HemaApp IR: Noninvasive Hemoglobin Measurement Using Unmodified Smartphone Cameras and Built-in LEDs

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Abstract
We propose a standalone demo prototype of HemaApp, a smartphone application that noninvasively monitors the hemoglobin concentration in the blood. A previous version HemaApp using a supplemental light attachment combined with an unmodified camera has been presented at Ubicomp 2016, however the current version is an improvement from the 2016 system demonstrating no external attachments. In this paper, we present the newest version of HemaApp, which combines the unmodified smartphone's camera, white LED flash, and IR sensor on the phone's laser autofocus system.

Author Keywords
Hemoglobin; Mobile Health; Noninvasive Blood Screening; ICTD; Infrared; Chromatic Analysis

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

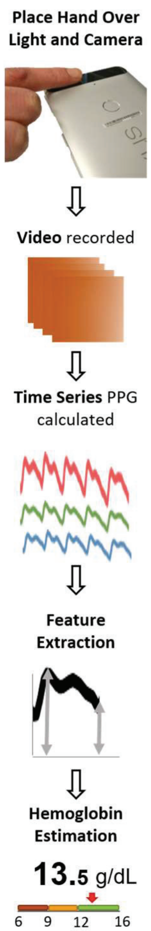

Figure 1: The HemaApp system performs a chromatic analysis of the user's blood through their finger and estimates their hemoglobin using a machine learning solution

Introduction

Hemoglobin measurement is a standard clinical tool and commonly used for screening anemia and assessing a patient's response to iron supplement treatments. This is typically achieved using a blood draw to analyze the hemoglobin content directly. However, recent advances in noninvasive optical analysis of the blood has shown the feasibility of quantifying hemoglobin concentration in the blood using calibrated chromatic analysis [1, 2]. These technologies usually use a pair of multi-wavelength light emitter and sensor placed on the finger to measure the optical absorption properties of blood that enters the finger. A noninvasive optical solution has multiple advantages. First, a noninvasive solution improves sanitation of the test. Many anemia screenings are performed in the field or clinics with less sanitization capabilities, which makes it difficult to draw blood with needles that either need to be replaced or thoroughly sanitized before reuse. Second, optical solutions are reusable. Invasive blood draw solutions still require the sensor system for analysis, but requires needles, cuvettes, and often chemical reagents for every test. In contrast, a noninvasive solution uses a set of LEDs and photodiodes that can be reused for thousands of times before any degradation or needing recalibration. Lastly, noninvasive solutions are painless.

HemaApp is a smartphone based noninvasive hemoglobin measurement system that relies on chromatic analysis of the blood using optical sensing systems built into the phone. Other noninvasive optical hemoglobin measurement systems require dedicated sensors, usually in the form of a finger clip. The goal of HemaApp is to reduce the amount of custom hardware needed to achieve the same hemoglobin measurement achieved by other noninvasive solutions on the market.

In this paper, we present the progression of the HemaApp system, which started as a camera based system that uses a custom LED attachment [], to the newest version that sources all necessary sensing capability on the smartphone. The newest version uses the smartphone camera paired with the white LED to measure the blood's absorption in visible light, while relying on the time-of-flight IR laser focus system to measure the blood's IR absorption property.

Background

Hemoglobin is the protein molecule in the blood that carries oxygen throughout the body. Hemoglobin concentration is the amount of hemoglobin per volume compared to the whole blood, which is composed of red blood cells which contains hemoglobin, white blood cells, and plasma. Conceptually, the measure of hemoglobin is a measure of the oxygen carrying capacity of the patient's blood. Our system enables hemoglobin measurement through a chromatic analysis of the blood at the user's fingertip by measuring the absorption properties of the blood at different wavelengths of light. The technique HemaApp relies on to capture the absorption properties of the blood through the finger is called photoplethysmography (PPG). When the heart beats, blood is ejected from the heart into the artery, which ultimately moves blood throughout the arterial system. When a constant light is shined on the finger and a photo sensor is placed in close vicinity to the light, each time blood is pushed into the finger by the heart, a small increase in the amount of light absorbed by the influx of blood can be detected. This change in light absorption is attributed to the blood as the surround tissue (e.g. skin, bone, and muscle) do not change in absorption properties at the time scale of seconds or even minutes. By

Figure 2:The HemaApp system has gone through a few iterations of improvements. The first version relied on custom hardware. The second version replaces the custom LEDs with a standard white flash LED with a change in the capture algorithm. The newest version attempts to reintroduce IR light by accessing the phone's time of flight IR sensor next to the camera.

leveraging PPG measurements, HemaApp extracts the blood optically. To analyze the concentration of hemoglobin, it is necessary to then analyze the absorption property of the whole blood. Different components in the blood have varying absorption properties as shown in Figure 1, and the absorption of whole blood at each wavelength is a linear combination of the absorption coefficient of each component at that wavelength and concentration of each component. Thus, if we shine multiple wavelengths of light at the finger and measure the PPG for each wavelength, we can then profile the blood's absorption across wavelengths and compute the concentration of hemoglobin. Typical noninvasive, optical hemoglobin measurement system have relied on measuring the blood's absorption from about 600nm to 1300 nm using custom LEDs and photodiodes.

