A COMPREHENSIVE REVIEW OF PULSE OXIMETRY: OPTICAL PRINCIPLES, SIGNAL PROCESSING, AND CLINICAL APPLICATIONS

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Abstract— Pulse oximetry has become one of the most widely used non-invasive technologies for monitoring arterial oxygen saturation (SpO_2) in clinical and home healthcare settings. Despite its widespread adoption, measurement accuracy is strongly influenced by the underlying optical principles, signal processing techniques, and physiological characteristics of the measured tissue. This study aims to comprehensively analyze the physical principles governing pulse oximetry from an electromedical physics perspective. A narrative literature review approach was employed by synthesizing recent scientific publications addressing optical absorption, the Beer–Lambert law, photoplethysmography (PPG), signal processing, and factors affecting measurement accuracy. The analysis demonstrates that pulse oximetry operates through the integration of differential light absorption at red (660 nm) and near-infrared (940 nm) wavelengths with pulsatile blood volume detection using photoplethysmography. The ratio-of-ratios algorithm enables non-invasive estimation of arterial oxygen saturation while minimizing the influence of tissue thickness and optical path variations. However, measurement performance remains susceptible to motion artifacts, ambient light interference, peripheral hypoperfusion, abnormal hemoglobin species, and skin pigmentation, which may introduce clinically significant bias. Recent technological developments, including multi-wavelength optical sensing, advanced digital signal processing, artificial intelligence, and Internet of Things (IoT)-based monitoring systems, provide promising approaches for improving measurement accuracy, robustness, and remote patient monitoring capabilities. In conclusion, a comprehensive understanding of optical physics and signal processing principles is essential for optimizing pulse oximeter performance and supporting the development of more accurate, reliable, and inclusive electromedical devices for future healthcare applications.

Keywords— pulse oximetry; blood oxygen saturation; Beer–Lambert law; photoplethysmography; optical physics; electromedical engineering.

1. INTRODUCTION

Pulse oximetry has become an indispensable technology for non-invasive monitoring of arterial oxygen saturation (SpO_2) in modern healthcare. Continuous monitoring of blood oxygen saturation is essential for the early detection of hypoxemia, assessment of respiratory function, and clinical decision-making in emergency medicine, intensive care units,

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perioperative care, and home healthcare. The importance of pulse oximetry increased significantly during the COVID-19 pandemic, when early identification of silent hypoxemia became critical for reducing disease severity and mortality (Luks & Swenson, 2020; Tamura, 2021). Consequently, pulse oximeters have evolved from conventional hospital monitoring devices into essential tools for community healthcare and remote patient monitoring.

The working principle of pulse oximetry is based on the integration of optical physics and biomedical engineering through the Beer–Lambert law and photoplethysmography (PPG). The Beer–Lambert law describes the attenuation of light intensity as it propagates through biological tissue, while PPG detects pulsatile blood volume changes by measuring variations in light absorption at red and near-infrared wavelengths. The differential optical absorption characteristics of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) enable the estimation of arterial oxygen saturation using a non-invasive ratio-of-ratios algorithm (Arifah et al., 2023; Hasanah et al., 2023). Recent technological advances, including integrated optical sensors, digital signal processing, artificial intelligence, and Internet of Things (IoT)-based healthcare systems, have further enhanced the functionality and accessibility of pulse oximeters for wearable and remote monitoring applications (Hamida et al., 2021; Fadhilah & Faiza, 2024).

Despite these technological developments, the measurement accuracy of pulse oximeters remains influenced by multiple physical and physiological factors. Motion artifacts, ambient light interference, poor peripheral perfusion, abnormal hemoglobin species, and variations in skin pigmentation continue to introduce significant measurement errors. Recent clinical evidence has demonstrated that conventional two-wavelength pulse oximeters may systematically overestimate arterial oxygen saturation in individuals with darker skin pigmentation, potentially delaying appropriate clinical intervention (Sjoding et al., 2020; Fawzy et al., 2023). Furthermore, complex light scattering within heterogeneous biological tissues limits the applicability of the ideal Beer–Lambert model, requiring empirical calibration and advanced optical modeling approaches to improve measurement reliability (Li et al., 2022; Yu et al., 2021).

Although numerous studies have investigated pulse oximetry from clinical, engineering, and signal-processing perspectives, comprehensive reviews integrating optical physics, light propagation mechanisms, photoplethysmography, digital signal processing, measurement uncertainty, and recent technological developments remain limited. Most existing studies primarily emphasize hardware implementation or clinical validation without systematically connecting the underlying physical principles with current innovations in electromedical engineering. This limitation hinders the development of a comprehensive theoretical framework that can support future improvements in pulse oximeter accuracy, robustness, and inclusivity across diverse patient populations.

