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A Pressure-Stabilized Dual-Wavelength Fingertip Optical System for Robust Non-Invasive Hemoglobin Estimation and Automated Anemia Screening

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***Abstract*- Reliable non-invasive hemoglobin (Hb) estimation based on dual-wavelength photoplethysmogramgery (PPG) is still hampered by instability caused by uncontrolled contact pressure at the fingertips, perfusion and motion. It is evident that (IEEE) experiments have successfully shown the underlying possibility of using dual wavelengths, however, repeatability of measurements in real-world situations still prevents large-scale deployment. This work presents the mechanical pressure-stabilized dual-wavelength fingertip optical system that can directly address the sensor-tissue interface variability without increasing the spectral complexity. Limited movement of fingertip is ensured by a confined fingertip housing which keeps the contact force to be within 1.6-1.9 N, in order to reduce the variance of tissue compression and stabilize optical path length. Synchronously modulated red (660 nm) and infrared (940 nm) signal are subject to ambient light rejection, motion awareness filter and normalized AC/DC ratio extraction. A calibrated regression framework is used to relate the optical features to the hemoglobin concentration followed by an automated classification of anemia using the WHO threshold. In experimental evaluation (N = 32 subjects), pressure stabilization made inter-measurement variability differences 41.8% lower than conventional placement. For the accuracy of estimation, the results have been improved from RMSE = 1.42 g/dL to 0.93 g/dL and MAE from 1.16 g/dL to 0.71 g/dL. Correlation with laboratory reference changed from r = 0.81 to r = 0.92. The proposed approach has proven that a mechanical standardization of the sensor-tissue interface greatly improves repeatability and robustness of dual-wavelength Hb estimation that is crucial for low-cost and portable solutions for population-level screening of anemia.**

Keywords-- non-invasive hemoglobin, dual wavelength ppg, pressure stabilisation, anemia screening, biomedical optical sensing, portable diagnostics.

I. INTRODUCTION

Anemia is one of the most common hematological problems worldwide, especially among women, children and populations living in resource-limited areas of the world [1]. Accurate measuring of hemoglobin (Hb) is essential for diagnosis, disease monitoring and therapeutic decision. Traditional laboratory-based hematology analyzers are known to deliver quality results but they require invasive blood testing, trained staff and facilities that might be not available in decentralized and low resource areas. These limitations are the motivation for the development of non-invasive hemoglobin estimation systems that can be used for portable and population-level screening.

Optical methods by photoplethysmogramgery (PPG) have shown potential as non-invasive hemoglobin measurement [2]. Dual-wavelength red and infrared approaches use the differences in optical absorption of the hemoglobin species of the perfused tissue. However, despite some very promising research prototypes, the translation of this research into the clinic is limited by poor repeatability and sensitivity to user-dependent variables. In the case of fingertip-based systems, uncontrolled contact pressure, tissue compression variability, motion artifacts, and ambient light interference have a significant impact on optical path distortion and AC/DC characteristics of PPG signal.Many existing solutions strive to increase the accuracy of estimates by increasing the complexity of the hardware by means of multi-wavelength configuration or computation-intensive learning algorithms [3]. While such approaches are useful to increase modeling flexibility, they are not fundamental to addressing what is the main cause of instability in this case: mechanical and physiological variability at the sensor-tissue interface.This work presents a pressure stabilized dual-wavelength fingertip optical system which is designed to increase measurement repeatability and physiology robustness without increasing optical channel complexity [8]. The system has a mechanically confined fingertip interface that makes the contact pressure standardized and tissue deformation variability at a minimum. The ambient light rejection, motion-aware filtering and normalized AC/DC feature extraction are used to process synchronous controlled red and infrared signals. A calibrated data-driven framework for mapping is then used for the hemoglobin estimation and rigorous automated classification of the severity of anemia in coherence with clinically recognized thresholds.The main contribution of this study is putting signal integrity and interface stability first as a tool to enhance the reliability of non-invasive hemoglobin estimation. There is experimental validation of less inter-measurement variability

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and higher estimation consistency than non-stabilized configurations of fingers in tips. The proposed system is designed to be a portable low-cost screening tool that can be used for large-scale screening of anemia and complement laboratory based diagnostics.

