Non-Invasive Blood Glucose Monitor Based on Spectroscopy Using a Smartphone

Vishnu Dantu, Jagannadh Vempati, and Srinivasan Srivilliputhur

Abstract - **Development of a novel method for non-invasive measurement of blood glucose concentration using smartphone is discussed. Our research work has three major contributions to society and science. First, we modified and extended the Beer-Lambert's law in physics to accommodate for multiple wavelengths. This extension can aid researchers who wish to perform optical spectroscopy. Second, we successfully developed a creative and non-invasive way for diabetic patients to measure glucose levels via a smartphone. Researchers and chemists can now use their smartphones to determine the absorbance and, therefore, concentration of a chemical. Third, we created an inexpensive way to perform optical spectroscopy by using a smartphone. Monitoring blood glucose using a smartphone application that simply uses equipment already available on smartphones will improve the lives of diabetic patients who can continuously check their blood glucose levels while avoiding the current inconvenient, unhygienic, and costly invasive glucose meters.**

I. INTRODUCTION

Currently, 366 million people worldwide have diabetes[23]. This year, diabetes will cause more than 27 million ambulance trips in the United States alone. The question is, "How can we prevent diabetic patients from being victims of hyperglycemic seizures and other complications of diabetes caused by a failure to monitor glucose levels constantly?" Many of these seizures arise from diabetic patients failing to consistently monitor their blood glucose levels because current glucose meters require them to prick a finger to collect blood samples for testing. Klonoff [1] explains the current methods used to measure glucose levels. Klonoff also describes the drawbacks of each method. The leading methods in measuring glucose noninvasively include Near-Infrared Spectroscopy [7] - [22] Far-Infrared (FIR) Spectroscopy [4], and Optical Rotation of Polarized Light [2] [3]. In Near-Infrared Spectroscopy, a light source of the near-infrared spectrum passes through the finger. This method analyzes the amount of light a finger absorbs at a certain wavelength for each blood-glucose level. The main problem with the current method of Near-Infrared Spectroscopy is that because many factors affect a finger's absorbance of light other than glucose concentration, the method requires frequent recalibration. If patients are using medication that alters their blood, are ill, are dehydrated, or experience a change in their blood-oxygen saturation level, then their finger's absorbance of light changes.

Far-Infrared Spectroscopy is also being explored as a method of non-invasively measuring glucose. This method measures the amount of absorption of Far-Infrared Radiation contained in body heat. Blood glucose absorbs part of the FIR that the body emits, and the amount of absorption is linear to the glucose concentration. The problem with FIR spectroscopy is that the signal size of thermal emissions in the human body is too small to consistently and accurately measure blood glucose levels in real-life situations.

The third leading research in measuring glucose requires observing the optical rotation of polarized light as the light passes through a finger. As polarized light passes through a liquid with a high glucose concentration, the plane of polarization rotates proportionally to the glucose concentration. However, the main problem with planes of polarization is the signal size for the rotation of the plane is low, and precise glucose levels cannot be determined. Our research modified the method of Near-Infrared Spectroscopy to more accurately measure glucose levels without invasive methods. The Beer-Lambert's Law [5] in optics uses Near Infrared Spectroscopy to determine the quantity of a material. Absorption of light by a material is proportional to the quantity of the material. This quantity can be found by passing a laser beam (incident light) through the material and analyzing the intensity of the transmitted light coming through the material. The Beer-Lambert's law also established an equation to measure absorption by using the theory that the intensity of transmitted light exponentially decays as it passes through the material. Therefore absorption is:

$$\log\left(\frac{\boldsymbol{intensity\ of\ incident\ light}}{\boldsymbol{intensity\ of\ transmitted\ light}}\right)$$

The above relationship provides how much of the incident light is absorbed by the material. According to Beer-Lambert's Law, the amount of absorbance should be proportional to the concentration of the material being analyzed. In the next section we describe the experimental setup.

II. EXPERIMENTAL SETUP

Due to the availability of powerful CPUs in most mobile phones, it is now possible to use mobile phone software for continuous calibration and regression. Therefore, the smartphone is an ideal base for a glucose monitor. In

Vishnu Dantu is with University of North Texas, Denton, TX 76203 USA (e-mail: vishnudantu@my.unt.edu).

Jagannadh Vempati is with the Network Security Lab, Department of Computer Science, University of North Texas, Denton, TX, 76203 USA (e-mail: jagannadhvempati@my.unt.edu).

