ANALYSIS OF BIOMEDICAL PHYSICS IN PULSE OXIMETERS: PRINCIPLES OF PHOTOPLETHYSMOGRAPHY, PHOTOELECTRIC SENSORS, AND SIGNAL PROCESSING

[1]Cahya Maulana, [2]Muhammad Ilham

[1,2,] Department of Medical Engineering Technology, Faculty of Health Sciences,

Universitas Muhammadiyah PKU Surakarta, Surakarta, Indonesia

Email: ncahya4556@std.umpku.ac.id

Abstract—Pulse oximeter is a non-invasive biomedical device widely used to monitor arterial oxygen saturation (SpO_2) and pulse rate in clinical and ambulatory settings. This article presents a comprehensive review of the biomedical physics underlying pulse oximeter technology, emphasizing the integration of optical physics, electronic instrumentation, and digital signal processing. The discussion covers the principles of photoplethysmography (PPG), the application of the Beer–Lambert law to biological tissues, and the optical absorption characteristics of oxygenated and deoxygenated hemoglobin at wavelengths of 660 nm and 940 nm. Furthermore, the article analyzes the operation of key hardware components, including dual-wavelength light-emitting diodes (LEDs), silicon photodiodes, transimpedance amplifiers, analog filters, analog-to-digital converters, and digital signal processing algorithms based on the ratio-of-ratios method for SpO_2 estimation. The review also discusses signal acquisition, conditioning, and calibration processes required to improve measurement accuracy under various physiological conditions. In addition, the study examines technical limitations and clinical challenges such as motion artifacts, peripheral hypoperfusion, dysfunctional hemoglobin, ambient light interference, and skin pigmentation bias that may affect measurement reliability. Recent technological developments are also reviewed, including multi-wavelength pulse oximetry, wearable reflectance photoplethysmography, flexible biosensors, and artificial intelligence-based signal processing techniques that enhance measurement robustness and clinical applicability. Overall, this review highlights the multidisciplinary nature of pulse oximeter technology and demonstrates how advances in biomedical physics, optical sensing, electronics, and intelligent signal processing continue to improve the performance, reliability, and future development of non-invasive physiological monitoring systems.

Keywords—Biomedical physics; pulse oximeter; photoplethysmography; photoelectric sensor; signal processing; oxygen saturation

1. INTRODUCTION

Monitoring arterial oxygen saturation (SpO_2) is an essential component of patient assessment because it provides critical information regarding respiratory and cardiovascular function. Early detection of hypoxemia is particularly important in preventing severe complications, making

ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib

continuous and non-invasive monitoring indispensable in modern healthcare systems [1]. Pulse oximetry has become the standard technology for measuring oxygen saturation due to its ability to provide rapid, real-time, and non-invasive physiological measurements with minimal patient discomfort [2].

The principle of pulse oximetry was first introduced by Takuo Aoyagi in 1972, utilizing the different optical absorption characteristics of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) at two distinct wavelengths. This innovation transformed patient monitoring and is now routinely applied in operating rooms, intensive care units, emergency departments, neonatal care, and home healthcare environments [3]. The widespread use of pulse oximeters during the COVID-19 pandemic further highlighted their importance as essential diagnostic tools for early detection of silent hypoxemia [4].

From an engineering perspective, pulse oximeters integrate multidisciplinary concepts, including biomedical physics, optical spectroscopy, electronic instrumentation, and digital signal processing. The measurement process is fundamentally based on photoplethysmography (PPG), the Beer–Lambert law, and ratio-of-ratios algorithms that estimate arterial oxygen saturation from optical signals acquired using dual-wavelength light-emitting diodes and photodiodes [5], [6]. Advances in analog front-end circuits, signal conditioning, analog-to-digital conversion, and embedded processing have significantly improved measurement accuracy and system reliability.

Despite these advances, conventional pulse oximeters still encounter several technical and clinical challenges. Motion artifacts, peripheral hypoperfusion, ambient light interference, dysfunctional hemoglobin, and skin pigmentation bias may reduce measurement accuracy and compromise clinical decision-making [2], [7]. Consequently, recent research has focused on developing multi-wavelength pulse oximetry, wearable reflectance photoplethysmography, flexible biosensors, and artificial intelligence-based signal processing to enhance robustness and clinical applicability [8], [9].