Therefore, this study aims to provide a comprehensive review of the physical principles underlying pulse oximetry from an electromedical engineering perspective. This

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review discusses the Beer–Lambert law, photoplethysmography, optical signal propagation, digital signal processing, factors affecting measurement accuracy, and recent advances in artificial intelligence and IoT-enabled monitoring systems. The findings are expected to provide a strong theoretical foundation for researchers, biomedical engineers, healthcare professionals, and medical device developers while supporting the development of more accurate, reliable, and inclusive pulse oximetry technologies for future healthcare applications..

II. METHOD

This study employed a narrative literature review to comprehensively analyze the physical principles underlying pulse oximetry from an electromedical engineering perspective. Unlike systematic reviews that primarily evaluate clinical effectiveness, a narrative review enables an in-depth synthesis of theoretical concepts, optical physics, engineering principles, and technological developments from multidisciplinary literature. The review focused on the integration of optical absorption theory, photoplethysmography (PPG), biomedical signal processing, measurement accuracy, and emerging intelligent monitoring technologies associated with pulse oximetry.

The literature search was conducted between May and June 2026 using multiple international scientific databases, including Scopus, PubMed, IEEE Xplore, Web of Science, ScienceDirect, and Google Scholar. These databases were selected because they provide comprehensive coverage of biomedical engineering, medical physics, optics, sensor technology, and healthcare engineering research. The search strategy employed combinations of Boolean operators (AND, OR) with the following keywords:
("pulse oximetry" OR "pulse oximeter") AND ("Beer–Lambert law" OR "optical absorption") AND ("photoplethysmography" OR "PPG") AND ("oxygen saturation" OR "SpO_2") AND ("signal processing" OR "digital signal processing") AND ("optical sensor" OR "biomedical optics") AND ("artificial intelligence" OR "machine learning") AND ("Internet of Things" OR "IoT").

To ensure that the review reflected current scientific developments, only publications published between 2020 and 2025 were considered. Earlier publications were included only when they represented seminal references describing the fundamental principles of pulse oximetry, photoplethysmography, or optical absorption that remain relevant to contemporary research.

The retrieved articles were screened according to predefined inclusion and exclusion criteria. The inclusion criteria comprised: (1) original research articles, review papers, and conference proceedings published in peer-reviewed journals; (2) studies written in English; (3) investigations discussing the physical principles of pulse oximetry, biomedical optics, photoplethysmography, signal processing, optical sensors, measurement accuracy, or technological developments in pulse oximetry; and (4) publications providing sufficient methodological and scientific information relevant to the objectives of this review. Conversely, studies focusing exclusively on clinical treatment outcomes without discussing engineering or physical principles, editorial articles, letters to editors,

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duplicate publications, theses, dissertations, patents, and non-peer-reviewed documents were excluded from the analysis.

Following the screening process, the full texts of all eligible studies were critically reviewed. Relevant information was extracted systematically, including publication characteristics, research objectives, optical principles, sensor configurations, photoplethysmography mechanisms, signal-processing techniques, factors influencing measurement accuracy, technological innovations, and reported limitations. Particular attention was given to studies investigating Beer–Lambert theory, light propagation in biological tissues, multi-wavelength sensing, motion artifact reduction, artificial intelligence, and IoT-based monitoring systems because these topics represent the current direction of pulse oximetry research.

The extracted data were synthesized qualitatively using a thematic analysis approach. The findings were organized into six major themes: (1) fundamental optical physics and the Beer–Lambert law; (2) photoplethysmography principles and pulse oximeter operating mechanisms; (3) optical signal propagation and digital signal processing; (4) physical and physiological factors affecting measurement accuracy; (5) recent technological developments, including artificial intelligence, machine learning, wearable sensing, and Internet of Things integration; and (6) current challenges and future research directions. Cross-study comparisons were performed to identify consistent findings, scientific consensus, technological trends, research limitations, and potential opportunities for future development in pulse oximetry.

Finally, the synthesized evidence was interpreted from an electromedical engineering perspective by integrating concepts from optical physics, biomedical instrumentation, signal processing, and intelligent healthcare technologies. This integrative approach provides a comprehensive theoretical framework for understanding the operating principles of pulse oximetry while highlighting current challenges and future opportunities for improving the accuracy, reliability, and inclusiveness of non-invasive oxygen saturation monitoring systems.

