Noninvasive Hemoglobin Measurement Using Unmodified Smartphone Camera and White Flash

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***Abstract*— We show that a mobile phone can measure hemoglobin levels using the built-in RGB camera and white LED without modification. Prior work has demonstrated that a smartphone using the built-in RGB camera with the aid of visible and IR lights can achieve a Pearson correlation results between 0.69-0.82 and an RMSE value between 1.26-1.56 g/dL. Our system builds upon the prior work and demonstrates that with only the built-in white LED, the estimation of hemoglobin level has a Pearson correlation of 0.62 with an RMSE of 1.27 g/dL. This extension work demonstrates that it is feasible to measure hemoglobin without using an IR source.**

I. INTRODUCTION

The combination of a smartphone camera and flash LED to measure the blood pulses from the fingertip, known as photoplethysmograph (PPG), is a well-established technology. Apps on smartphones are available to consumers to test their heart rate and track their cardiovascular health. These apps work by having the user place their finger over the camera and flash to measure the absorption of blood as it fluctuates each time the heart beats. Optical measurement using a smartphone has also been demonstrated for measuring the blood oxygenation and hemoglobin concentration when used in conjunction with a custom light attachment on the phone.

HemaApp is a cellphone-based application that uses the camera on the back of the phone to measure the PPG signal from a user's finger (Figure 1) to measure the hemoglobin level of a person noninvasively. In our previous work [8], we proposed HemaApp as a system that utilized the unmodified back camera with a custom attachment that is placed over the phone camera to provide a spectrum of illumination using a white LED, IR LEDs, or an incandescent bulb. To use the attachment, the user's finger is placed over the LED attachment and the camera. Each light source is cycled through in sequence, and the resulting PPG is recorded for each light source. The hemoglobin level is then computed based on the absorption ratios between the different wavelengths. This paper presents an extension to the HemaApp system to allow for hemoglobin measurements using only the built-in camera and white LED. Through a new advance in color channel gain balance technique that allows all color channels to be recorded simultaneously, the new HemaApp avoids having to record each wavelength of the white LED in sequence. We will refer to the custom lighting version of HemaApp as HemaApp V.1 and the built-in LED version of HemaApp as HemaApp V.2.

In a study of 32 participants, HemaApp's hemoglobin level estimate had a Pearson correlation value R = 0.62 and an RMSE = 1.27 g/dL when compared with another optical hemoglobin measurement device, the Masimo Pronto 7. For comparison, HemaApp V.1 using a white LED and IR LED in a similar study achieves a correlation result between 0.69 – 0.82, with an RMSE value between 1.26 – 1.56 g/dL. This result gives evidence that using an unmodified phone is possible with the new gain balancing technique.

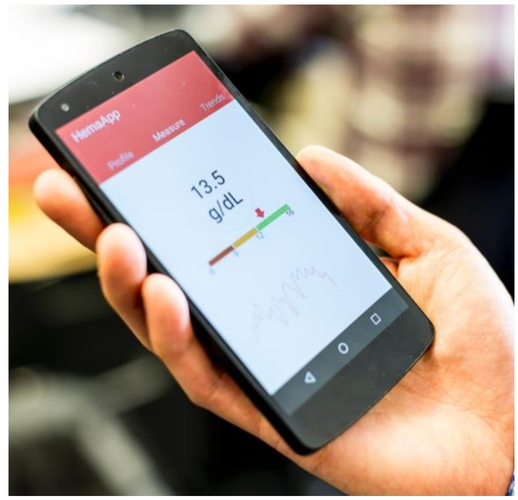

Figure 1. HemaApp is a smartphone application that measures the hemoglobin level using the phone's built-in camera and white flash LED.