Srinivasan Srivilliputhur is with the Material Science and Engineering Department, University of North Texas, Denton, TX 76203 USA (e-mail: Srinivasan.Srivilliputhur@unt.edu).

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comparison to the deficiencies of the existing models, the glucose monitor application that we built is very sensitive to small variations of glucose levels. In our research work, we built a device to measure blood glucose using a smartphone camera. By modeling the Beer-Lambert's law and Near Infrared Optical Spectrometry, we designed an application that measures the intensity of transmitted light and calculates the subject's blood glucose level. We built a setup as shown in Figure 1. The finger of a patient (sample of analysis) is placed between the smartphone camera and a near-infrared light source of a set wavelength. The intensity of the transmitted light is then analyzed using an application installed on the smartphone.

Figure 1: Experimental Setup

According to Beer-Lambert's Law, the amount of absorbance should be proportional to the concentration of the material being analyzed. The original setup was simple and was made up of low-cost objects. We used a near-infrared laser light and a HTC One X Android phone. We then attached the laser beam and the phone to a cardboard plank--leaving room for a finger to fit between the tip of the remote and the smartphone's camera lens.

A. Application Development

The smartphone application used for data collection was developed on the android platform. Because smartphones are ubiquitous in society, the application developed in this project is ideal. The application developed collects frames from the smartphone's camera, and measures the RGB (red, green, and blue) intensities for 100 pixels of each frame.

III. Procedure

Our noninvasive blood glucose monitor system measures the absorption of radiated light by glucose using optical spectroscopy. A light beam is passed through a fingertip (sample) placed on the lens of a smartphone in our setup. The smartphone's camera acts as a photo detector by collecting and analyzing the spectrometric properties of the transmitted light beam. Following analysis, the Android application searches for a correlation between mg/dL glucose levels in the blood and certain properties of the transmitted light. In our research to find concentration, we modified the Beer-Lambert's law (refer to section IV.A) to accommodate multiple wavelengths. In doing so, we found that the ratio of intensity change in the 510 nm transmitted wavelength to the intensity change in the 475 nm transmitted wavelength is proportional to the concentration. This is an innovative finding because it allows diabetic patients to be able to directly measure their blood glucose concentration by simply having a laser beam pass through their fingers. To test our modification, we placed the surface of the fingertip (the area of analysis) on a smartphone's camera lens. We transmitted a beam of near-infrared light through the finger, align the smartphone camera take a picture of the area of analysis, and observed the intensity of the Blue and Green wavelengths that the camera captured. We measured the ratio of the intensity of Blue (475 nm) to the intensity of the Green (510 nm) transmitted light. This ratio was compared with the blood glucose level measured by an invasive glucose monitor. After taking several measurements, we identified a linear relationship between the ratio and the actual glucose level.

IV. Results and Discussion

A. Beer-Lambert's law modification

The Beer-Lambert's law establishes absorbance is proportional to concentration, so we assumed that a change in concentration values is proportional to a change in transmittance values. We also assumed the total change of the transmitted green, blue, and red wavelengths are proportional to the concentration values. In doing so, we determined that concentration should be proportional to ratio of the intensity of the transmitted green wavelength to the intensity of the transmitted blue wavelength. Our extension of the Beer Lambert's Law is shown below:

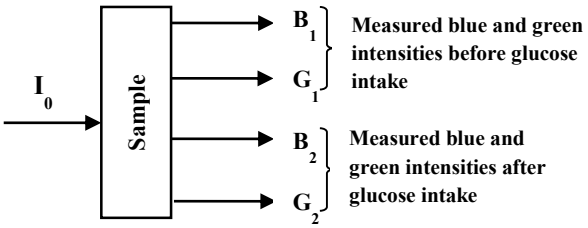
Beer Lambert's Law:

$$Concentration\ of\ Blue = log\left(\frac{B_2}{I_0}\right)\ ;\ log\left(\frac{B_1}{I_0}\right)$$

$$Change\ of\ concentration\ with\ respect\ to\ Blue:$$

$$log\left(\frac{B_2}{I_0}\right) - log\left(\frac{B_1}{I_0}\right) = log\left[\frac{B_2}{B_1}\right]$$

$$Change\ of\ concentration\ with\ respect\ to\ Green:$$



$$log\left(\frac{G_2}{I_0}\right) - log\left(\frac{G_1}{I_0}\right) = log\left[\frac{G_2}{G_1}\right]$$

$$Total\ Change\ in\ concentration\ (\Delta c)\ [normalized\ by\ unitconcentration\ of\ glucose] = log\left(\frac{B_2}{B_1}\right) - log\left(\frac{G_2}{G_1}\right)$$