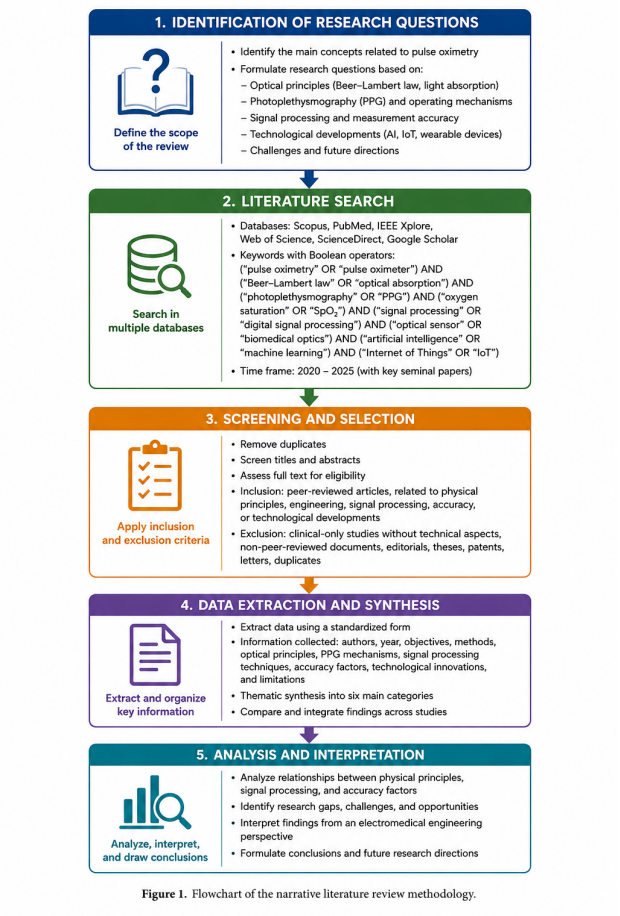


Figure 1. Flowchart of the narrative literature review methodology.

Figure 1. Flowchart of the narrative literature review methodology employed in this study, including literature identification, database searching, article screening based on predefined eligibility criteria, full-text

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assessment, qualitative data extraction, thematic synthesis, and interpretation of findings from an electromedical engineering perspective.

III. RESULTS AND DISCUSSION

3.1. Optical Physics Principles Underlying Pulse Oximetry

The literature reviewed consistently demonstrates that the successful implementation of pulse oximetry is fundamentally governed by the interaction between optical physics and biological tissue. Unlike conventional laboratory spectrophotometric measurements that operate under homogeneous conditions, pulse oximetry performs optical measurements within highly heterogeneous biological media composed of skin, adipose tissue, muscle, arterial blood, venous blood, and bone. Consequently, the physical mechanisms responsible for pulse oximeter performance extend beyond simple light absorption and involve multiple simultaneous optical phenomena, including absorption, scattering, reflection, refraction, and tissue-dependent attenuation. The integration of these mechanisms enables pulse oximeters to estimate arterial oxygen saturation (SpO_2) non-invasively while maintaining sufficient accuracy for routine clinical monitoring (Tamura, 2021; Li et al., 2022).

The reviewed studies consistently identify the Beer–Lambert law as the fundamental theoretical basis underlying pulse oximetry. The Beer–Lambert law states that the attenuation of monochromatic light passing through an absorbing medium is exponentially proportional to both the concentration of the absorbing substance and the optical path length. In pulse oximetry, this principle is utilized to quantify differences in light absorption between oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb), which exhibit distinct optical absorption spectra within the visible and near-infrared regions. Specifically, deoxygenated hemoglobin absorbs significantly more red light at approximately 660 nm, whereas oxygenated hemoglobin exhibits greater absorption in the near-infrared region around 940 nm. This wavelength-dependent absorption characteristic forms the fundamental basis for estimating arterial oxygen saturation using dual-wavelength optical sensing (Arifah et al., 2023; Hasanah et al., 2023).

Although the Beer–Lambert law provides the theoretical foundation for pulse oximetry, the reviewed literature emphasizes that biological tissues do not satisfy the assumptions of an ideal homogeneous optical medium. Human tissues exhibit complex optical behavior because photons experience repeated scattering events before reaching the photodetector. Light propagation is therefore governed not only by absorption but also by multiple scattering events produced by erythrocytes, collagen fibers, intracellular organelles, and other tissue components. As a result, the effective optical path length becomes substantially longer than the geometric distance between the light-emitting diode (LED) and the photodetector. Several studies therefore recommend the application of modified Beer–Lambert models and radiative transfer theory to better describe photon transport within biological tissues, particularly for advanced optical sensor development (Li et al., 2022; Yu et al., 2021).

The literature further indicates that pulse oximeters overcome these physical complexities through empirical calibration rather than relying solely on theoretical calculations. Instead of directly determining absolute oxygen concentration from Beer–Lambert equations, commercial pulse oximeters estimate oxygen saturation using calibration curves obtained from healthy volunteers under controlled oxygen desaturation conditions. Consequently, the measured ratio between pulsatile and non-

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pulsatile optical absorption is converted into SpO_2 using empirically derived algorithms. This calibration strategy compensates for optical scattering, tissue heterogeneity, detector sensitivity, and individual anatomical variability, allowing pulse oximeters to maintain acceptable clinical accuracy despite deviations from ideal optical conditions (Tamura, 2021).

