Optics in Pulse Oximetry: Correlation with Oxygen Saturation Accuracy

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Abstract:
Non-invasive oximetry is essential for continuous blood oxygen monitoring in routine and critical care. Evidence suggests pulse oximeters may be biased by melanin absorption, affecting accuracy in individuals with darker skin. In this prospective study of 100 ICU patients, simultaneous SpO_2 and SaO_2 were recorded, and skin tone was objectively measured using ITA° at dorsal hand site. LED emission spectra were also analyzed. Within the $85\% - 100\% SaO_2$ range, two of the three devices exceeded the 3% ARMS threshold. The most accurate oximeter had a longer-wavelength, narrower-band infrared LED, underscoring the need for optimized optics and objective pigment evaluation.

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***Abstract*—Non-invasive oximetry is essential for continuous blood oxygen monitoring in routine and critical care. Evidence suggests pulse oximeters may be biased by melanin absorption, affecting accuracy in individuals with darker skin. In this prospective study of 100 ICU patients, simultaneous SpO_2 and SaO_2 were recorded, and skin tone was objectively measured using ITA° at dorsal hand site. LED emission spectra were also analyzed. Within the 85%-100% SaO_2 range, two of the three devices exceeded the 3% ARMS threshold. The most accurate oximeter had a longer-wavelength, narrower-band infrared LED, underscoring the need for optimized optics and objective pigment evaluation.**

***Index Terms*—oxygen saturation, pulse oximetry, optical instrumentation, skin colorimetry.**

I. Introduction

Understanding how light interacts with human skin is essential in various medical technologies, including both diagnostic and therapeutic applications [1]. The transmission of light through the skin is primarily affected by its optical behavior, particularly the absorption and scattering coefficients [2]. These optical properties are determined by the skin's composition and are influenced by the concentration of intrinsic chromophores such as melanin, hemoglobin, and water. The interaction of these chromophores with light is complex, and their varying concentrations can significantly impact the performance of noninvasive optical techniques.

Pulse oximetry is a noninvasive and widely applied method to assess arterial oxygen saturation. It relies on the emission of red ($\approx 660nm$) and infrared ($\approx 940nm$) light from two LEDs, both located within the "optical window" (600–$1100nm$), a spectral region where light penetrates tissues more effectively. The oximeter calculates SaO_2 by analyzing the ratio of pulsatile to total transmitted light at these two wavelengths as it passes through tissue such as a fingertip or earlobe [3].

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Although hemoglobin is the primary chromophore that absorbs in these ranges, melanin also absorbs light within this spectrum [4], which may compromise the accuracy of the measurement in individuals with higher concentrations of melanin [5].

In this study, our objective was to investigate the influence of device-related optical factors on oximetry accuracy within the Brazilian population, known for its wide diversity in skin pigmentation [6]. By comparing pulse oximeter readings to arterial blood gas analysis (ABG) as the reference standard, and incorporating both colorimetry for objective skin tone quantification and emission spectroscopy of the devices' LEDs, we sought to evaluate the extent to which skin pigmentation and LED spectral characteristics affect measurement reliability.

II. Methodology

This prospective cross-sectional study was conducted in the adult intensive care unit (ICU) of a tertiary-care hospital to compare arterial oxygen saturation (SaO_2, gold standard by blood gas analysis) with peripheral oxygen saturation (SpO_2) measured by three different pulse oximeter models. Ethical approval was obtained from the Institutional Research Ethics Committee under CAAE 74692423.7.0000.5407 and all participants (or their legal surrogates) provided written informed consent prior to enrollment.

We included 100 patients aged 18 years and older who were admitted to the ICU and performed ABG in 2024 by regular medical prescription. We excluded patients who could not perform finger oximetry due to physical impediment, bandage dressing, or poor peripheral perfusion.

Patients had their oxygen saturation levels measured using both pulse oximetry and arterial blood gas analysis concurrently. Three different ANVISA/FDA approved oximeters were employed for the measurements: finger oximeters G-Tech Oled graph (G-Tech Optoelectronics Corporation, Miaoli, Taiwan) and Multilaser HC023 (Multilaser, São Paulo, Brazil),

and the pulse oximeter Nihon Kohden Life Scope G5 CSM-15000 (Nihon Kohden Corporation, Tokyo, Japan), which is already used at the hospital.

To study the influence of skin tone, colorimetry was performed on the dorsal part of the hand used for oximetry. The device employed was the colorimeter/spectrophotometer Delta Vista 450G (Delta Color, São Leopoldo, Rio Grande do Sul, Brazil) with BCRA Series II calibration certificate, and aperture size of 4 mm. To characterize the skin shades, we utilized the Individual Typology Angle (ITA°) that simplifies the color components into a single parameter, and is calculated using Eq. (1) [7].

$$ITA° = (\frac{180}{\pi})arctan[\frac{(L° - 50)}{b°}] \quad (1)$$

where L* corresponds to the luminosity [0 to 100] and b* to blue and yellow tones [-50 to 50].

