensor is an optical sensor used for hemoglobin level measurement (Hudhajanto et al., 2022; Khan et al., 2021). The selection of NodeMCU ESP8266 is based on its built-in Wi-Fi connectivity, compact physical size, affordable price, extensive support from the developer community, and compatibility with Arduino IDE (Yuhefizar et al., 2019). A breadboard is an experimental circuit board used to assemble and connect electronic components in a circuit (Dhruba et al., 2021; Ramesh et al., 2021). Its function is to organize and test circuit configurations without the need for soldering, making experiments and design changes easier. The use of a switch in this project may be to control power or turn off the power supply to specific parts of the circuit, providing the ability to control or turn off specific components as needed. OLED is used as a display to show information on the measurement of hemoglobin levels (Resika et al., 2018). An OLED screen is chosen for its ability to produce clear images and low power consumption. The battery is used to provide power to the project. The use of a battery allows the project to function portably without having to be directly connected to an external power source. The circuit diagram is illustrated in Figure 2.

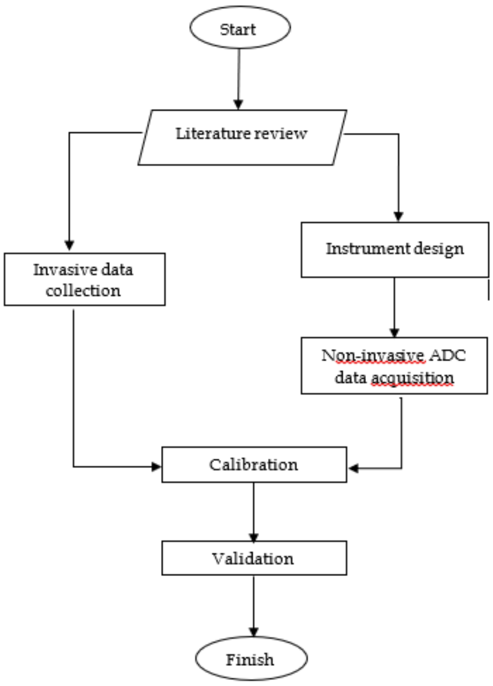

Figure 1. Research flowchart

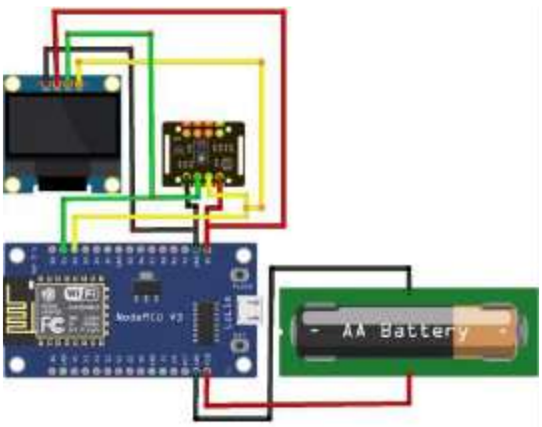

Figure 2. Design Circuit of electrical components of non-invasive tools

Data collection techniques

Data collection techniques Samples were taken from ten men with an age range of 10-25 years. The MAX30102 sensor measures the signal by placing the index finger on the sensor surface. This treatment is carried out five times to determine the precision of the data. Hemoglobin measurement is done using invasive devices to calibrate sensor data. The invasive tool used is the Family Dr. The measurement results of the two are compared to find out the equation model.

Data calibration and validation

Calibration is performed by comparing the measurement results of the MAX30102 sensor with hemoglobin levels. The results of the equation are then entered into the NodeMCU program. Data validation is done by retesting a tool that has been calibrated with an invasive tool. The data sample used was five people in the age range of 18-25 years. Data collection was repeated five times, and the average was calculated using equation 1 (Lafifa & Rosana, 2023). At the validation stage, the standard deviation value of the measurement will be found using Equation 2 and the accuracy of the tool using equation 3 (Muthmainnah et al., 2022). Where "$\bar{x}$" is the mean, "sd" is the standard deviation, "Xi" is the i-th sample, and "n" is the amount of data.

