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Research Article

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Racial Bias in Pulse Oximetry: The Role of Hemoglobin Variants and Microvascular Physiology in Pulse Oximetry Disparities

Precious Ochuwa Imokhai, B.S.[1]*, Jenny W. Zhang, B.S.[2], Karen Jiang, BSN.[3], Jia Tian[4], Sarah Kazemeini, B.S.[5], Sai Bhargav Vuppala, B.S.[6], Julia Vinagolu-Baur, MS, MBA[7], Kelly Frasier, DO., MS[8]

[1,2,4,6]Rocky Vista University Montana College of Osteopathic Medicine, Billings, MT, USA
[3]Rocky Vista University Colorado College of Osteopathic Medicine, Parker, CO, USA
[5]Kirk Kerkorian School of Medicine at UNLV, Las Vegas, NV
[7]Norton College of Medicine, SUNY Upstate Medical University, Syracuse, NY, USA
[8]Northwell Health Department of Dermatology, New Hyde Park, NY

***Corresponding Author:** Precious Ochuwa Imokhai, 4130 Rocky Vista Way, Billings, Montana, USA 59106. Email: poimokhai@gmail.com

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Abstract

The medical device pulse oximetry remains crucial for patient care in operating rooms, intensive care units, and outpatient facilities but produces inaccurate readings of oxygen saturation in patients with darker skin tones. The traditional explanation of melanin absorption as the main cause of SpO_2 inaccuracies has been disputed by new evidence showing biological factors such as hemoglobin variants and vascular physiology and perfusion differences contribute to these measurement errors. However, these factors remain underexplored.

This review evaluates the impact of hemoglobinopathies (such as sickle cell trait, beta-thalassemia, and methemoglobinemia) on pulse oximeter accuracy because these conditions modify light absorption and oxygen-binding properties, which may worsen measurement errors. Racial variations in microvascular function through capillary density and endothelial responses and vasoconstriction mechanisms could influence SpO_2 signal processing, especially during low-perfusion conditions. The combination of melanin with hemoglobin variants and vascular differences creates a higher risk of undetected hypoxemia in patients with darker skin tones. The current pulse oximeter calibration standards fail to properly address physiological variations between different racial and ethnic groups, which creates doubts about device precision and clinical safety. The FDA and WHO regulatory agencies do not require testing for racial bias during pulse oximeter validation even though such disparities exist.

This review integrates non-melanin-related causes of SpO_2 inaccuracies while identifying research gaps and proposing solutions that include multi-wavelength sensors and AI-driven calibration and improved regulatory policies. The advancement of medical technology with equitable standards requires addressing these gaps to enhance clinical decision-making and protect patient safety throughout all population groups.

Keywords: hypoxemia, skin pigmentation, pulse oximetry, perfusion, diagnostic bias, sickle cell disease, thalassemia, carboxyhemoglobin, methemoglobinemia

Introduction

The noninvasive technique of pulse oximetry measures arterial oxygen saturation (SpO_2) and it serves as a vital tool across perioperative care and ICU and outpatient facilities. The perioperative setting requires pulse oximetry to monitor oxygenation levels during anesthesia and recovery phases so healthcare providers can identify hypoxemia early for prompt intervention. Pulse oximetry shows promise in lowering hypoxemia rates in operating and recovery rooms, according to Pedersen et al. (2014), but its impact on patient mortality and morbidity remains unclear.[1] The ICU uses pulse oximetry as its standard tool for continuous patient monitoring of critical cases because it delivers essential real-time data for ventilated patient care. The SpO_2/FiO_2 diagrams and photoplethysmography-derived signals serve advanced ICU functions to evaluate gas exchange and shunt and ventilation/perfusion mismatch.[2] Outpatient facilities use pulse oximetry to track patients who have chronic respiratory diseases such as COPD and sleep apnea. Portable and wearable pulse oximeters have advanced remote monitoring capabilities that enable healthcare providers to detect hypoxemia early and reduce hospital admission rates.[3]