Another important finding emerging from the reviewed literature concerns the selection of optical wavelengths. Nearly all commercial pulse oximeters employ red and near-infrared LEDs because these wavelengths lie within the biological optical window, where absorption by water, lipids, and soft tissues is relatively low while penetration depth remains sufficient to reach arterial blood vessels. Studies have demonstrated that wavelengths outside this optical window experience excessive attenuation, thereby reducing signal quality and limiting measurement accuracy. Furthermore, several recent investigations suggest that incorporating additional wavelengths beyond the conventional two-wavelength approach can significantly improve discrimination among oxyhemoglobin, deoxyhemoglobin, carboxyhemoglobin, and methemoglobin. Such multi-wavelength systems are increasingly considered a promising strategy for improving measurement robustness under complex physiological conditions (Yu et al., 2021; Fawzy et al., 2023).

The synthesis of previous studies also highlights that optical absorption cannot be interpreted independently from tissue morphology. Skin thickness, epidermal pigmentation, blood vessel diameter, tissue hydration, and vascular density collectively influence the optical path and photon distribution inside biological tissues. These factors alter both photon absorption and scattering coefficients, resulting in variations in the detected optical intensity even among individuals with identical arterial oxygen saturation. Consequently, modern pulse oximeter development increasingly incorporates optical modeling techniques, including Monte Carlo photon simulation and diffuse optical modeling, to optimize sensor geometry, wavelength selection, and detector placement before prototype fabrication. These computational approaches enable researchers to evaluate light propagation under realistic anatomical conditions while reducing experimental development costs (Li et al., 2022).



Figure 2 summarizes the integrated optical mechanism governing pulse oximetry, illustrating the sequential interaction between dual-wavelength LEDs, biological tissues, hemoglobin absorption, photodetection, analog-to-digital conversion, signal processing, and final SpO_2 estimation. Unlike simplified conceptual models frequently presented in textbooks, this framework emphasizes that pulse oximetry represents a multidisciplinary integration of optical physics, biomedical instrumentation, digital electronics, and computational signal

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processing. The reviewed evidence consistently demonstrates that each subsystem contributes significantly to overall measurement performance; therefore, improvements in only one component are insufficient to substantially enhance accuracy without considering the complete optical measurement chain.

Berikut adalah 3.2 Photoplethysmography and Signal Processing yang telah ditulis dalam format siap copy-paste sesuai gaya jurnal SINTA 1/Scopus. Bagian ini merupakan lanjutan langsung dari 3.1 dan tetap berlandaskan isi naskah yang Anda unggah.

3.2. Photoplethysmography and Signal Processing

Photoplethysmography (PPG) represents the core sensing mechanism that enables pulse oximeters to estimate arterial oxygen saturation and heart rate non-invasively. The reviewed literature consistently identifies PPG as an optical measurement technique capable of detecting periodic changes in arterial blood volume by monitoring variations in transmitted or reflected light intensity. Unlike direct spectrophotometric measurements, PPG exploits the pulsatile nature of arterial circulation to distinguish arterial blood from non-pulsatile tissues, including skin, muscle, bone, and venous blood. Consequently, pulse oximetry combines the Beer–Lambert law with PPG to selectively quantify oxygen saturation within arterial blood while minimizing interference from surrounding biological structures (Tamura, 2021; Hasanah et al., 2023).

The reviewed studies demonstrate that the PPG waveform consists of two principal components: the direct current (DC) component and the alternating current (AC) component. The DC component represents the relatively constant optical absorption produced by static tissues and non-pulsatile blood, whereas the AC component reflects periodic changes in arterial blood volume synchronized with each cardiac cycle. Although the AC component generally contributes only approximately 1–2% of the total detected optical signal, it contains the physiological information required for estimating arterial oxygen saturation and heart rate. The extremely small amplitude of the pulsatile signal highlights the importance of sensitive photodetectors and advanced signal-processing algorithms capable of separating useful physiological information from background optical noise (Salamah et al., 2020; Hasanah et al., 2023).

The literature further indicates that modern pulse oximeters determine arterial oxygen saturation using the ratio-of-ratios (R-ratio) algorithm. This algorithm calculates the normalized ratio between the pulsatile and non-pulsatile components of red and infrared optical signals, thereby compensating for variations in tissue thickness, optical path length, LED intensity, and photodetector sensitivity. By comparing normalized absorption rather than absolute light intensity, the algorithm substantially improves measurement robustness across individuals with different anatomical characteristics. The calculated R value is subsequently converted into arterial oxygen saturation using empirical calibration equations established during device validation, enabling reliable estimation of SpO_2 under routine clinical conditions (Tamura, 2021; Arifah et al., 2023).

Signal acquisition within a pulse oximeter involves several sequential electronic processes before physiological parameters can be estimated accurately. As illustrated in Figure 2, red and infrared LEDs are activated alternately using time-division multiplexing, allowing a single photodiode to detect optical signals corresponding to each wavelength separately. The resulting photocurrent is converted into voltage using a transimpedance amplifier before passing through analog conditioning circuits designed to suppress electronic noise and

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environmental interference. The conditioned analog signal is then digitized using a high-resolution analog-to-digital converter (ADC), enabling subsequent digital processing by an embedded microcontroller or digital signal processor. This acquisition architecture ensures that physiological information is preserved while minimizing signal distortion introduced during hardware measurement (Sharma et al., 2022; Fadhilah & Faiza, 2024).