*(Differentiating w.r.t **intensity (I)** while assuming (B/G) as a variable)*

$$\text{Final Equation: } \frac{d(\Delta c)}{dI} = \frac{G_2}{B_2} - \frac{G_1}{B_1}$$

A. Experiments with sugar water

Initially we tested our smartphone application on solutions of water with different concentrations of sugar to see if sugar water does indeed absorb light more than regular water. In this experiment, we had a control group of plain water which was compared to an experimental group of sugar water with 6g, 15g and 18g of sugar respectively. We had 20 repeated trials. The averages of all these repeated trials are shown in the Figure 2. With the rise in the concentration of sugar, we observed a decrease in transmittance values.

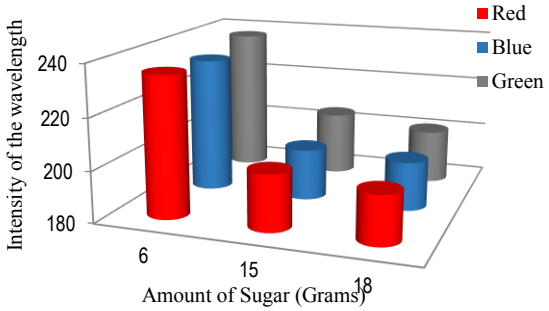


Figure 2: Effect of Quantity of Sugar on the Intensity of Different Wavelengths of Light

B. Human Subjects

After confirming the change with sugar water, we tested our device on human subjects. We did two types of experiments. First, we gave 50 subjects a Cola beverage of 50g of sugar. Fifteen minutes later, we collected readings from both a standard glucose monitor and the smartphone. We then analyzed the data. We observed an increase in glucose levels as well as an increase in the change in transmittance values collected by the smartphone device for all of our subjects. We then took 18 subjects and observed their change in blood-glucose concentration and blue-to-green ratios after 45 minutes. We found that, after 45 minutes, the concentration of each of the subjects' blood glucose increased. The percentage change of Blue to Green intensity ratio after 15 and 45 minutes of glucose intake for the subjects is shown in Figure 3.

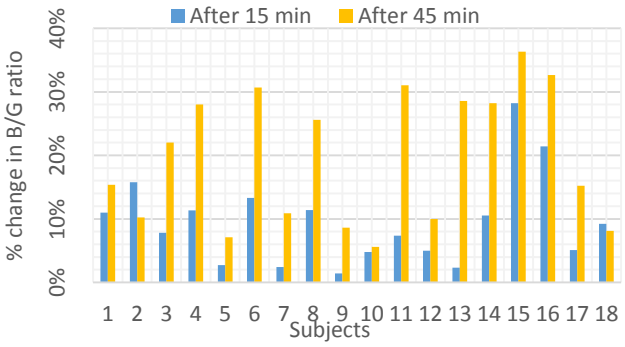


Figure 3: Percentage change of Blue to Green intensity ratio after 15 and 45 minutes of glucose intake

We then put these data into a Statistical T-Test to compare transmittance values 15 minutes after glucose intake with transmittance values 45 minutes after glucose intake. The null hypothesis assumed that as time after glucose intake increases, transmittance values do not change. *The T-Test returned a p-value of .005, proving that our data sets were statistically different and allowing us to reject our null hypothesis.* We next compared mg/dL glucose values (taken using the traditional invasive monitor) with their transmittance values. To our surprise, we found that the ratio of the intensity of the transmitted Blue wavelength (475 nm) to the intensity of the Green wavelength (510 nm) was proportional to the measured blood glucose level in the body for each of our subjects. The linear relationship between glucose values (mg/dL) and B/G transmittance values of a healthy 20-year-old male is shown in Figure 4.