II. BACKGROUND

A. Hemoglobin Screening

Hemoglobin is the protein molecule in the blood that carries oxygen throughout the body. Conceptually, the measure of hemoglobin is a representation of the oxygen carrying capacity of the patient's blood. This is distinct from oxygen saturation, which measures the oxygen carrying efficiency of the blood. Currently, options to monitor hemoglobin include a full blood analysis using a complete blood count (CBC) [2], blood analysis using a finger prick [5], or optical measurements through the finger using a specialized finger probe [1, 4, 7]. Noninvasive measurement is desirable for both sanitation and ease of use when measuring frequently because it avoids puncturing the skin.

B. Hemachrome Analysis

Hemachrome analysis is the measure of blood coloration to analyze the components in the blood. HemaApp aims to

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measure the concentration of hemoglobin as compared to the concentration of plasma in the blood. The Beer-Lambert law states that the absorption of light is proportional to the concentration and thickness of the medium, given by:

$$\boldsymbol{I_{measured} = I_0 e^{-\alpha[C]d}} \quad (1)$$

where I_0 is the incident light intensity, α is the absorption coefficient, $[C]$ is the concentration, and d is the thickness of the medium that the light travels through. When the finger is illuminated with a single wavelength of light, the measured intensity $I_{measured}$ represents the absorption due to tissues, hemoglobin, and plasma:

$$\boldsymbol{I_{m,\lambda} = I_{0,\lambda} e^{-d(\alpha_{tissue,\lambda}[tissue] + \alpha_{Hb,\lambda}[Hb] + \alpha_{plasma,\lambda}[Plasma])}} \quad (2)$$

where λ is the wavelength of the incident light. To obtain the ratio of $[Hb]$ and $[Plasma]$, it is necessary to eliminate the absorption by the finger tissue. This is accomplished by measuring the time varying intensity as the thickness of the arteries oscillate with respect to the heartbeat.

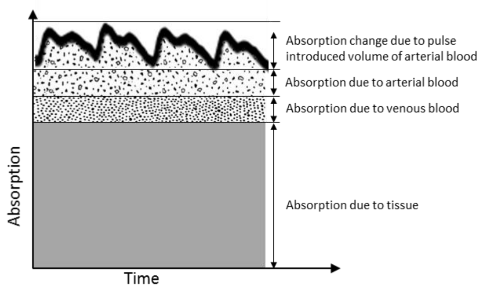

Figure 2. Light absorbed by living tissue. The absorption of light changes due to the change in volume of blood when the heart pulses. Adapted from Webster09 [9].

The change in arterial thickness Δd affects only the path length for Hb and $Plasma$. By measuring the ratio of the maximum and minimum intensity of the light received, the effect of the tissue is removed:

$$\boldsymbol{\frac{I_{peak,\lambda}}{I_{trough,\lambda}} = e^{\Delta d(\alpha_{Hb,\lambda}[Hb] + \alpha_{plasma,\lambda}[Plasma])}} \quad (3)$$

where the ratio of intensities can then be expressed as:

$$\boldsymbol{I_{R,\lambda} = \ln\left(\frac{I_{peak,\lambda}}{I_{trough,\lambda}}\right) = \alpha_{Hb,\lambda}[Hb]\Delta d + \alpha_{plasma,\lambda}[Plasma]\Delta d} \quad (4)$$

The measured ratio of peak and trough values of the light intensity provide a measure of absorption due to the different components of blood.

Finally, the absorption of the blood in each wavelength is calculated by equation 4. By dividing by the amplitude of the baseline, any effect the tissue has on the absorption is eliminated. The absorption ratio between two wavelengths, known as a ratio of ratios, is then calculated.

$$\boldsymbol{R_{\lambda 1,\lambda 2} = \frac{I_{R,\lambda 1}}{I_{R,\lambda 2}}} \quad (5)$$

III. HemaApp

The HemaApp system consists of the phone application that records a video when a user covers the camera and flash, and a server side algorithm that converts that video into a hemoglobin reading by performing a series of signal processing and machine learning steps.