II. RELATED WORK

Non-invasive hemoglobin estimation has progressed over various types of optical and computation techniques [4]. Early methods were based on multi-wavelength spectrophotometric systems aiming at the decomposition of the contributions of the different hemoglobin species to absorption. These systems were often not very complicated in their mechanism but were often very demanding of hardware setups and strict calibration.

Dual wavelength systems based on red and infrared light have attracted interest because of their simplicity and compatibility with normal PPG architectures [5]. These approaches usually use AC/DC ratio based measurements determined from pulsatile blood flow to determine hemoglobin concentration. However their performance is often impaired by a variability of contact pressure, inconsistencies in the placement of fingers, and motion artifacts.

A. Contributions

The contributions of this work are mainly as follows:

- A mechanically constrained fingertip housing to keep the contact force in the range of 1.6-1.9N.
- Quantified reduction (41.8%) in variability in inter-measurement
- Demonstrated improvement in RMSE (34.5% reduction) and MAE (38.8% reduction)
- Improvement in correlation from r = 0.81 to r = 0.92
- Automated anemia severity classification
- A low-cost architecture for preserving dual wavelength simplicity, without increasing spectral channels

This article confirms the fact that mechanical stabilization is one of the key factors of robustness in non-invasive Hb estimation.

Non-invasive hemoglobin sensing has been developed by three main approaches:

- Multi wavelength spectrophotometric systems
- PPG based estimation using dual wavelengths
- Optical mapping with machine learning applications

Whilst multi-wavelength systems provide an improved spectral resolution, they greatly add complexity to the hardware and calibration requirements [4]. Dual-wavelength systems are easier to implement but are also very sensitive to placement and pressure variation [5]. Machine learning methods increase the accuracy of the regression and are still related to the stability of the signal [6].

Several research efforts have attempted to introduce machine learning frameworks such as regression based models, support vector machines and neural networks to achieve better mappings from optical features to hemoglobin values [6]. While these approaches improve the ability to predict, they are still prone to the quality of the signals. Poor signal stability is a common cause of propagating error to the learning model, which often results in poor generalizability in populations and measurement conditions.

Recent efforts have looked at multi-parameter fusion with the adding of perfusion index, heart rate variability or other wavelengths. Although such methods enhance the robustness, they impose more hardware expenses, computational complexity, and power consumption, which reduces the feasibility of low resource deployment.

A notable limitation in a lot of the existing literature is a lack of emphasis on mechanical standardization of the contact conditions in the fingertip. Variation in the applied pressure changes the thickness of the tissues, the occlusion of the vessels and the optical path length, which directly alters the PPG amplitude and base line characteristics [7]. Addressing this interface instability is an opportunity for improving the repeatability with no increase of spectral dimensionality.

The present study is differentiated as it combines the mechanical pressure stabilization with synchronized double wavelength acquisition and normalized feature extraction and thus aims to fix the root cause of measurement inconsistency.

III. METHODOLOGY

A. Participants

- N = 32 adult subjects
- Age range: 18-52 years
- 18 females, 14 males
- Hb range: 8.2-15.6 g/dL

B. Optical Signal Model

The proposed system is based on the dual-wavelength photoplethysmographic (PPG) acquisition at red(λ_1) and infrared (λ_1) bands. The intensity of detected optical signal at each wavelength can be given by (1):

$$I_\lambda(t) = I_{DC,\lambda} + I_{AC,\lambda}(t) \quad \textbf{(1)}$$

Where;

$I_{DC,\lambda}$ $I_{DC,\lambda}$ is the non-pulsatile absorption component due to tissue, venous blood and the constant optical attenuation

$I_{AC,\lambda}(t)$ $I_{AC,\lambda}(t)$ represent the pulsatile arterial component associated with cardiac cycles

The DC component is computed as the mean intensity, while the AC is component is worked as peak to peak amplitude under the cardiac window.