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \mathrm{Xi} \quad (1)$$

$$sd = \sqrt{\frac{\sum_{i=1}^{n}(Xi-\bar{x})^2}{n-1}} \quad (2)$$

$$\%Accuracy = 100\% - \left|\frac{invasive - non\ invasive}{invasive}\right| \times 100\% \quad (3)$$

Result and Discussion

The MAX30102 sensor features an IR light source with a wavelength of 880 nm and a red-light source with a wavelength of 660 nm. The sensor also includes a receiver to detect signals. Hemoglobin consists of oxyhemoglobin and deoxyhemoglobin (Akinbosede et al., 2022; Ryan et al., 2016). Oxyhemoglobin is hemoglobin that carries oxygen and tends to absorb more IR light due to its bright red color (Pinto et al., 2020). In contrast, deoxyhemoglobin is darker red in color and carries carbon dioxide, so it absorbs more red light (Shangguan et al., 2022). The wavelengths that pass through after being absorbed by hemoglobin are captured by the receiver and transmitted to the display as ADC signals. The absorption of light by hemoglobin is illustrated in Figure 3.

The results of the MAX30102 sensor measurements and invasive hemoglobin measurement for 10 individuals are depicted in Figure 3. The x-axis represents the hemoglobin values measured with the invasive device, while the y-axis represents the output from the MAX30102 sensor in the form of ADC values. The blue-colored graph represents the output derived from the IR light, and the orange-colored graph represents the output from the red light. The working principle of the MAX30102 sensor as a light sensor is based on photodetection, where light is converted into an electrical signal (Pratama et al., 2020). Photodetector components, such as photodiodes or phototransistors, detect light and generate an electric current proportional to the light intensity (Rahmat & Ambaransari, 2018). This signal can be converted into digital form through ADC (Murti et al., 2020). The variation in hemoglobin values in each sample will result in differences in ADC values.

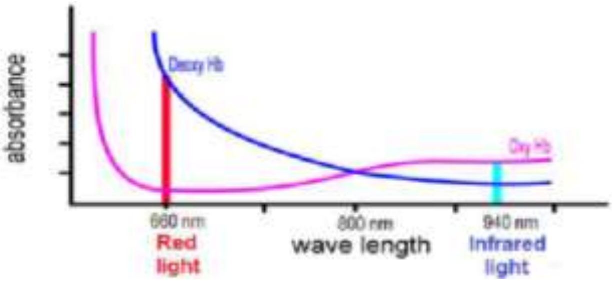

Figure 3. Absorbance of RED and IR rays to hemoglobin (Kemalasari & Rochmad, 2022)

Hemoglobin consists of oxyhemoglobin, which is more likely to be detected by IR light, and deoxyhemoglobin, which can be better detected by red light. For sensor calibration purposes, the outputs of both wavelengths are summed. The calibration results are shown in Figure 5. The relationship between the MAX30102 sensor and the invasive hemoglobin measurement is expressed by the equation $y = 0.0164x - 13.478$ with an $R^2 = 0.9114$. This equation is used to program the NodeMCU so that the output of the non-invasive device will be in the form of hemoglobin values. Based on the calibration results, it is found that the ADC values contribute to the model by 91%. While the remaining 9% is attributed to other factors, one influential factor is skin thickness and variability in skin pigmentation. These differences have been reported to have a minor impact on optical sensor measurements. Another contributing factor is environmental light, which can affect the sensor's response (Dhruba et al., 2021).