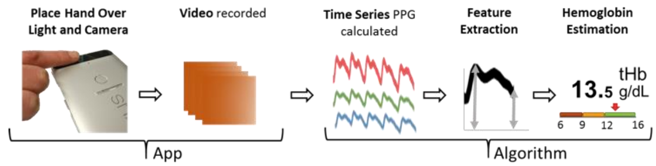

Figure 3. System overview of HemaApp.

A. Phone Hardware and App

The back facing RGB CMOS camera is used in the development of the HemaApp system. An RGB camera has three broadband color channels, giving a relatively even response to the entire optical spectrum. These cameras typically respond to light from the near infrared spectrum; however, to reduce glare from the infrared spectrum, manufacturers typically insert an IR filter, limiting the camera to visible spectrums.

The absorption property of the blood is about two orders of magnitude higher in the blue and green wavelengths than it is in the red wavelengths. This means that under the same exposure settings, either the red channel will completely dominate and the green and blue channels will be unobservable, or the red channel will be clipped for the green and blue channels to be measureable. Prior work in using the smartphone camera and flash to perform pulse oximetry has suggested the use of white balancing techniques such as incandescent light mode [3]. In this mode, the blue channel is amplified to alleviate the issue slightly.

We take this concept further by manually setting each color channel gain individually to adjust the relative exposures between channels. The current system is built on the Huawei Nexus 6p with an Android version 6 operating system. The Android 6.0+ uses the new Camera 2.0 API. This new API gives developers fine grain control of the individual amplification gain for each color channel. The white balance gain set for HemaApp V.2 is R = 0.25 | G = 0.85 | B = 3.00, where a gain of 0.0 turns off the color channel and a gain of 4.0 is the maximum. These values were determined empirically with 20 subjects of varying skin tones to determine the signal quality for each color channel. In this experiment, the amplitude of the fluctuation channel due to blood absorption was measured for each color channel under various gain settings. The above setting gave the most balanced fluctuation across channels while still maintaining a low noise that occurs at high gain settings. Although the maximum achievable gain is 4.0, this results in very noisy measurements. The frame rate is set at 30 fps and an auto exposure routine is used to set the integration to properly expose the camera once the finger is placed over the flash and camera.

A blue with yellow phosphorus fluoresced white LED is used in the development of HemaApp V.2. This type of LED generates white light using a blue LED coated with a yellow phosphorous coating which fluoresces a yellow light under illumination by the blue light. The resulting mixture creates a white light with a strong narrowband blue light mixed with a broadband light between 500-700nm. This type of white LED is more commonly used in a smartphone than a tri-color white LED which composes of one red, one green, and one blue LED, due to the quality of the white light produced.

As described in the Section II.B, optical hemoglobin level is typically measured using a combination of visible and near infrared at 1300nm to estimate plasma volume. Due to the limitation of smartphone CMOS cameras and the white LED, only absorption changes between 400 – 700nm can be observed. Our system, instead, relies on the blue absorption to estimate plasma volume. Blue wavelengths can act as a proxy due to the bilirubin in the plasma, which has strong blue wavelength absorption. Note that the bilirubin concentration in the blood would thus likely affect the accuracy of the system. HemaApp has thus far been tested in populations that are unlikely to have high levels of bilirubin.

B. *Algorithm*

This section will describe the algorithm that calculates a hemoglobin value from a video collected from the camera. HemaApp's algorithm is partially derived from our previous publication on HemaApp V.1.

1) *Video Processing*

The video recorded using the app is in RGB MPEG4 format. Each recording is 1 minute long, which at 30 fps, contains 60 sec * 30 frames/sec =1800 frames. With the resting heart rate of typical healthy adults being between 60 to 90 bpm, each recording captures a significant number of pulses for analysis. Each frame of the video contains three 2D arrays of pixel values for each color channel. A mean value is computed from each color channel for each frame, giving three values per frame. By computing the mean value for the entire video, a 1 minute video is converted into three time-series vectors each containing 1800 values. These time series are the PPG measurements for each color wavelengths.