The fundamental operation of pulse oximetry depends on the absorption of light at wavelengths of 660 nm (red) and 940 nm (infrared). The technique depends on the unique absorption characteristics of oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (Hb) because deoxygenated hemoglobin absorbs red light more strongly than oxygenated hemoglobin absorbs infrared light.[4] A pulse oximeter measures light absorption fluctuations during cardiac cycles through a pulsatile vascular bed, which includes locations such as fingertips and earlobes.[5] The device uses photodetectors to measure transmitted light intensity before applying the Beer–Lambert law to calculate red-to-infrared light absorption ratios. The calculated ratio enables the estimation of oxygenated hemoglobin percentage in arterial blood.[6] The calibration process of these devices takes into account tissue-specific variables such as light scattering and path length, but measurement accuracy remains susceptible to external factors including motion artifacts and poor perfusion and abnormal hemoglobins.[7] Research now indicates that skin pigmentation affects measurement precision which leads to healthcare

disparities between different racial groups.[8] This review aims to examine the physiological and technological limitations of pulse oximetry that may contribute to racial disparities in care. Specifically, it will explore the impact of hemoglobin variants on SpO_2 accuracy, assess vascular and microcirculatory differences between racial groups, evaluate calibration limitations in device design, and discuss potential regulatory and technological strategies to address these disparities and improve diagnostic equity.

Hemoglobin Variants and Their Impact on SpO_2 Readings

Hemoglobin is an important protein that carries oxygen in red blood cells, and hemoglobinopathies such as sickle cell disease (SCD) can cause the production of a dysfunctional or altered protein. Inaccurate SpO2 readings can occur due to alterations in light absorption, thus making it important to examine the variability in oximeter accuracy with individuals of hemoglobinopathies across different racial groups. For example, in the United States (US), SCD is not equally distributed, with a recent study reporting 90% of those hospitalized for SCD being Black.[9] In addition, in recent newborn screening programs across the US, SCD affected approximately one in every 350 non-Hispanic Black newborns, equating to a birth prevalence of 28.54 per 10,000 live births.[10] The impact of hemoglobinopathies, along with the findings that individuals with darker skin pigmentation impact the accuracy of pulse oximetry, is a phenomenon that further increases the risk of undetected hypoxemia in this population.[11] One study revealed inaccurate pulse oximetry readings in approximately 12% of darker-skinned individuals compared to 4% in fair-skinned individuals.[11] The discrepancy in pulse oximetry readings raises questions regarding the impact of skin color on the pulse oximeters in determining the accurate SpO2 readings of individuals with hemoglobin variants.

A functional hemoglobin found in the body is named as HbA whereas if a mutation were to occur in the β-globin gene due to a hemoglobinopathy disease like SCD, it can result in an abnormal hemoglobin shape like hemoglobin S (HbS). When there are low oxygen levels, the HbS can undergo dramatic changes to its shape causing an almost crescent-like appearance that obstruct blood flow, reduce tissue oxygenation and alter the optical properties of blood.[12] In addition, in low oxygen levels, there is a shift in the Soret band- the main absorption peak of hemoglobin- from approximately 414nm to 430nm, a difference of 16nm.[13] When combined with factors such as, skin colour and SCD, a difference of 16nm in wavelength can impact the absorption spectra of pulse oximeters.

The clinical implications of these findings are particularly concerning in hospital settings, where treatment decisions—such as the initiation of certain treatments like oxygen, or the underlying symptoms for diseases—are relied heavily on SpO_2 readings. In a study of around 39 pulse oximetry measurements in ambulatory settings, 33 SCD patients showed SpO_2 inaccuracies, especially when the pulse oximeter values dropped below 93%.[14] Given that SCD patients have impaired oxygen transport due to abnormal hemoglobin, inaccurate SpO_2 readings can lead to delayed recognition of hypoxia, misdiagnosis, and unequal care.