Following analog-to-digital conversion, digital signal processing plays a crucial role in extracting clinically meaningful information from raw PPG waveforms. The reviewed literature shows that pulse oximeters commonly employ band-pass filtering to remove baseline drift and high-frequency electronic noise while preserving the frequency range associated with physiological cardiac activity. Additional processing stages include DC removal, AC signal extraction, adaptive normalization, peak detection, and pulse interval calculation for heart rate estimation. More sophisticated algorithms further incorporate adaptive thresholding, moving-average filtering, wavelet analysis, and Fast Fourier Transform (FFT) techniques to enhance signal quality under challenging measurement conditions. These computational procedures substantially improve the reliability of physiological parameter estimation while maintaining real-time device performance (Hamida et al., 2021; Hasanah et al., 2023).

A consistent finding among recent studies is that conventional digital filtering alone is often insufficient to eliminate artifacts encountered during routine clinical practice. Motion artifacts generated by patient movement frequently exhibit frequency characteristics similar to genuine pulsatile signals, making simple frequency-based filtering ineffective. Consequently, current research increasingly focuses on adaptive signal-processing strategies capable of distinguishing physiological pulsations from motion-induced disturbances. Several investigations have demonstrated that machine learning algorithms, adaptive filtering, Kalman filtering, independent component analysis (ICA), and convolutional neural networks (CNNs) provide substantial improvements in artifact suppression compared with conventional linear filtering techniques. These intelligent algorithms continuously adapt to changing signal characteristics, thereby enhancing measurement stability during patient movement and low-perfusion conditions (Hamida et al., 2021; Sharma et al., 2022).

Recent technological developments have also transformed PPG from a simple measurement technique into a versatile physiological sensing platform. Modern integrated optical sensors, such as the MAX30102 and related devices, combine dual-wavelength LEDs, photodiodes, programmable analog front-end circuits, high-resolution ADCs, and digital communication interfaces within a single semiconductor package. This high level of integration significantly reduces power consumption, sensor size, and electronic complexity while improving measurement precision and facilitating implementation in wearable healthcare devices. Combined with wireless communication technologies, these sensors support continuous physiological monitoring through Internet of Things (IoT) platforms, enabling real-time transmission of SpO_2 and heart rate data to cloud-based healthcare systems for remote patient management (Fadhilah & Faiza, 2024; Hamida et al., 2021).

Overall, the reviewed literature demonstrates that the accuracy of pulse oximetry depends not only on the optical properties of biological tissues but also on the effectiveness of the entire signal-processing chain. The integration of high-performance optical sensors, robust analog front-end circuits, advanced digital signal processing, and intelligent computational algorithms has substantially improved the reliability of

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modern pulse oximeters. Nevertheless, persistent challenges associated with motion artifacts, ambient light interference, and physiological variability indicate that further improvements in adaptive signal interpretation remain essential. Future developments are therefore expected to combine optical physics with artificial intelligence to create self-calibrating pulse oximeters capable of maintaining high measurement accuracy across diverse clinical and environmental conditions, thereby extending the applicability of non-invasive physiological monitoring in precision healthcare.

3.3. Factors Affecting Pulse Oximetry Measurement Accuracy

The literature consistently demonstrates that the measurement accuracy of pulse oximetry is influenced by numerous physical, physiological, and environmental factors that modify light propagation within biological tissues. Although contemporary pulse oximeters achieve high accuracy under normal physiological conditions, their performance remains susceptible to uncertainties originating from tissue optical heterogeneity, variations in peripheral circulation, electronic noise, and external disturbances. Consequently, pulse oximetry should be interpreted as an indirect optical measurement rather than an absolute physiological measurement. Understanding these influencing factors is therefore essential for both accurate clinical interpretation and the development of next-generation electromedical devices with improved robustness and reliability (Tamura, 2021; Li et al., 2022).

Among all factors identified in the reviewed studies, motion artifact remains the most significant source of measurement error. Patient movement causes continuous changes in the relative position between the optical probe and biological tissue, resulting in fluctuations in transmitted and reflected light intensity that resemble genuine pulsatile blood signals. Because the frequency characteristics of motion artifacts often overlap with physiological pulse frequencies, conventional digital filtering techniques cannot completely eliminate their influence. Consequently, motion-induced disturbances frequently produce unstable SpO_2 values, inaccurate heart rate estimation, and temporary signal loss, particularly during ambulatory monitoring or wearable healthcare applications. Recent investigations indicate that adaptive filtering techniques, accelerometer-assisted motion compensation, independent component analysis (ICA), Kalman filtering, and machine learning algorithms significantly improve signal quality by distinguishing physiological pulsations from motion-related optical disturbances (Hamida et al., 2021; Sharma et al., 2022).