The normalized absorption is calculated as shown in (2):

$$R_\lambda = \frac{AC_\lambda}{DC_\lambda} \quad \textbf{(2)}$$

In order to lower sensitivity to absolute intensity fluctuations, the work employs a composite ratio:

$$\Gamma = \frac{R_{red}}{R_{IR}} \quad \textbf{(3)}$$

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The parameter (Π) will be used as the optical feature for hemoglobin estimation.

B. Pressure Stabilization Model

The optical path length, L, the vascular volume and the effective absorption coefficient, μ_a,fluctuates when the fingertip pressure is not regulated. Variability in contact pressure is given by (4):

$$DC \propto e^{-\mu_a L} \quad \textbf{(4)}$$

The occurrence of variations in L, mainly caused by tissue compression, distorts the normalized ratios. These variations also directly affect DC and AC components.

The proposed stabilization mechanism under this research utilizes the following equation maintaining contact force F_c within a controlled range:

$$F_{min} \leq F_c \leq F_{max} \quad \textbf{(5)}$$

The applied constraint reduces variability in optical path length:

$$\Delta L_{stabilized} < \Delta L_{non-stabilized} \quad \textbf{(6)}$$

The variance is also reduced as a result.

C. Signal Acquisition and Processing

The photodiode signal can be modelled with an aim to project ambient light rejection capabilities and do away with cross talk situations as shown (7):

$$S(t) = S_{LED}(t) + S_{ambient}(t) + n(t) \quad \textbf{(7)}$$

Where;

$S_{LED}(t)$: desired signal

$S_{ambient}(t)$: environmental elimination

$n(t)$: electronic noise

D. Hemoglobin Estimation Model

Appling for a univariate mapping (8):

$$\hat{H}b = \beta_0 + \beta_1 \Gamma \quad \textbf{(8)}$$

For multivariate mapping (9):

$$\hat{H}b = \beta_0 + \beta_1 R_{red} + \beta_2 R_{IR} \quad \textbf{(9)}$$

Where;

$\hat{H}b$ is the hemoglobin concentration

β_i represents the regression coefficients obtained

Minimization of square error applies the following equation (10):

$$min\beta \sum_{i=1}^{N} \left(Hb_i - \hat{H}b_i\right)^2 \quad \textbf{(10)}$$

E. Performance Metrics

The system performance is evaluated using the following:

Root Mean Square Error (RMSE) (11):

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(Hb_i - \hat{H}b_i\right)^2} \quad \textbf{(11)}$$

Mean Absolute Error (MAE) (12):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|Hb_i - \hat{H}b_i\right| \quad \textbf{(12)}$$

The correlation coefficient (13):

$$R = \frac{\sum(Hb_i - \bar{H}b_i)\,(\hat{H}b_i - \grave{H}b_i)}{\sqrt{\sum(Hb_i - \bar{H}b_i)^2 \sum(\hat{H}b_i - \grave{H}b_i)^2}} \quad \textbf{(13)}$$

IV. EXPERIMENTAL SET UP AND EVALUATION

The system was tested under controlled conditions with adults as the subjects. Each participant was exposed to multiple measurements of the tip of the finger under both a pressure stabilized and conventional non stabilized configuration to test for repeatability.Ground truthing was done by comparing hemoglobin values to standard laboratory hematology analysis. At each trial, optical features and predicted hemoglobin values were measured.

Performance measures that were involved are as follows:

- Mean absolute error (MAE)
- Root mean square error (RMSE)
- Correlation coefficient
- Standard deviation of inter-measurement

The research also applied Repeatability analysis on within-subject variability from repeated trials.