Blood disorders known as Thalassaemias cause patients to develop low hemoglobin levels and reduced oxygen delivery capacity. Alpha and beta represent the two primary thalassaemia forms because normal hemoglobin exists from two protein chains. The β-thalassemia form exists predominantly in Mediterranean populations whereas alpha-thalassemia and beta-thalassemia dominate Southeast Asia and Africa.[15] The smaller number of operational hemoglobin molecules in affected people results in insufficient tissue oxygen delivery. Normal or inaccurately elevated SpO2 readings may show up on pulse oximeters. Pulse oximeters calculate oxygen saturation through hemoglobin oxygen binding ratios instead of total hemoglobin concentrations which results in this discrepancy. Limited research exists regarding how beta-thalassemia and alpha-thalassemia directly impact pulse oximeter accuracy measurements. The modified hemoglobin structure present in these diseases may influence how pulse oximeters display readings. The formation of HbH and Hb Barts in α-thalassemia produces tetramers with modified oxygen binding properties. The beta4 structure of HbH and the gamma4 structure of Hb Barts display extreme oxygen affinity which causes them to poorly transport oxygen.[16] The tetramers might create errors in pulse oximetry readings because they disrupt the measurement process. The SpO2 interpretation becomes challenging because fetal hemoglobin (HbF) levels tend to rise in beta-thalassemia and related hemoglobinopathies because HbF binds oxygen more tightly. Pulse oximetry can produce inaccurate readings of oxygen saturation because hemoglobin becomes less willing to release oxygen to tissues.[16] A Tanzanian patient cohort study revealed that the increase in HbF levels commonly found in patients with milder SCD forms resulted in higher pulse oximeter SpO2 readings.[17] Thalassemia patients require careful evaluation of their SpO_2 readings.

Methemoglobinemia represents a blood disorder which creates methemoglobin (MetHb) as a non-oxygen-binding form of hemoglobin through the oxidation of hemoglobin iron from its normal ferrous (Fe^{2+}) state to ferric (Fe^{3+}) iron.[18] The accumulation of MetHb in blood reduces total oxygen delivery capacity while preventing oxygen from reaching tissues. MetHb shows distinct light absorption characteristics which disrupts pulse oximetry readings causing low readings when the SpO2 is greater than 85% but providing high numbers when the SpO2 is actually low.[18] Because pulse oximeters can only recognize normal hemoglobin forms, the MetHb in the blood can lead to inaccurate readings.

Carboxyhemoglobin forms instead of oxyhemoglobin (HbO_2) when carbon monoxide binds to hemoglobin.[19] The main problem occurs because COHb has the same light absorption pattern at 660 nm as oxyhemoglobin which leads oximeters to incorrectly identify COHb as functional oxygenated hemoglobin. The inability of pulse oximeters to detect HbO_2 and COHb as different compounds results in incorrect SpO_2 readings that show elevated or normal values despite severe tissue hypoxia. The clinical presentation of patients with carbon monoxide poisoning shows normal SpO_2 readings that mask their critical oxygen delivery deficiency.[19]

The clinical use of pulse oximetry remains poorly evaluated for patients with hemoglobinopathies and their diverse effects between racial groups while new technologies and population changes are not considered. Most pulse oximeters are calibrated with healthy individuals with normal levels. Standard pulse oximeter readings are unreliable in these populations because the assumptions do not hold in patients with hemoglobin variants such as HbS, HbF, or MetHb. A further source of diagnostic bias involves skin pigmentation. Evidence often

provides falsely high SpO_2 readings in individuals with darker skin.[11] Conventional pulse oximeters operate on the assumption that the only forms present are oxyhemoglobin and deoxyhemoglobin and thus have difficulty identifying dysfunctional or abnormal hemoglobins. When using pulse oximetry on patients with hemoglobinopathies, their results must be interpreted with attention and care.

Microvascular Physiology and Pulse Oximetry Accuracy

The absorption of light during pulse oximetry depends heavily on capillary density together with microcirculatory perfusion. The distribution of capillaries, which results from genetic factors, developmental processes, and environmental conditions, affects optical path length and light absorption. These physiological differences may contribute to variability in readings across racial and ethnic groups. Systematic reviews have linked increased rates of occult hypoxemia in patients with darker skin to differences in microvascular characteristics.[20] Additionally, studies conducted in urban and intensive care settings using high-fidelity paired oxygenation assessments have shown that low perfusion states can disproportionately impact SpO_2 readings in racial minority patients.[21] The risk of clinical errors in vulnerable populations increases because small differences in capillary density produce measurement inaccuracies in oxygen saturation.[22]

The endothelium controls vascular tone by means of vasodilation and vasoconstriction through the production of nitric oxide (NO). New evidence shows that NO availability and endothelial responsiveness differ between races, which could explain why peripheral oxygen delivery varies between different racial groups. In populations with reduced NO production, enhanced vasoconstriction during physiological stress or cold exposure may decrease local perfusion, thereby impairing pulse oximeter signal quality.[23] Because pulse oximeters rely on pulsatile blood flow, these endothelial dynamics further affect accuracy. As a result, individuals with altered vasoregulatory responses may display disproportionately low SpO_2 readings despite normal arterial oxygenation levels.[22]