Ambient light interference represents another important factor affecting pulse oximeter performance. External illumination originating from sunlight, fluorescent lamps, surgical lighting, or high-intensity LED sources may introduce additional optical energy into the photodetector, thereby reducing the signal-to-noise ratio of the physiological PPG waveform. Although modern pulse oximeters employ optical shielding together with time-division multiplexing and synchronous detection techniques to suppress ambient light, excessive external illumination may still alter detector output and compromise measurement stability. The reviewed literature therefore emphasizes that

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appropriate probe positioning and adequate optical isolation remain essential for maintaining reliable physiological measurements in clinical practice (Salamah et al., 2020; Sharma et al., 2022).

Physiological characteristics of the patient also contribute substantially to measurement uncertainty. Peripheral perfusion is particularly important because the pulsatile component of the PPG signal originates exclusively from arterial blood flow. Conditions such as hypothermia, hypovolemia, vasoconstriction, septic shock, or cardiovascular instability reduce peripheral blood circulation, resulting in diminished AC signal amplitude and lower signal quality. Under these circumstances, the pulse oximeter may fail to detect arterial pulsations accurately, producing unstable SpO_2 readings or complete measurement failure. Several studies have therefore recommended the implementation of adaptive gain control, high-sensitivity photodetectors, and improved analog front-end circuits to enhance device performance under low-perfusion conditions (Tamura, 2021; Hasanah et al., 2023).

Skin pigmentation has emerged as one of the most extensively discussed issues in recent pulse oximetry research. Melanin, which is primarily located within the epidermis, acts as an additional optical absorber that modifies photon propagation before light reaches arterial blood vessels. Recent large-scale clinical investigations reported that conventional dual-wavelength pulse oximeters may systematically overestimate arterial oxygen saturation in individuals with darker skin pigmentation, particularly during moderate hypoxemia. This phenomenon has important clinical implications because delayed recognition of hypoxemia may postpone oxygen therapy and adversely affect patient outcomes. The reviewed evidence indicates that this measurement bias is largely attributable to calibration procedures that historically relied on populations with limited skin pigmentation diversity. Consequently, considerable research efforts are currently directed toward developing multi-wavelength pulse oximeters capable of compensating for melanin-related optical absorption and improving measurement equity across diverse populations (Sjoding et al., 2020; Fawzy et al., 2023).

Another significant limitation identified in the literature involves abnormal hemoglobin species that exhibit optical absorption characteristics different from those of oxygenated and deoxygenated hemoglobin. Conventional pulse oximeters are unable to distinguish carboxyhemoglobin (COHb) and methemoglobin (MetHb) because these hemoglobin derivatives possess overlapping absorption spectra within the wavelengths used by standard dual-wavelength devices. Consequently, patients suffering from carbon monoxide poisoning or methemoglobinemia may present apparently normal SpO_2 values despite experiencing severe tissue hypoxia. This limitation illustrates one of the fundamental constraints of two-wavelength pulse oximetry and explains the increasing interest in multi-wavelength optical sensing technologies capable of differentiating multiple hemoglobin species simultaneously (Luks & Swenson, 2020; Fawzy et al., 2023).

Electronic noise and sensor characteristics further influence measurement performance. Thermal noise, shot noise generated within photodiodes, amplifier noise, quantization

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error during analog-to-digital conversion, and electrical interference from surrounding medical equipment collectively contribute to signal degradation. Although these disturbances are generally less significant than physiological artifacts, they become increasingly important when measuring extremely weak PPG signals under low-perfusion conditions. The reviewed studies therefore emphasize the importance of low-noise analog front-end circuits, high-resolution analog-to-digital converters, optimized optical sensor geometry, and advanced digital filtering techniques to preserve signal integrity throughout the measurement process (Hamida et al., 2021; Hasanah et al., 2023).