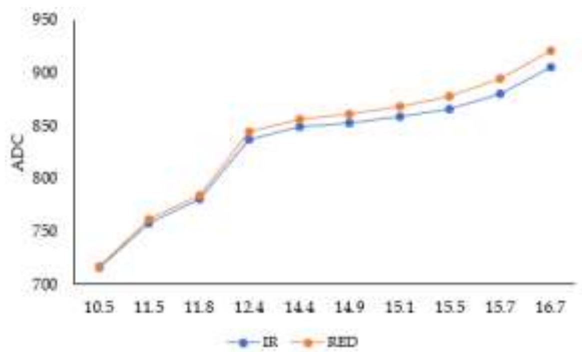

Figure 4. Measurement results of MAX30102 sensors and invasive hemoglobin analyzers

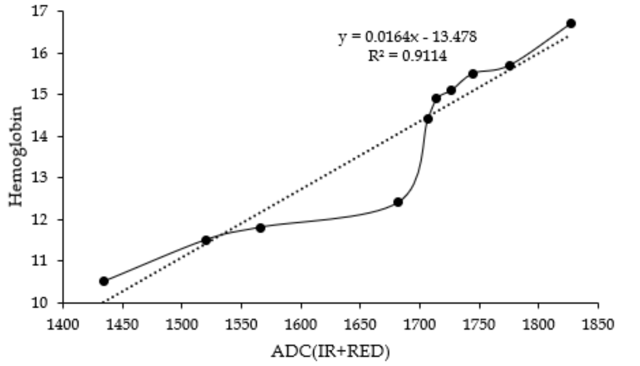

Figure 5. Sensor calibration graph

Table 1. Validation data

Invasive (g/dl)	Non-invasive (g/dl)	STD	Accuracy (%)
13.30	13.26	0.34	99.69
13.90	13.62	0.26	97.98
15.40	15.44	0.36	99.74
16.30	16.50	0.24	98.77
17.20	17.20	0.39	100.00
Average		0.32	99.24

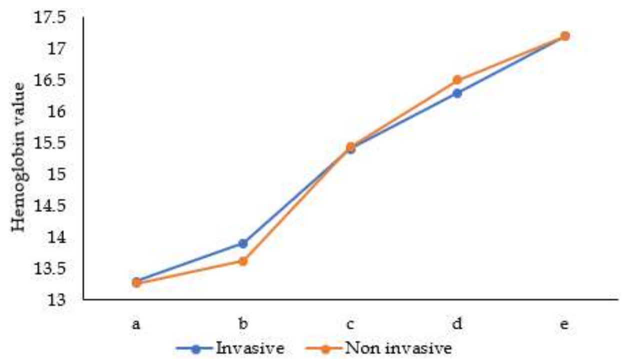

Figure 6. Comparison of invasive and non-invasive tools

Validation of the non-invasive hemoglobin measurement device was conducted by collecting data from five individuals aged 18-25 years. The collected data was then compared with the invasive hemoglobin measurement device. Table 1 presents the validation results of the sensor. The first column represents the hemoglobin values measured with the invasive device. The second column shows the results obtained from the non-invasive measurement device. The hemoglobin values in the validation table range from 13.30 to 17.20, indicating that the measurement results fall within the normal range according to health standards. This range is consistent with the normal hemoglobin range in adults, typically reflecting good health conditions (Khan et al., 2021). Monitoring and understanding hemoglobin values within this normal range provides a positive indication of the subjects' health in the study. The third column indicates the standard deviation derived from the non-invasive measurements. The fourth column represents the percentage accuracy of the non-invasive device compared to the invasive measurement. The average standard deviation value is 0.32, and the average accuracy level is 99.24%.

Figure 6 represents the validation graph of the non-invasive hemoglobin measurement device. It can be observed that the results obtained from the non-invasive device closely approximate the values obtained from the invasive measurement device. Out of the five data points, only two show slight differences, while three data points are closely aligned or nearly identical. This indicates that the non-invasive measurement device can be considered as an alternative hemoglobin measurement tool.