Autonomic regulation of blood flow also appears to vary across racial groups, possibly due to differences in thermoregulatory responses. Some populations are more likely to experience colder extremities, potentially linked to unique patterns of autonomic and metabolic regulation. This can reduce finger perfusion—where pulse oximeters are typically placed. In cold conditions, this vasoconstriction-induced reduction in perfusion has been shown to contribute to lower oxygen saturation readings.[22] The combination of inadequate blood flow with microvascular congestion during critical illness can worsen measurement errors that stem from temperature fluctuations. Research indicates that minority patients experience higher rates of undiagnosed hypoxemia during acute illness.[21]

Low blood flow—such as during shock, severe infection, or fluid loss—is known to interfere with the signal used by pulse oximeters. When perfusion to small vessels is limited, the resulting weak light signal can distort waveforms and compromise oxygen saturation reliability.[22, 24] Research also suggests that minority patients are more likely to experience conditions affecting capillary function and microcirculation, increasing the likelihood of inaccurate readings.[25] When reduced blood flow is combined with devices that were not calibrated with diverse populations in mind, the risk of occult hypoxemia increases—potentially delaying diagnosis and treatment in already at-risk populations.[21, 24]

Cold exposure leads to decreased pulse oximetry reliability because vasoconstriction and poor peripheral perfusion occur simultaneously. The autonomic nervous system responds to decreasing ambient temperatures by inducing vasoconstriction, which reduces blood flow to peripheral tissues—where oximeter sensors are usually placed.[26] This decreased perfusion weakens the optical signal and increases the likelihood of SpO_2 measurement errors. Studies indicate that microvascular differences between racial and ethnic groups affect vasoregulatory responses because of variations in endothelial function and microvascular physiology.[26] The same pulse oximeter under identical environmental conditions produces varying readings between populations which could lead to disparate clinical results for people with unique thermoregulatory characteristics.

Studies consistently show that pulse oximetry accuracy varies by race, largely due to low perfusion states and temperature-induced vasoconstriction. Systemic illness further increases the risk of oxygenation misclassification in minority populations, as intrinsic microvascular differences affect how light is absorbed during SpO_2 measurement.[24] Autonomic and thermoregulatory variations across racial groups add to the problem—especially when environmental temperatures shift.[26] The combination of physiological and environmental factors amplifies disparities in hypoxemia diagnosis and management, underscoring the need for racially inclusive calibration algorithms in pulse oximeter technology.

Despite growing awareness of these issues, research on how microvascular function interacts with oximeter performance remains limited. Most existing studies have focused primarily on skin pigmentation as the main cause of measurement bias, without fully exploring other physiological contributors. The research gaps identified here highlight the need for a more comprehensive framework—one that integrates clinical data, microvascular assessments, and device recalibration strategies—to advance pulse oximetry toward greater diagnostic equity.

Interaction Between Melanin, Hemoglobin, and Vascular Factors

Pulse oximeters are a commonly utilized medical tool to estimate blood oxygen saturation (SpO_2) in patients. However this tool has proven to display inaccuracies especially when used on patient's of a darker skin tone. Various medical diagnoses such as hemoglobin variants and anemia along with skin pigmentation all contribute to inaccuracies in pulse oximeters. It is vital that healthcare providers understand how these factors contribute to inaccurate metrics in order to properly conduct clinical assessments and administer prompt treatment.[27] Studies have shown that pulse oximetry devices continuously overestimate oxygen saturation especially in individuals with darker skin tones. This difference is caused primarily by an elevation in melanin levels which tends to absorb an increased amount of red light. This can interfere with the pulse oximetry device's ability to read signals. Overestimation of SaO2 (arterial oxygen saturation) is also noticeable especially in patients whose SaO2 levels are lower than 90%.[28] This poses a threat to the healthcare system as undetected hypoxemia in patients can result in delayed treatment and negative outcomes.