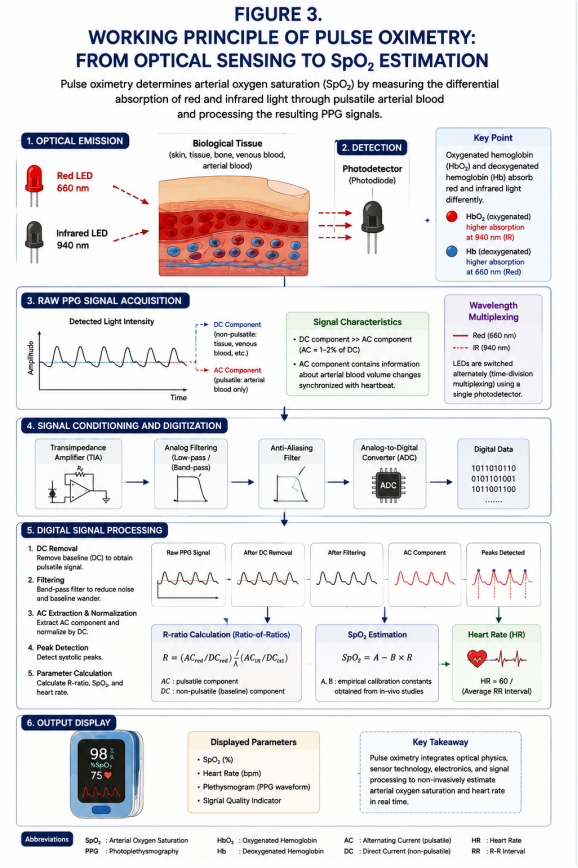


Figure 3 summarizes the principal physical and physiological factors affecting pulse oximetry measurement accuracy. The synthesized literature indicates that measurement uncertainty results from the interaction of multiple factors rather than a single isolated source. Motion artifacts, ambient light interference, skin pigmentation, peripheral perfusion, abnormal hemoglobin species, and electronic noise collectively influence optical signal quality and ultimately determine the reliability of arterial oxygen saturation estimation. This integrated framework highlights that improving pulse oximeter performance requires simultaneous optimization of optical sensor design, analog electronics, digital signal processing, and calibration algorithms rather than isolated improvements to individual hardware components.

Overall, the reviewed evidence demonstrates that pulse oximetry accuracy depends on a complex interaction among optical physics, biological variability, electronic instrumentation, and computational signal analysis. While conventional pulse oximeters provide reliable monitoring for most routine clinical applications, emerging challenges associated with diverse patient populations, wearable healthcare, and continuous remote monitoring require more sophisticated sensing technologies. Future research is therefore expected to focus on adaptive multi-wavelength optical systems, artificial intelligence-based signal interpretation, personalized calibration strategies, and physics-informed computational models capable of reducing measurement bias while improving the reliability and inclusiveness of non-invasive blood oxygen saturation monitoring systems.

3.4. Recent Technological Advances in Pulse Oximetry

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Recent advancements in pulse oximetry have significantly enhanced the accuracy, portability, and clinical applicability of non-invasive oxygen saturation monitoring. The reviewed literature indicates that the integration of multi-wavelength optical sensors, advanced digital signal processing, artificial intelligence (AI), and Internet of Things (IoT) technologies has substantially improved measurement performance under challenging physiological conditions. Machine learning algorithms have demonstrated considerable potential for reducing motion artifacts and enhancing signal interpretation, while wearable pulse oximeters enable continuous real-time monitoring in both clinical and home healthcare settings. Furthermore, cloud-based healthcare platforms facilitate remote patient monitoring and early clinical intervention through wireless transmission of physiological data. These technological developments demonstrate that modern pulse oximetry has evolved from a conventional monitoring device into an intelligent biomedical sensing system capable of supporting personalized and remote healthcare services (Hamida et al., 2021; Fadhilah & Faiza, 2024).

3.5. Future Challenges and Research Directions

Despite substantial technological progress, several challenges remain in achieving highly accurate and equitable pulse oximetry measurements across diverse patient populations. The reviewed studies emphasize that measurement bias associated with skin pigmentation, abnormal hemoglobin species, low peripheral perfusion, and motion artifacts continues to limit the reliability of conventional dual-wavelength pulse oximeters. Future research should therefore focus on the development of multi-wavelength optical sensing, physics-informed computational modeling, adaptive calibration algorithms, and artificial intelligence-based signal interpretation to improve measurement robustness and reduce clinical bias. In addition, further integration with wearable technologies and IoT-based healthcare systems is expected to support continuous physiological monitoring and precision medicine. Overall, these advances will contribute to the development of next-generation pulse oximeters that are more accurate, reliable, and inclusive for diverse clinical applications and patient populations (Li et al., 2022; Fawzy et al., 2023).

IV. CONCLUSION

This review comprehensively analyzed the physical principles underlying pulse oximetry from an electromedical engineering perspective by integrating concepts of optical physics, photoplethysmography, biomedical signal processing, and recent technological developments. The synthesized literature demonstrates that pulse oximetry fundamentally relies on the interaction between dual-wavelength optical absorption and pulsatile blood volume changes, enabling non-invasive estimation of arterial oxygen saturation through the Beer–Lambert law and photoplethysmographic principles. However, measurement performance remains strongly influenced by multiple physical and physiological factors, including motion artifacts, ambient light interference, peripheral perfusion, skin pigmentation, abnormal hemoglobin species, and electronic noise, all of which contribute to measurement uncertainty under clinical conditions. Recent advances in multi-wavelength optical

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sensing, artificial intelligence, digital signal processing, wearable technologies, and Internet of Things (IoT)-based healthcare systems have significantly improved the capability of pulse oximeters to provide more accurate, reliable, and continuous physiological monitoring. Nevertheless, further research is required to develop adaptive calibration strategies, intelligent signal-processing algorithms, and physics-informed computational models capable of minimizing measurement bias while improving inclusiveness across diverse patient populations. Overall, this review provides a comprehensive theoretical framework that bridges optical physics and electromedical engineering, thereby supporting future research and the development of next-generation pulse oximetry systems with enhanced clinical performance and broader healthcare applications.