2) *Feature Extraction*

To perform hemachrome analysis, a series of signal processing steps is required to extract the peaks and troughs in the PPG signal. This involves first performing a spline interpolation to increase the time resolution of the PPG. The frequency content of the PPG signal is typically under 8 Hz, which can be captured by the 30 Hz sampling rate of our system. However, the exact peak value of the PPG is important for the analysis. A cubic spline method is well suited for this reconstruction because of the fundamentally smooth signal of the PPG.

On the spline interpolated signal, a peak finding algorithm as described in our previous publication is applied to determine the peaks and troughs of the PPG. This involves calculating the heart rate with a Fast Fourier Transform and selecting a dominant peak between the expected ranges of 0.8-2Hz. Then we use the heart rate to determine and remove extraneous peaks, such as peaks from the dicrotic notch. For each pulse, a $R_{\lambda1,\lambda2}$ is calculated for the wavelength pair. Finally, the median $R_{\lambda1,\lambda2}$ is calculated for the 1 minute recording.

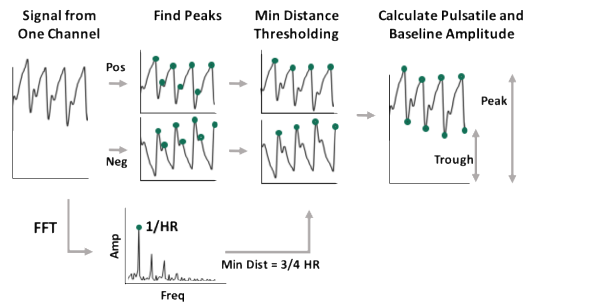

Figure 4. A peak detection algorithm is applied to the PPG signal. The heart rate is estimated using an FFT. The heart rate is then used to remove extraneous peaks too close to subsequent peaks.

3) *Linear Regression*

In theory, with multiple ratio of ratios, the hemoglobin concentration can be estimated using empirically measured absorption coefficients for each compound for the wavelengths used. However, these equations assume narrow band emitters, which is a poor approximation for the white LEDs used by the phone. Instead, our system translates the ratio of ratios directly to a hemoglobin concentration through a calibration curve generated based on the data we collected in a separate validation. By observing the different features extracted from the pulse signal, we selected the ratio of ratios $\boldsymbol{R_{G,B}}$ and $\boldsymbol{R_{R,B}}$, in particular the summation of the two, as the feature that best tracks hemoglobin concentration. A linear regression between $\boldsymbol{R_{G,B} + R_{R,B}}$ and the ground truth generates a model that converts PPG to hemoglobin levels.

IV. Validation & Results

To evaluate our system, we conducted a 32 participant study that measured the hemoglobin level using two systems: HemaApp V.2 and the Masimo Pronto 7, with participants ranging from 18 to 35 years old and having various skin tones. The performance of Masimo Pronto 7 has been evaluated in several independent clinical trials, demonstrating a mean error of about 1 g/dL against a blood test CBC golden standard. Although the performance of our system against the Pronto 7 does not directly represent the performance of our system against a blood test, the result of this test provides an estimate of how well the system would perform compared to a blood test.

For each test, a participant first had their hemoglobin measured using the Masimo Pronto 7. Next, they were measured by the HemaApp three times. Each recording was one minute long. The participant was asked to remove their hand between each measurement.

A. *Accuracy*

For each one minute measurement, the $R_{G,B} + R_{R,B}$ is calculated. For each subject, three measurements were made and the median value of $R_{G,B} + R_{R,B}$ is used in the linear regression. We noted that in our 32 subjects, five subjects deviated from the regression significantly. We treated them as outliers in the regression, and fit the linear regression based on the 27 remaining data points instead. When considering the outliers, R=0.42 and the RMSE=1.93. When outliers are removed, R=0.62 while the RMSE=1.27. For comparison, Pronto's RMSE=1.1 [6].