Furthermore, disease processes such as methemoglobin and carboxyhemoglobin, can also affect pulse oximeter accuracy. Both of these processes not only impact the ability of the pulse oximeter to absorb light but also this can lead to inaccurate readings of oxygen saturation.[29] A prominent example is in methemoglobinemia which can cause Sa02 readings to plateau at approximately 85% regardless of the patient's real oxygen saturation. A possible explanation for the discrepancies in these pulse oximetry readings can be due to the original manufacturing and testing of pulse oximetry products. During the original production of pulse oximetry devices, the products were calibrated and tested predominantly on light-skinned individuals, leading to inaccuracies when used on patients of increased melanin.[30]These systemic biases in healthcare technology have resulted from the historical exclusion of diverse people in pulse oximetry testing. In particular patients of African descent and Indigenous patients are disproportionately affected by the persistence of clinically significant misestimations caused by the failure to modify calibration algorithms based on melanin absorption kinetics. This emphasizes the necessity of enforcing regulations that demand diverse representation in trials for medical devices. Pulse oximeters are proven to have inaccuracies yet are still utilized daily to assess for patient oxygenation status and determine treatment modality. These inaccuracies contribute to the racial disparities in the healthcare industry and reflect a history of systemic bias.

In addition, factors such as low perfusion, impact light's ability to both absorb and scatter altogether. Low perfusion not only diminishes the pulsatile component detected but it also reduces signal strength, all of which increase the likelihood of measurement errors. Melanin, the pigment that makes up skin color, in increased amounts also absorbs an increased amount of red light.[31] Factors such as low perfusion and melanin all increase the inaccuracies of SpO2 readings and when combined lead to a compounded effect.[32]Furthermore, health conditions such as anemia, decreased hemoglobin levels, have also an increased prevalence among racial groups such as African Americans (47.2%) and American Indian/Natives (42.9%) in contrast to the general population (26.8%). The large differences in statistics between ethnic racial groups and the general population showcase how this can be exacerbated for patients with more melanin.[33] In addition, studies have shown that African American populations have nearly twice the risk of experiencing occult hypoxemia when compared to Caucasian populations.[34] This means that for patients who are anemic and belong to one of the racial groups that are already impacted by inaccurate readings due to their darker skin tones, this can only further delay necessary treatments.

Overestimation of oxygen saturation by darker skin patients not only leads to delay in detection and treatment of hypoxemia but also results in poorer patient outcome. A study comparing pulse oximeter readings with arterial blood gas measurements identified that Black patients were three times as likely as White patients to have low oxygen saturation that would not be detected by pulse oximeter readings. The coincidence of increased anemia prevalence in patients with increased melanin and the limitation of the sensitivity of pulse oximetry in dark-skinned individuals suggests a compounded risk. This emphasizes the need for clinicians to consider these when assessing actual oxygenation status in such groups. It also promotes adding other more direct hemoglobin and oxygenation measurements to prevent erroneous evaluations.[35]This necessitates appropriate evaluation of oxygenation in these patients by clinicians using more direct methods to measure hemoglobin and oxygen's bound form in tissues to enable accurate assessment.[35] In addition, calibrating pulse oximeters for diverse skin tones and varying hemoglobin constituents is crucial to provide reliable oxygen saturation readings for all patients.

Not only is saturation overestimated in darker skin, thus postponing the identification of hypoxemia, but it also worsens patient outcomes. Since most clinical trials and validations were conducted on white patients, the devices were statistically optimized for the optical properties of light skin. This does not take into account how a darker skin patient would scatter and absorb light differently. An increase in melanin absorbs additional red and infrared wavelengths, which interferes with the accuracy of these measurements.[36] Of note is the fact that certain information regarding ethnicity in product development of pulse oximeters by companies such as Masimo corporation, one of the largest companies working on pulse oximetry, were not typically provided. Instead, much of the earliest research in pulse oximetry, including work conducted by Masimo, often involved predominantly white populations in product testing. This has been a consistent issue across many medical devices, in which early development prototypes were conducted on individuals with pale skin. This lack of diversity among trial subjects for medical products has been recognized more within the past few years. Therefore, current pulse oximetry devices on the market all consistently omit the fact that patients with darker skin scatter and absorb light differently. More melanin absorbs more red and infrared wavelengths, and this distorts the accuracy of the readings.[36]

Disease states like hemoglobinopathies have also been a cause of inaccurate Spo2 values. A common occurrence is despite patients presenting within the normal range of Spo2 values they were actually undergoing hypoxic events which only made clinical decision-making more challenging.[37] Furthermore, some disease states like sickle cell disease, impact the oxygen-carrying capacity as well as the light-absorbing capacity of hemoglobin. These distort the optical reading by pulse oximeters and cause deceptive SpO_2 readings. Other significant factors to consider like impaired blood flow due to vasoconstriction and reduced cardiac output further reduce the readings of pulse oximeter sensitivity.[37] This adds to reduced signal intensity and increased reading errors. Accumulation of these factors cumulatively increase the likelihood of SpO_2 false reading leading to faulty quantification of true oxygenation status. Perception and comprehension of these constraints are critical to healthcare professionals so they can make decisions regarding patient status effectively.