To perform LED emission spectroscopy, we used two fiber-optic spectrometers positioned in front of the diodes: the International Light RPS900-R (International Light Technologies, Peabody, MA, USA) and the Avantes AvaSpec-NIR512-1.7-EVO (Avantes BV, Apeldoorn, The Netherlands).

III. Results and Discussion

The statistical analysis for each oximeter in the range of 86-100% SaO_2 is displayed in Table I, and shows that 2 of the 3 do not meet the regulatory authorities requirement (FDA / ANVISA), which is ARMS<3. The mean bias for Nihon Kohden was also smallest, suggesting its readings were closer on average to the arterial blood gas reference, and its narrower limits of agreement imply reduced random error relative to the other two oximeters. Concordance correlation coefficients were highest for Nihon Kohden, reflecting better overall agreement with SaO_2 measurements. The R2 values, which indicates the strength of linear association, were relatively low for all devices, meaning a low correlation between two techniques that measure the same thing.

TABLE I
TABLE 1: COMPARISON OF OXIMETER PERFORMANCE METRICS

Parameter	***Multilaser (n=96)***	***G-Tech (n=99)***	***Nihon Kohden (n=100)***
Wavelength (nm)	670, 910	670, 920	660, 960
ARMS [%]	3.36	3.61	2.91
Mean Bias [%] (95% CI)	1.15 ± 3.18 (0.50, 1.79)	1.45 ± 3.33 (0.79, 2.12)	0.61 ± 2.85 (0.05, 1.18)
Upper LoA (95% CI)	7.37 (6.27, 8.47)	7.97 (6.83, 9.11)	6.21 (5.24, 7.18)
Lower LoA (95% CI)	-5.08 (-6.18, -3.98)	-5.06 (-6.20, -3.93)	-4.98 (-5.95, -4.01)
CCC (95% CI)	0.34 (0.15, 0.50)	0.37 (0.19, 0.53)	0.46 (0.29, 0.64)
R^2	0.14	0.20	0.23

We used the spectrometers described in section II to measure the LED emission spectra of each oximeter. Both red and infrared spectra were fitted to Gaussian curves and are presented in Fig. 1. The most accurate oximeter (Nihon Kohden) exhibited an infrared LED with a longer peak wavelength and a narrower emission bandwidth, and its red LED had a slightly shorter peak wavelength. These observations align with literature showing that narrow and shifted LED spectra can reduce measurement error, especially across diverse skin types [8]. Moreover, as shown in Fig. 2, LEDs with peak wavelengths further from hemoglobin isobestic point ($\approx 800nm$) results in more distinct absorption profiles for HbO_2 and Hb, improving signal separation and oximeter accuracy. In this study, the higher wavelength IR LED resulted in a 32% larger distance between the hemoglobin extinction curves, which may explain the better accuracy of the device. When analyzing the red LED's, we can see that the center wavelengths are closer to each other.

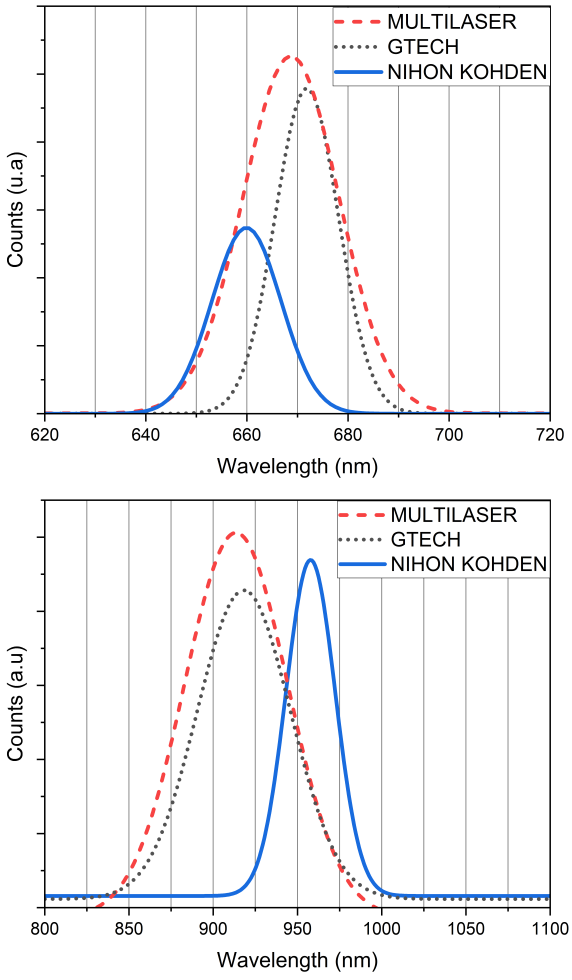

Fig. 1. Gaussian fitting of LED emission (Red and Infrared, respectively) spectra for each oximeter (G-Tech, Multilaser, and Nihon Kohden).