Therefore, this article presents a comprehensive review of the biomedical physics underlying pulse oximeter technology. The discussion focuses on the principles of photoplethysmography, optical absorption theory based on the Beer–Lambert law, photoelectric sensor technology, electronic instrumentation, digital signal processing, current technical limitations, and recent technological developments. This review is expected to provide engineering students, researchers, and biomedical engineers with a comprehensive understanding of the scientific principles that support the development of modern pulse oximetry systems.

II. METHOD

This study employed a qualitative literature review approach to analyze the biomedical physics principles underlying pulse oximeter technology. The review was conducted by systematically collecting and evaluating scientific publications related to pulse oximetry, photoplethysmography (PPG), optical sensing, biomedical instrumentation,

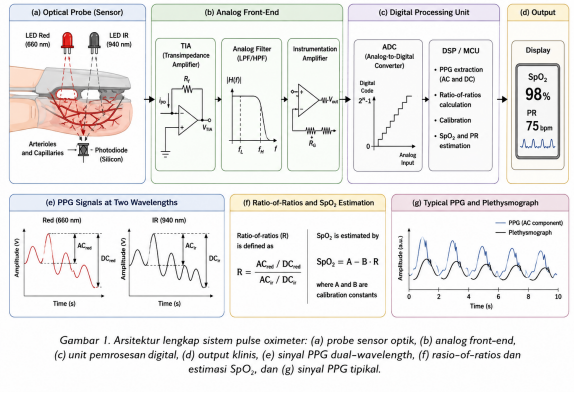
ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib

and digital signal processing. The literature sources included peer-reviewed journal articles, textbooks, international standards, and technical reports published in reputable scientific databases. The selected references primarily discussed the physical principles of light absorption, electronic sensor technology, signal conditioning, SpO_2 estimation algorithms, and recent technological developments in pulse oximetry.

The literature selection process consisted of four stages: identification, screening, eligibility assessment, and qualitative analysis. Initially, publications related to pulse oximeter technology and biomedical physics were identified using relevant keywords such as pulse oximeter, photoplethysmography, Beer–Lambert law, photoelectric sensor, oxygen saturation, and signal processing. Subsequently, duplicate and irrelevant publications were excluded. Only studies presenting theoretical foundations, engineering implementations, clinical applications, or technological advancements of pulse oximeters were included in the review.

The collected literature was analyzed descriptively by examining the relationships among optical physics, electronic instrumentation, and digital signal processing involved in non-invasive oxygen saturation measurement. The analysis focused on the operation of the dual-wavelength optical sensor, consisting of red (660 nm) and infrared (940 nm) light-emitting diodes (LEDs), silicon photodiodes, analog front-end circuits, analog-to-digital converters (ADC), digital signal processors (DSP), and the ratio-of-ratios algorithm used to estimate arterial oxygen saturation (SpO_2). Furthermore, current technical limitations, including motion artifacts, peripheral hypoperfusion, ambient light interference, dysfunctional hemoglobin, and skin pigmentation bias, were analyzed together with recent technological developments such as multi-wavelength pulse oximetry, wearable sensors, and artificial intelligence-based signal processing.

The analytical framework adopted in this review is illustrated in Figure 1. The framework describes the functional architecture of a pulse oximeter, beginning with optical signal acquisition by the probe sensor, followed by analog signal conditioning, analog-to-digital conversion, digital signal processing, and clinical output generation. The figure also illustrates dual-wavelength PPG signals, the ratio-of-ratios algorithm, and the typical photoplethysmography waveform used for SpO_2 estimation. This framework served as the basis for organizing the discussion and evaluating each subsystem from the perspective of biomedical physics and engineering.



Gambar 1. Arsitektur lengkap sistem pulse oximeter: (a) probe sensor optik, (b) analog front-end, (c) unit pemrosesan digital, (d) output klinis, (e) sinyal PPG dual-wavelength, (f) rasio-of-ratios dan estimasi SpO_2, dan (g) sinyal PPG tipikal.

Fig. 1. Functional architecture of the pulse oximeter system consisting of (a) optical probe, (b) analog front-end, (c) digital

ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib

processing unit, (d) clinical output, (e) dual-wavelength photoplethysmography (PPG) signals, (f) ratio-of-ratios algorithm for SpO_2 estimation, and (g) typical PPG waveform.

III. RESULTS AND DISCUSSION

A. Optical Characteristics of Pulse Oximeter

The operation of pulse oximeters is based on the different optical absorption characteristics of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb). Two wavelengths, namely 660 nm (red) and 940 nm (infrared), are selected because they provide the highest sensitivity for differentiating oxygenation status.

Table 1. Optical characteristics of hemoglobin at different wavelengths.