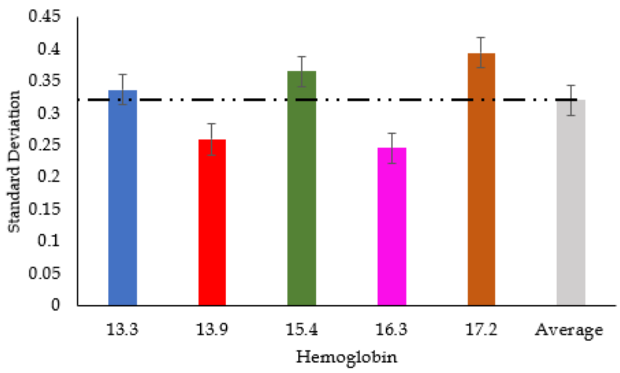

Figure 7. Standard deviation value

Figure 7 displays the distribution of standard deviation values. It can be observed that the standard deviation values differ for each sample. Three data points have values above the average, while two data points have values below the average. However, overall, the standard deviation values are good, staying below 0.5. A smaller standard deviation indicates higher data precision, making it more reliable. Figure 8 displays the distribution of accuracy values. It can be observed that accuracy levels vary for each measurement. Two data points have accuracy values below the average, while three data points have accuracy levels above the average. However, overall, the accuracy values for each measurement are good, exceeding 95%. Higher accuracy values indicate better performance of the device.

Hemoglobin measurement using optical sensors is a promising non-invasive method in healthcare monitoring (Man et al., 2022). Based on the research findings, this device exhibits good standard deviation, indicating consistency in measurements. Validation against invasive methods shows reasonably good accuracy, making it highly potential for replacing invasive methods. Non-invasive methods reduce the risk of infection and patient discomfort as blood sampling is not required (Whitehead et al., 2019). The advantage of non-invasive methods is the potential for continuous hemoglobin monitoring compared to invasive methods that require repeated sampling.

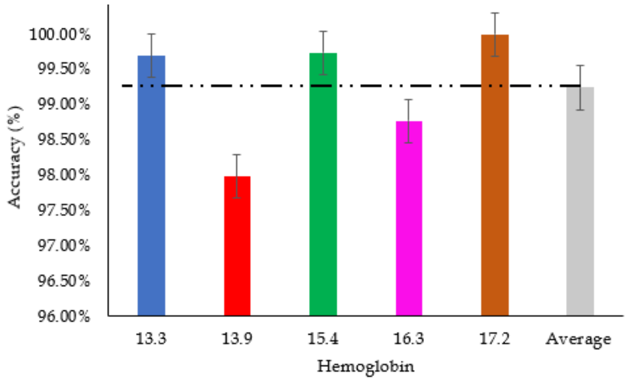

Figure 8. Accuracy value

However, the development of optical sensor technology for non-invasive hemoglobin measurement has some limitations (Wittenmeier et al., 2021). Accuracy is limited under certain conditions, such as for fingers with specific thickness or skin pigmentation different from the average, which may affect accuracy (Lamhaut et al., 2011). Non-invasive methods are also susceptible to interference from environmental factors that can influence measurement results. Nevertheless, these challenges can be addressed with advancements in continuously evolving technology.

Conclusion

The non-invasive hemoglobin measurement device developed in this study has an average standard deviation of 0.32 and an average accuracy of 99.24%. This device is considered to have high consistency in measurements and is accurate.

Acknowledgments

We would like to express our gratitude to the Physics study program at UIN Malang for the support and facilities provided.

Author Contributions

Conceptualization, M. M, F. Z. A, I. T.; methodology, M. M, F. Z. A, I. T.; validation, M. M. and F. Z. A.; formal analysis, M. M.; investigation, M. M. and F. Z. A.; resources, M. M, N. C, W. S; data curation, M. M.: writing—original draft preparation, M. M and F. Z. A.; writing—review and editing, M. M, M. T.; visualization, M. M, F. Z. A, I. T. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of Interest
The authors declare no conflict of interest.

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