During the COVID-19 pandemic, pulse oximetry inaccuracy was especially prominent. Accurate SpO_2 readings were critical for triage of ventilator support but the intrinsic inaccuracies of pulse oximeters in individuals with darker skin pigmentation may have resulted in misclassification of patient oxygenation status. This had implications for ventilator allocation decisions.[38] Overestimation of oxygen saturation may have resulted in underestimation of patient severity with a possibility of inadequate respiratory support. This is demonstrated in a retrospective study of over 7,000 COVID-19 patients that showed pulse oximeters overestimated the blood oxygen levels in nonwhite patients, leading to differences in patient eligibility

for COVID-19 equipment and treatment.[39] These are important and serious concerns to be prevented to prevent further racial disparities in healthcare, especially in circumstances which rely on these types of measurements for treatment and resource allocation.

Limitations of Current Pulse Oximeter Calibration Standards

Although pulse oximeters are widely used devices that clinicians rely on, current calibration standards have limitations that should be addressed. One major issue is the lack of transparency from manufacturers about the demographics of participants included in their device testing.[40] Because it's challenging to determine how well pulse oximeters perform across different patient populations, this raises concerns about hidden biases and potential inaccuracies. Current FDA guidelines recommend including at least 2 darkly pigmented subjects or 15% of the study group in premarket studies.[41] However, this recommendation is based on U.S. census racial data rather than actual skin tone diversity across the population. Additionally, the FDA does not require manufacturers to explicitly test for racial bias when approving these devices. A recent article emphasized that earlier guidelines had limited requirements for racial and skin-tone diversity.[42] This can contribute to problems with clinical accuracy in individuals with darker skin

Subjective scales like the Fitzpatrick scale are often applied inconsistently in studies. This may lead to challenges in accurately assessing skin pigmentation. A recent study reinforces that Fitzpatrick scale's emphasis on lighter skin tones.[43] Objective measurement tools such as colorimeters and spectrophotometers should be utilized in place of these subjective scales. Various melanometry approaches also found that objective tools offer a more reliable way to measure skin tone.[44] This ultimately improved the accuracy of pulse oximeter calibration and assessment, and implementing these objective methods in place of subjective scales can improve the reliability of skin tone assessments in device calibration.

Another limitation comes from calibration issues in pulse oximetry have been shown to contribute to racial disparities in measurement accuracy. Black patients are more likely to have undetected hypoxemia despite normal SpO_2 readings.[45] Many pulse oximeters were initially calibrated using data from primarily light-skinned individuals, which means they do not account for the way melanin affects light absorption. In patients with darker skin, this can lead to overestimation of oxygen levels because the device misreads how much light is absorbed.

Pulse oximeters are typically validated using data from volunteers who are lighter-skinned. This limits the generalizability of device performance across diverse patient populations. Most validation studies involve comparisons to arterial blood gas (ABG) measurements but are often conducted in relatively homogenous groups.[46] Such homogeneity means that calibration may not capture variations caused by physiological or demographic factors, and this can lead to inaccuracies when used on patients whose characteristics differ significantly from the validation group. Recent research has also demonstrated that these validation methods can introduce skin pigmentation biases.[47] This highlights the limitations of current testing protocols which do not fully account for skin pigmentation variability.

Enhancing Accuracy in Pulse Oximetry Through Technological Innovations

To enhance accuracy, advanced pulse oximeters integrate multiple LEDs, typically eight per wavelength, to ensure strong signal capture and consistent reliability. This setup maintains well-balanced red and near-infrared light transmission across the measurement site, leading to more dependable oxygen saturation calculations.[48] Additionally, an integrating sphere has been introduced to provide uniform illumination, improving measurement precision by creating consistent reflections within its coated surface.[49] This evenly distributes light across the tissue, minimizing variability caused by differences in blood flow and skin pigmentation, thereby reducing errors from uneven illumination sources.[50]