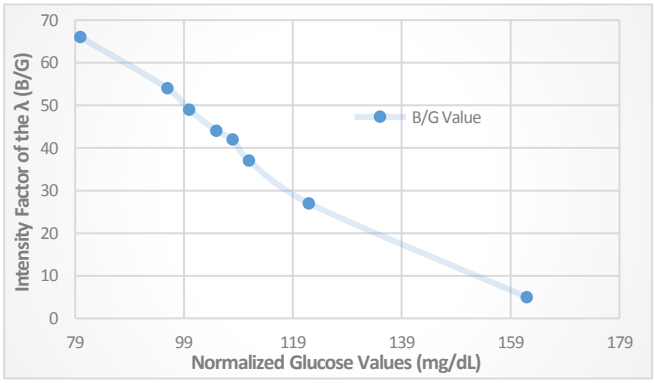


Figure 4: This graph represents the data of a 20 year old healthy male. In this graph, a correlation between the blue to green transmitted light intensity ratio and actual glucose levels measured by an invasive commercial glucose monitor

As demonstrated in Figure 4, as an increase in glucose values occurs, accompanied by a decrease in the ratio of the transmitted blue wavelength to the transmitted green wavelength. This pattern was consistent for all our subjects. After observing this, we returned to the original Beer-Lambert's law (section IV A) to see if the ratio of two wavelengths is also proportional to concentration. We used data from two instances, one where there was little or no glucose in the body (when a subject is fasting) and another when there is a high glucose level (after the subject has eaten).

V. Conclusion and Future Work

The World Health Organization indicates that more than 366 million people have to live with diabetes, which caused over 1.1 million deaths in 2005 and will double by 2030 [6]. Early detection and control of the disease is necessary and can save many lives. Because of the various qualms that exist regarding the traditional invasive method, diabetic patients hesitate to measure their blood glucose until their health has been severely compromised. In addition, for these diabetic patients, monitoring blood glucose values daily is too expensive or inconvenient. Thus, these diabetic patients become negligent, exacerbating the health problems associated with the disease. The non-invasive aspect of our smartphone application alleviates hesitations about taking glucose reading. Because our application is built for a smartphone, it provides easy-access to all age groups.

Our approach to medicine not only provides patients with cost–efficient healthcare but also is healthier (Invasive

monitors penetrate the skin and have a high potential to cause blood-borne infections) than an invasive approach to detecting glucose. We are currently doing more testing in using our method of optical spectroscopy on the smartphone to measure drinking-water purity. This research work can be applied in third-world countries. We are doing this by measuring the absorbance of certain pollutants that are commonly present in impure water sources such as fluoride, dust, salt, and sodium bicarbonate. The absorbance of these materials can thus lead to the determination of the presence of these materials.

The flow diagram of the model is discussed is Figure 5. In the current technique the data is analyzed externally using analytical tools like Matlab. But in the future the data can be analyzed and calibrated within the smartphone. This information can be sent to the doctor remotely for diagnostics, making it feasible for the patient.

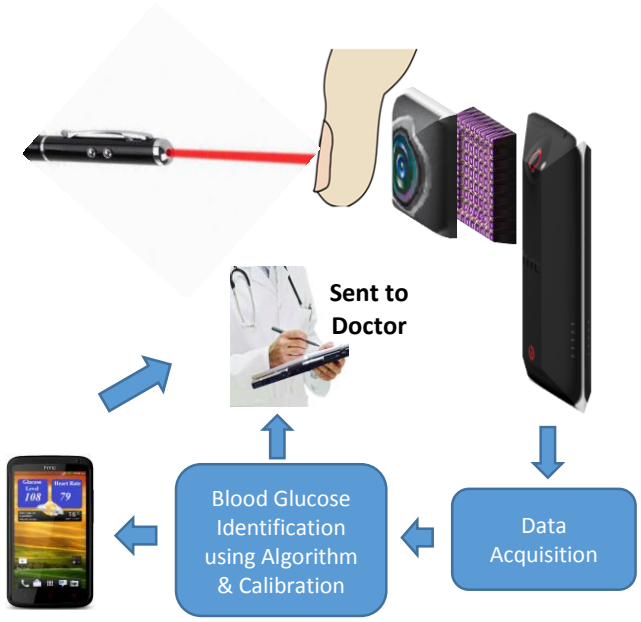


Figure 5: Flow diagram of the model

Despite the unprecedented success of our method, there are some issues that need to be addressed to make it reliably accessible to the society. For reliable and repeatable measurements, we need to design a finger-glove that exposes the uniform cross-section of a finger for all subjects, counteracts unfavorable light conditions during measurements, and tests the reliability of our method on patients suffering from other chronic diseases.

VI. Acknowledgment

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