We achieve the similar sensing capabilities by measuring the visible spectrum using the RGB camera with the white LED, and measure a near IR spectrum with the 940nm ToF autofocus system. We address a major limitation of using a smartphone camera camera for doing hemoglobin measurement, which is a lack in sensitivity to wavelengths above 1000nm. Other optical hemoglobin measurement system relies on wavelengths beyond 1000nm to measure the water content in the blood to estimate plasma volume to provide a reference for blood volume. Due to the high absorption of water above 1000nm, ToF sensor necessarily need to operate below 1000nm and CMOS cameras do not have sensitivity above 1000nm. Instead of relying on IR wavelengths to measure the water content in the plasma, our system utilizes the absorption of the proteins that consist of about 10% in the blood plasma as a proxy for capturing the plasma. This is accomplished by leveraging the blue absorption of the plasma. By illuminating the finger with a white LED, the blue component of the white light is absorbed by the proteins in the plasma, allowing the system to capture the plasma volume.

HemaApp System

The first version of HemaApp (HemaApp V1), published at Ubicomp '16 [3], demonstrates comparable performance as the Masimo Pronto 7, an FDA approved finger clip based system. In [], the HemaApp V1 relies on the optical sensing capability of the smartphone camera paired with a custom LED attachment. With a mixture of IR light and visible spectrum light, the HemaApp V1 achieves a hemoglobin estimation with a Pearson correlation score of 0.82 and a RMSE of 1.26 g/dL as compared to a blood draw in a study of 31 participants with hemoglobin concentrations ranging from 8.3 – 15.8 g/dL. This result compares favorably with the Masimo Pronto 7's in the same study, which had a Pearson correlation score of 0.81 and a RMSE of 1.28 g/dL. This study showed that the smartphone camera has the potential for being used as the sensor for measuring hemoglobin, however, a custom lighting source was still needed.

A follow-up work of HemaApp (HemaApp V2), published at EMBC '17 [4], extends the HemaApp V1's concept of using the smartphone camera by excluding the use of an external lighting source and instead use only the white LED present on the smartphone. This system focuses on using only the visible light spectrum for analysis because the white LED does not contain IR wavelengths, which invariably results in fewer machine learning features for estimation. One major improvement in HemaApp V2 is a set of color channel

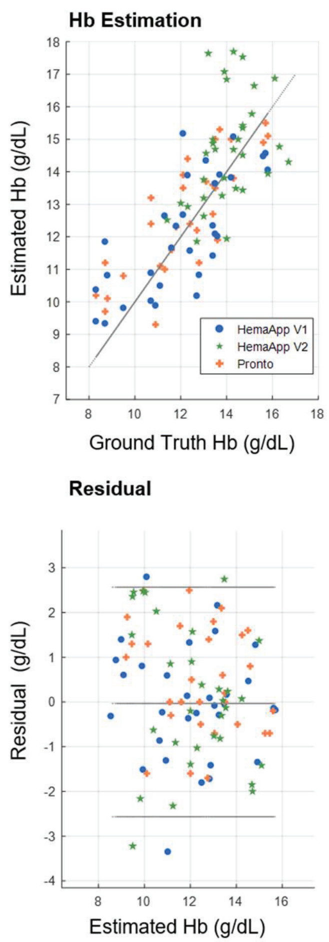

Figure 3: The first and second versions of HemaApp showed similar hemoglobin estimation performance as the FDA approved Masimo Pronto.

gain balancing techniques that allows simultaneous capturing of the red/green/blue color channels. In V1, each light wavelength is captured in sequence rather than simultaneously, which results in inaccuracies in the measurement of blood absorption as each wavelength is measured at a different time. In a feasibility study with 32 participants using the Masimo Pronto 7 as ground truth, the V2 system's hemoglobin estimation showed a Pearson correlation of 0.62 with an RMSE of 1.27 g/dL. The decrease in accuracy can be attributed to the lack of IR wavelengths.

The newest version of HemaApp (HemaApp V3), aims to recreate the accuracy reported in HemaApp V1, while maintaining the independence from custom attachments to the smartphone. The autofocus system in select new generation Android phones (i.e. Nexus 6p, LG G5, and Pixel) uses an IR laser and diode system for time-of-flight (ToF) focusing. The Nexus 6P employs an 850nm LED while the Pixel employs a 940nm LED. As demonstrated in HemaApp V1, both wavelengths contribute to improved estimation. One of the major advances is we access this IR sensor through an Android kernel upgrade and repurposed it as an IR pulse sensor. The ToF sensor samples at 30Hz, like the camera, and is conveniently located next to the camera as it is used for focusing the back camera. The total distance that needs to be covered by the finger is about 2 cm (figure). A typical adult finger can easily cover both the camera and the IR sensor, but this may present to be a bit of a challenge for young children and infants. For young children, it may be easier to perform the measurement on their thumb or big toe.

HemaApp V3 is in clinical and field validation. To test that the new setup works well, a replication of the clinical study done in HemaApp V1 is being conducted. In addition to the clinical study, the University of Washington team has partnered with various NGOs located in Peru for a series of in-the-field deployment of HemaApp V3. NGOs in these countries are actively screening for anemia by visiting communities with high percentage of the population afflicted with anemia. Our partnership is allowing the HemaApp system to penetrate highly anemic communities and to be tested against blood tests that are already being done. Each of these community anemia screening efforts see thousands of patients a month, which will hopefully provide new data to improve the current HemaApp algorithm and provide insight into the usability of the system by community health workers.

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