C. Ethical Compliance

The ethics of the study were approved by the Institutional Ethics Committee of Paavai Engineering College. Written informed consent was obtained from all the participants.

D. Protocol

- Number of measurements each subject = 5 measurements
- Stabilized configuration, non-stabilized configuration tested
- Reference analyzer: Sysmex XN - Series Automated Hematology Analyzer
- Duration of measurement: 60 seconds

V. RESULTS AND DISCUSSION

The pressure-stabilized configuration had less inter-measurement variability than the non-stabilized configuration. Standard deviation across repeated trials was significantly reduced indicating improved repeatability.

Estimation error measures indicated better consistency when pressure stabilization was used. The correlation of predicted and reference hemoglobin values was improved compared with conventional fingertip placement.

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The results indicate that mechanical interface control is a critical factor to improve the robustness of optical estimation. Rather than relying solely on the algorithmic complexity or the use of additional wavelengths, maintaining stable physiological coupling is a significant measure for improving the reliability of the measurement.

Table 1.

Configuration	MAE (g/dL)	RMSE (g/dL)	Correlation (r)
Non-stabilized	1.16	1.42	0.81
Stabilized	**0.71**	**0.93**	**0.92**

While the system does not replace the use of laboratory diagnostics, its performance supports its use as a screening and monitoring tool. Limitations are that it is dependent on sufficient perfusions to the periphery, and the calibration needs to be performed on a population-specific basis.

VI. LIMITATIONS

Despite the shown enhancements in repeatability and estimation accuracy, a number of limitations have to be acknowledged.

First, the study was performed on a subsequent sample size (N = 32), which restricts the statistical generalizability of the regression model in broader demographic and pathological populations. Hemoglobin distribution in the current cohort even if representative of the mild to moderate range of anemia, did not include extensively severe anemia cases (<7 g/dL). Validation in larger and clinically more diverse populations is needed in the future.

Second, the proposed system is still dependent on good peripheral perfusion. Fingertip PPG measurements may be affected when there are conditions of vasoconstriction, hypothermia, hypotension or shock. Although pressure stabilization helps to reduce the mechanical variability, it does not make up for physiologically reduced pulsatility.

Third, the regression model is population-calibrated. The characteristics of optical absorption are dependent on the skin pigmentation, tissue thickness and vascular geometry. Even though normalized AC/DC ratios reduce the variability of intensities, cross-population implementation may need to be refined in connection to demographic-specific calibration.

Fourth, while mechanical stabilization has already gone a long way to decrease the variability of the contact force, the present design is passive force control (with a calibrated spring mechanism). While this approach is simple and inexpensive, real-time force feedback information is not achieved. Inclusion of an embedded force sensor could enable to adaptively compensate for this but would increase the complexity of the system and power consumption.

Fifth, there was a decrease in the motion artifacts through the use of digital filtering, but the study was done under controlled laboratory conditions. Performance in ambulatory or high-motion environments needs to be determined.

Finally, this system is designed to be a screening system and a monitoring system and not a substitute for laboratory hematology analyzers. Although, RMSE = 0.93 g/dL is clinically meaningful performance used for screening for classification; confirmatory laboratory testing is still needed for decision making in the diagnostics.

VII. CONCLUSION

This study introduced a pressure stabilized dual-wavelength fingertip optical system to non-invasive hemoglobin estimation and anemia screening. Through the standardization of contact pressure and better signal integrity, the proposed design will improve the repeatability and robustness while not increasing hardware complexity.Experimental evaluation showed lower variability and higher consistency of estimation than non stabilised ones. An integrated approach of mechanical stabilization, synchronized acquisition, normalized feature extraction, and calibrated mapping is underpinned in the system for a reliable screening approach.The approach proposed here provides a portable low-cost solution that could be used for monitoring anemia at the population level, especially in resource-constrained environments. Future work can be focused on population validation for a larger number of people, adaptive calibration strategies and integration with mobile health platforms.

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