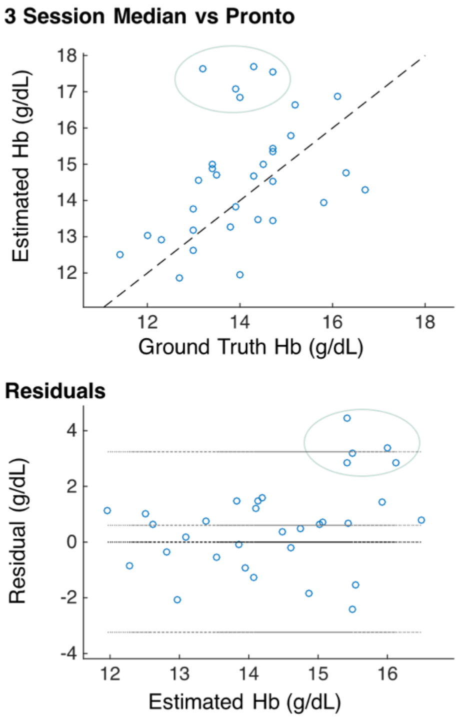

Figure 5. (Top) Linear regression results showing the HemaApp estimation of hemoglobin vs the Masimo Pronto's estimation. (Bottom) Bland-Altman plot showing the HemaApp estimation's residual against the Pronto.

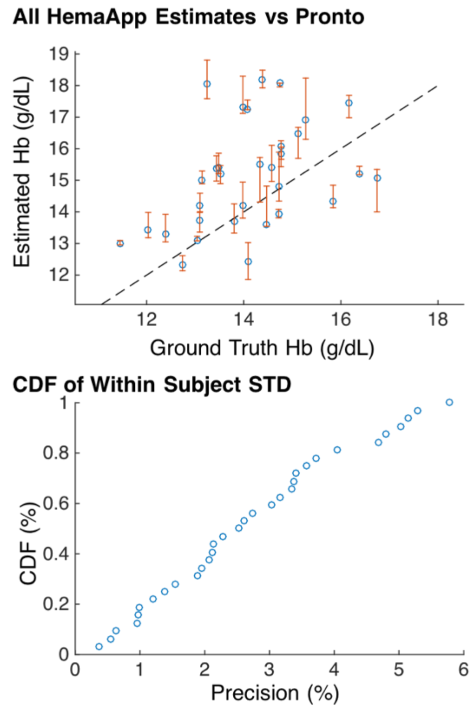

Figure 6. (Top) The linear regression shown with the median value for each subject and error bars indicating the two other readings. (Bottom) The CDF of the precision of each subject's readings.

B. *Precision*

Looking at the repeatability of the measurement for each subject, we separate the three Hb estimate as independent measurements and compare it to the Pronto measurement. The repeatability, calculated as the standard deviation divided by the mean of three measurements, are all under 6%, with 50th percentile of the CDF at 2.5% and 75th percentile at 3.6%. The Masimo Pronto's reported precision is 4.1% in a study where the device is used in two consecutive measurements [6].

V. Discussion & Conclusion

In this paper, we present an extension to a prior work that uses a smartphone camera to measure hemoglobin concentration noninvasively. We improve the hardware configuration by taking advantage of the independent color channel gain control to effectively amplify the weaker blue and green PPG signal. The better balance in color channels enables the simultaneous measurement of different wavelengths as opposed to the prior method, which relied on sequential measurements. The simultaneous measurement opens opportunity to use just the white LED for measurement, which was previously avoided due to the low accuracy achieved in the sequential method. The results of the white LED only HemaApp V.2 is comparable to the previous publication of HemaApp V.1 and demonstrates the possibility of a purely software-based smartphone hemoglobin measurement app for a variety of use cases, ranging from at home monitoring of anemia for pregnant women to in the field testing for nutritional deficiencies in children.

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