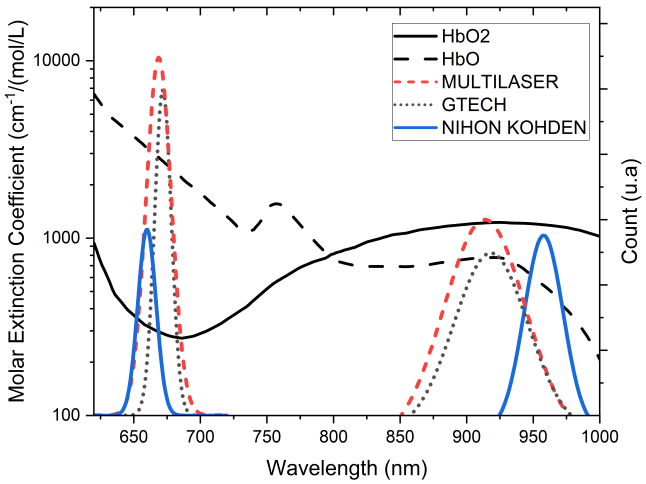

Fig. 2. Molar extinction coefficients of oxyhemoglobin (HbO_2) and deoxyhemoglobin (HbO), overlaid with Gaussian fits of the red and infrared LED emission spectra from each oximeter (G-Tech, Multilaser, and Nihon Kohden). Data available in https://omlc.org/spectra/hemoglobin/summary.html

To study the potential correlation between measurement error and skin tone, the ITA° degree was utilized. The Fig. 3 present the difference between blood gas analysis and oximetry readings as a function of the ITA° degree measured on the dorsal hand used for oximetry. By fitting a linear regression and estimating the difference between the bias at ITA -50° and ITA 50° we can determine the racial bias or differential bias (DB) for each device. The FDA suggest (not require) that the absolute differential bias (ADB) in the range of 85-100% SaO_2 (employed here) may not exceed 2.0%. Therefore, we found a DB on dorsal hand skin of 2.05 ± 1.00%, 2.04 ± 1.04%, -0.15 ± 0.90%, for G-Tech, Multilaser and Nihon Kohden, respectively.

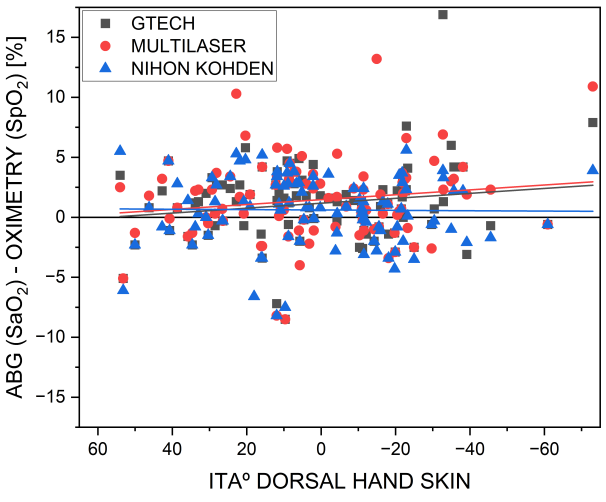

Fig. 3. Bias or difference between arterial blood gas and saturation (SaO_2-SpO_2) measured by oximeters (G-Tech, Multilaser, and Nihon Kohden) in relation to colorimetric ITA° skin tone, measured in dorsal hand region. Higher positive ITA° number represent lighter skin tone and vice versa.

Our study did not find clinically significant racial bias in oximetry measurements, a result that contrasts with findings from other publications in the field [9]. This discrepancy may be due to several important factors. First, many prior studies rely on self-reported race or ethnicity, which introduce subjective biases and inaccuracies. Additionally, multicenter studies that pool oximetry and ABG data from different hospitals can introduce bias because facilities vary in resources, staff training, and patient acuity.

IV. Conclusions

Our findings indicate that two of the three oximeters evaluated did not meet FDA/ANVISA accuracy standards within the 86–100% SaO_2 range, raising concerns about their clinical reliability in critical care. Spectral analysis showed that the best-performing device (Nihon Kohden) featured an infrared LED with a longer peak wavelength and narrower emission bandwidth, known to improve hemoglobin signal separation and overall measurement precision. Also, this device also exhibited the lowest differential bias across dorsal hand ITA° values, suggesting that the extended infrared wavelength may contribute to reduced skin tone–related bias. These findings underscore the importance of refining pulse oximeter optics, particularly LED wavelength selection and spectral bandwidth, to improve accuracy and ensure equitable performance across diverse patient populations.

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