Parameter	Red LED	Infrared LED
Wavelength	660	940
Main target	Deoxyhemoglobin	Oxyhemoglobin
Light source	AlGaInP LED	AlGaAs LED
Optical detector	Silicon Photodiode	Silicon Photodiode
Penetration depth	Low	High
Clinical function	Hb detection	HbO_2 detection

The difference in optical absorption enables the calculation of arterial oxygen saturation using the ratio-of-ratios algorithm.

B. Analog Front-End Performance

The analog front-end converts the photodiode current into voltage before digital processing.

Table 2. Typical electronic specifications of the analog front-end

Component	Typical Value
Photodiode current	1–100 nA
Feedback resistor (TIA)	10 kΩ–10 MΩ
ADC Resolution	16–24 bit
Sampling frequency	50–1000 Hz
Signal bandwidth	0.5–15 Hz
Signal-to-noise ratio	>20 dB

The analog front-end significantly influences measurement stability because the PPG AC component generally represents only 1–2% of the DC component.

C. Signal Processing Analysis

The ratio-of-ratios algorithm estimates oxygen saturation from AC and DC components at two wavelengths.

Table 3. Signal processing stages

Stage	Function
LED Multiplexing	Sequential optical emission
Photodiode Detection	Optical-to-electrical conversion
TIA	Current-to-voltage conversion
Analog Filter	Noise reduction
ADC	Digital conversion
DSP	AC/DC extraction
Ratio-of-Ratios	SpO_2 estimation
Display	Clinical output

The final output stage presents the processed physiological parameters to the user. After digital signal processing and calibration, the estimated arterial oxygen saturation (SpO_2) and pulse rate (PR) are displayed in real time through the user interface. This stage transforms the processed optical signals into clinically meaningful information that can be interpreted by healthcare professionals for patient monitoring and decision-making.

ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib

The dual-wavelength photoplethysmography (PPG) signals represent the optical responses obtained from red (660 nm) and infrared (940 nm) light sources. Each signal consists of a pulsatile alternating current (AC) component, which reflects periodic changes in arterial blood volume during the cardiac cycle, and a direct current (DC) component, which represents constant absorption from non-pulsatile tissues, venous blood, bone, and skin. The separation of AC and DC components at both wavelengths provides the fundamental information required for estimating arterial oxygen saturation using the ratio-of-ratios algorithm.

IV. CONCLUSION

This review has presented a comprehensive analysis of the biomedical physics principles underlying pulse oximeter technology by integrating concepts from optical physics, biomedical instrumentation, and digital signal processing. The operating principle of pulse oximeters is fundamentally based on photoplethysmography (PPG) and the Beer–Lambert law, where differences in the optical absorption characteristics of oxygenated and deoxygenated hemoglobin at wavelengths of 660 nm and 940 nm enable non-invasive estimation of arterial oxygen saturation (SpO_2). The performance of the system depends on the coordinated operation of optical sensors, analog front-end circuits, analog-to-digital conversion, and digital signal processing using the ratio-of-ratios algorithm.

The review also highlights several technical and clinical limitations, including motion artifacts, peripheral hypoperfusion, ambient light interference, dysfunctional hemoglobin, and skin pigmentation bias, which may reduce measurement accuracy under challenging conditions. Recent advances in multi-wavelength pulse oximetry, wearable photoplethysmography, flexible biosensors, and artificial intelligence-based signal processing demonstrate significant potential for improving measurement robustness, diagnostic reliability, and continuous patient monitoring.

Overall, pulse oximeter technology represents a multidisciplinary application of biomedical physics that continues to evolve through innovations in optical sensing, electronics, and intelligent signal processing. Future developments are expected to enhance measurement accuracy, broaden clinical applications, and support next-generation non-invasive physiological monitoring systems..

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to the Department of Medical Engineering Technology, Faculty of Health Sciences, Universitas Muhammadiyah PKU Surakarta, Indonesia, for providing academic support and facilities during the preparation of this review article.

REFERENCES

[1] A. Chan, K. Chan, dan M. Hosseini, "Pulse oximetry: Understanding its basic principles facilitates appreciation of its limitations," Respiratory Medicine, vol. 107, no. 6, pp. 789–799, 2013. DOI: 10.1016/j.rmed.2013.02.004.

[2] J. P. Phillips dan G. D. Clifton, "Pulse oximetry: Technology and clinical implications," Journal of Clinical Monitoring and Computing, vol. 36, no. 3, pp. 623–634, 2022. DOI: 10.1007/s10877-021-00720-5.