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REFERENCES

[[1] N. Arifah, E. Purwanti, and S. Sunarno, "Analisis sensor pulse oximetry MAX30100 pada sistem pemantauan SpO_2 berbasis Arduino," Jurnal Fisika dan Aplikasinya, vol. 19, no. 2, pp. 45–52, 2023, doi: 10.12962/j24604682.v19i2.14123.

[2] N. Fadhilah and R. Faiza, "Pengembangan sistem monitoring saturasi oksigen berbasis IoT menggunakan sensor MAX30102," Jurnal Teknologi Informasi dan Ilmu Komputer (JTIIK), vol. 11, no. 1, pp. 1–8, 2024, doi: 10.25126/jtiik.2024111234.

[3] A. Fawzy, T. D. Wu, K. Wang, L. G. Martin, S. Mandal, P. Oz, and D. L. Bhatt, "Racial and ethnic discrepancy in pulse oximetry and delayed identification of treatment eligibility among patients with COVID-19," JAMA Internal Medicine, vol. 183, no. 7, pp. 730–738, 2023, doi: 10.1001/jamainternmed.2023.1704.

[4] S. T. Hamida, K. Ahmed, M. Al-Jumaily, and J. Schmidtke, "Intelligent health monitoring system based on IoT with decision making using machine learning and neural network," Electronics, vol. 10, no. 21, Art. no. 2690, 2021, doi: 10.3390/electronics10212690.

[5] U. Hasanah, R. Setiawan, and B. S. Wibowo, "Pengolahan sinyal digital pada pulse oximeter: Reduksi noise dan peningkatan akurasi," Jurnal Elektro dan Telekomunikasi Terapan (JETT), vol. 10, no. 1, pp. 1256–1265, 2023, doi: 10.25124/jett.v10i1.4321.

[6] X. Li, J. Zhang, and J. Sun, "Advances in light transport modeling for non-invasive optical biosensors," Biosensors and Bioelectronics, vol. 197, Art. no. 113785, 2022, doi: 10.1016/j.bios.2021.113785.

[7] A. M. Luks and E. R. Swenson, "Pulse oximetry for monitoring patients with COVID-19 at home: Potential pitfalls and practical guidance," Annals of the American Thoracic Society, vol. 17, no. 9, pp. 1040–1046, 2020, doi: 10.1513/AnnalsATS.202005-418FR.

[8] E. Rahmawarni and H. Harmadi, "Rancang bangun pulse oximeter digital berbasis mikrokontroler ATMega328 dengan sensor MAX30100," Jurnal Fisika Unand, vol. 10, no. 3, pp. 314–321, 2021, doi: 10.25077/jfu.10.3.314-321.2021.

[9] F. Ramadhan, M. Kusriyanto, and E. N. Indra, "Sistem monitoring SpO_2 dan suhu tubuh berbasis IoT untuk pasien COVID-19 isolasi mandiri," Jurnal Nasional Teknik Elektro dan Teknologi Informasi (JNTETI), vol. 11, no. 2, pp. 107–115, 2022, doi: 10.22146/jnteti.v11i2.2456.

[10] U. Salamah, M. Z. Arief, and A. B. Prasetyo, "Desain alat ukur SpO_2 dan denyut jantung berbasis fotopletismografi untuk monitoring pasien," Jurnal Teknik Elektro, vol. 12, no. 2, pp. 53–60, 2020, doi: 10.9744/jte.12.2.53-60.

[11] M. Sharma, K. Barbosa, V. Ho, D. Griggs, T. Ghosh, P. Krishnamurthy, and P. Bhatti, "Wearable-based pressure injury prevention using deep learning-enabled photoplethysmography," IEEE Journal of Biomedical and Health Informatics, vol. 26, no. 1, pp. 108–117, 2022, doi: 10.1109/JBHI.2021.3056167.

[12] M. W. Sjoding, R. P. Dickson, T. J. Iwashyna, S. E. Gay, and 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.
[13] T. Tamura, "Current progress of photoplethysmography and SpO_2 for health monitoring," Biomedical Engineering Letters, vol. 11, no. 2, pp. 129–145, 2021, doi: 10.1007/s13534-021-00195-2.
[14] World Health Organization, *Pulse Oximetry: Expanding Access and Ensuring Quality Use*. Geneva, Switzerland: World Health Organization, 2022. [Online]. Available: https://www.who.int/publications/i/item/9789240048119
[15] L. Yu, Y. Shang, R. Srinivasan, and G. Yu, "Cerebral near-infrared spectroscopy (NIRS) for perioperative monitoring of brain oxygenation in children and adults," Cochrane Database of Systematic Reviews, no. 6, Art. no. CD010947, 2021, doi: 10.1002/14651858.CD010947.pub3.

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