Artificial intelligence (AI) and machine learning (ML) technologies are increasingly employed to address inaccuracies in blood oxygen level readings caused by factors such as skin pigmentation differences and movement artifacts. A recent study, Detecting Anomalies in Multi-Wavelength Photoplethysmography Using Artificial Intelligence, introduced an AI system capable of detecting and correcting discrepancies in pulse oximetry signals. The research included participants with varying skin tones to assess their impact on measurement accuracy. The analysis identified key signal characteristics, such as peak count variations and spectral density distribution across frequency bands.[51]

- Peak count reflects the intensity of pulsatile signals linked to each heartbeat, providing insights into blood circulation patterns.
- Peak variance assesses signal stability over time and detects potential fluctuations caused by noise.
- Peak width variability indicates signal consistency by evaluating how peak shapes change over time.
- Mean power spectral density (PSD) estimates signal power variations across frequencies, aiding in anomaly detection.
- Frequency band slope quantifies shifts in power levels between frequency bands, distinguishing physiological variations from background noise.

The AI system employed a combination of decision trees, random forests, support vector machines, and k-nearest neighbor algorithms to identify and rectify signal anomalies. This approach improved SpO_2 accuracy by 20–30%, particularly benefiting individuals with darker skin tones, who are more affected by pulse oximetry errors.[52]

Another study, Examining the Impact of Pulse Oximetry Inaccuracy on Machine Learning in Real-Life Situations, investigated how inaccuracies in SpO_2 readings affect the performance of ML models in clinical decision-making. Researchers compared models trained on arterial blood gas (SaO_2) values versus those using pulse oximetry-derived SpO_2 values. The findings revealed that relying solely on SpO_2 readings compromised model accuracy, especially in predicting hypoxemia in patients with darker skin tones. The study emphasized the need for ML calibration techniques that adjust SpO_2 values in real-time to account for patient-specific factors.[53]

Recent advancements in photoplethysmography (PPG) have focused on reducing measurement errors stemming from melanin absorption and variations in blood perfusion. One promising approach involves utilizing alternative wavelength combinations that better penetrate melanin while maintaining high sensitivity to blood oxygenation changes.[54] Additionally, researchers have explored PPG techniques that integrate both reflectance and transmittance modes to mitigate signal distortions caused by melanin concentration.[54]

Another innovative approach involves adaptive signal processing methods that dynamically adjust for perfusion-related variations by modifying signal parameters in response to real-time physiological feedback.[53] These methods analyze PPG signal patterns to detect inconsistencies and counteract disturbances caused by fluctuations in tissue perfusion levels.

Improving pulse oximetry accuracy also requires clinical trials that include racially diverse populations with varying skin tones and hemoglobinopathies. Many existing studies have predominantly focused on individuals with lighter skin tones, which can lead to disparities in device performance.[54] Without validation studies that accurately represent diverse populations, pulse oximetry devices may inadvertently contribute to healthcare inequities by failing to account for melanin-related absorption differences and variations in vascular physiology. During the creation of pulse oximeters, most devices were developed and calibrated using data from people of lighter skin tones. This directly contributes to the devices being less accurate for individuals with darker skin tones.[55] To combat these issues, the FDA has proposed new guidelines for pulse oximetry manufacturers. These guidelines state that clinical trials should include at least 150 people with varying skin tones, which ensures at least 25% of the trial data includes people with darker skin tones.[55] These changes should help to identify problems with the accuracy of pulse oximeter devices in all populations before they are distributed.

Conclusions

This review indicates that hemoglobin variants and differences in vascular physiology can shape disparities in pulse oximetry readings. Variants such as sickle cell trait and carboxyhemoglobinemia can interfere with how pulse oximeters interpret light absorption. Racial differences in vasoconstriction responses can also affect readings, and these biological factors contribute to a higher risk of occult hypoxemia in racially diverse populations. Despite these known differences, current device calibration methods have shown to be inadequate in diverse populations. Many devices are tested on limited and homogeneous populations, and this has led to an overestimation of oxygen levels in patients who are already more likely to be affected by hemoglobinopathies including sickle cell trait. This lack of validation raises concerns about clinical accuracy. The development of multi-wavelength sensors and artificial intelligence-driven calibration models show promise in improving measurement reliability across patient groups. While these advances may serve as potential solutions, greater transparency and inclusivity in device development is necessary. To ensure that all patients receive accurate and safe care, researchers and manufacturers should prioritize equity in technology design and development.

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