[3] L. Sjoding, R. P. Dickson, T. J. Iwashyna, S. E. Gay, dan T. S. Valley, "Racial bias in pulse oximetry measurement," New England Journal of

ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib

Medicine, vol. 383, no. 25, pp. 2477–2478, 2020. DOI: 10.1056/NEJMc2029240.

[4] S. Ghamari, "A review on wearable photoplethysmography sensors and their potential future applications in health care," International Journal of Biosensors & Bioelectronics, vol. 4, no. 4, pp. 195–202, 2018. DOI: 10.15406/ijbsbe.2018.04.00125.

[5] Z. Liang, J. Ward, S. Li, W. Chen, dan B. D. Elgendi, "Machine learning for real-time physiological assessment from remote photoplethysmography," npj Digital Medicine, vol. 5, no. 1, pp. 1–13, 2022. DOI: 10.1038/s41746-022-00700-y.

[6] World Health Organization, "Pulse Oximetry Training Manual," WHO Press, Geneva, 2011. [Online]. Tersedia: https://www.who.int/patientsafety/safesurgery/pulse_oximetry/en/.

[7] F. J. Bhavani-Shankar, K. Kumar, C. S. Moseley, dan R. Ahearn, "Pitfalls of pulse oximetry in critically ill patients," Critical Care Medicine, vol. 50, no. 4, pp. e345–e355, 2022. DOI: 10.1097/CCM.0000000000005400.

[8] S. L. Jacques, "Optical properties of biological tissues: A review," Physics in Medicine and Biology, vol. 58, no. 11, pp. R37–R61, 2013. DOI: 10.1088/0031-9155/58/11/R37.

[9] D. T. Delpy, M. Cope, P. van der Zee, S. Arridge, S. Wray, dan J. Wyatt, "Estimation of optical pathlength through tissue from direct time of flight measurement," Physics in Medicine and Biology, vol. 33, no. 12, pp. 1433–1442, 1988. DOI: 10.1088/0031-9155/33/12/008.

[10] S. Prahl, "Optical absorption of hemoglobin," Oregon Medical Laser Center, Portland, OR, 2020. [Online]. Tersedia: https://omlc.org/spectra/hemoglobin/.

[11] J. G. Webster, Ed., Design of Pulse Oximeters, 1st ed. Bristol, UK: IOP Publishing, 1997.

[12] M. Elgendi, "On the analysis of fingertip photoplethysmogram signals," Current Cardiology Reviews, vol. 8, no. 1, pp. 14–25, 2012. DOI: 10.2174/157340312801215782.

[13] P. D. Mannheimer, "The light-tissue interaction of pulse oximetry," Anesthesia & Analgesia, vol. 105, no. 6 Suppl, pp. S10–S17, 2007. DOI: 10.1213/01.ane.0000269522.84942.54.

[14] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," Physiological Measurement, vol. 28, no. 3, pp. R1–R39, 2007. DOI: 10.1088/0967-3334/28/3/R01.

[15] M. Nitzan, A. Romem, dan R. Koppel, "Pulse oximetry: Fundamentals and technology update," Medical Devices: Evidence and Research, vol. 7, pp. 231–239, 2014. DOI: 10.2147/MDER.S47319.

[16] A. Mendelson, "Pulse oximetry: Theory and applications for noninvasive monitoring," Clinical Chemistry, vol. 38, no. 9, pp. 1601–1607, 1992.

[17] R. A. Norris dan D. P. Gravel, "Artificial intelligence-enhanced pulse oximetry: Systematic review of machine learning approaches," Journal of Medical Devices, vol. 16, no. 2, pp. 021001, 2023. DOI: 10.1115/1.4056130.

[18] F. K. Kirchhoff, "Wearable pulse oximetry: Design considerations and clinical applications," IEEE Transactions on Biomedical Engineering, vol. 69, no. 8, pp. 2498–2510, 2022. DOI: 10.1109/TBME.2022.3155647.

[19] S. Faulkner dan M. Thomas, "Motion artifact reduction in wearable photoplethysmography: A systematic review," Sensors, vol. 22, no. 5, pp. 1917, 2022. DOI: 10.3390/s22051917.

[20] H. U. Chung dan B. H. Kim, "Skin-interfaced biosensors for advanced wireless physiological monitoring in neonatal and pediatric intensive-care units," Nature Medicine, vol. 26, no. 3, pp. 418–429, 2020. DOI: 10.1038/s41591-020-0792-9.

ISSN 3123-5549 (online) DOI 10.30659/pulse-jeib