Using Near-Infrared Light to Non-Invasively Determine Glucose Levels in the Blood

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Objective: The aim of the project was to find out whether it is possible to use Near-infrared (NIR) spectroscopy to determine the blood-glucose concentration. The initial step would in exploring the feasibility and achievability of the concept and then planned to shrink and integrate this functionality into a pragmatic wearable device.

Project Timeline:

The following diagram is a visual representation of the timeline regarding this project:

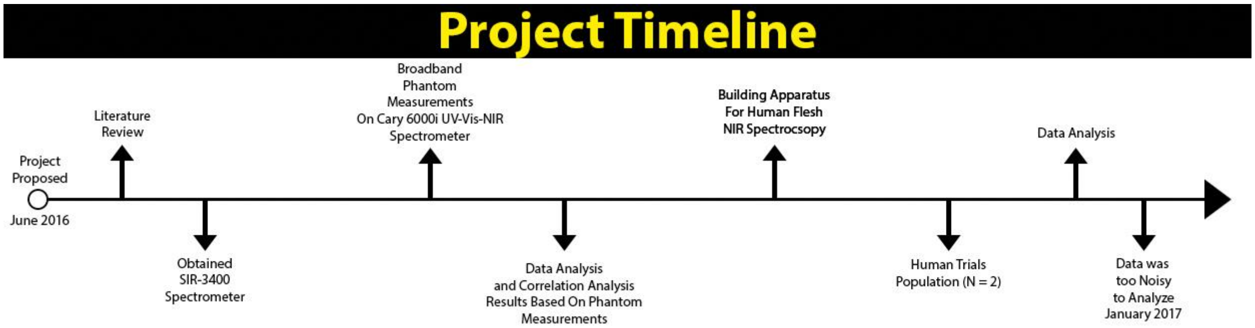

Fig. 1. The Project Timeline

Initially, the following literature was reviewed, in order to get a clear understanding of the matters:

Y. T. Liao, H. Yao, A. Lingley, B. Parviz and B. P. Otis, "A 3 μW CMOS Glucose Sensor for Wireless Contact-Lens Tear Glucose Monitoring," in *IEEE Journal of Solid-State Circuits*, vol. 47, no. 1, pp. 335-344, Jan. 2012. doi: 10.1109/JSSC.2011.2170633

John L. Smith, The Pursuit of Noninvasive Glucose: "Hunting the Deceitful Turkey", 4th ed. Illinois, 2006

Gennaro, Gelao, Roberto, Marani, Vito, Carriero, Anna, Gina Perri, "Design of A Dielectric Spectroscopy Sensor for Continuous and Non-Invasive Blood Glucose Monitoring ", *International Journal of Advances in Engineering & Technology*, vol. 3, pp. 55-64, May. 2012.

K. Yamakoshi and Y. Yamakoshi. Pulse glucometry: A new approach for noninvasive blood glucose measurement using instantaneous differential near-infrared spectrophotometry. *Journal of Biomedical Optics 11*(5), pp. 054028. 2006. . DOI: 10.1117/1.2360919.

K. Maruo et al. Noninvasive blood glucose assay using a newly developed near-infrared system. *IEEE Journal of Selected Topics in Quantum Electronics 9*(2), pp. 322-330. 2003. . DOI: 10.1109/JSTQE.2003.811283.

After gaining some information regarding the NIR spectroscopy, an initial setup was theorized and designed, as seen in the figure below.

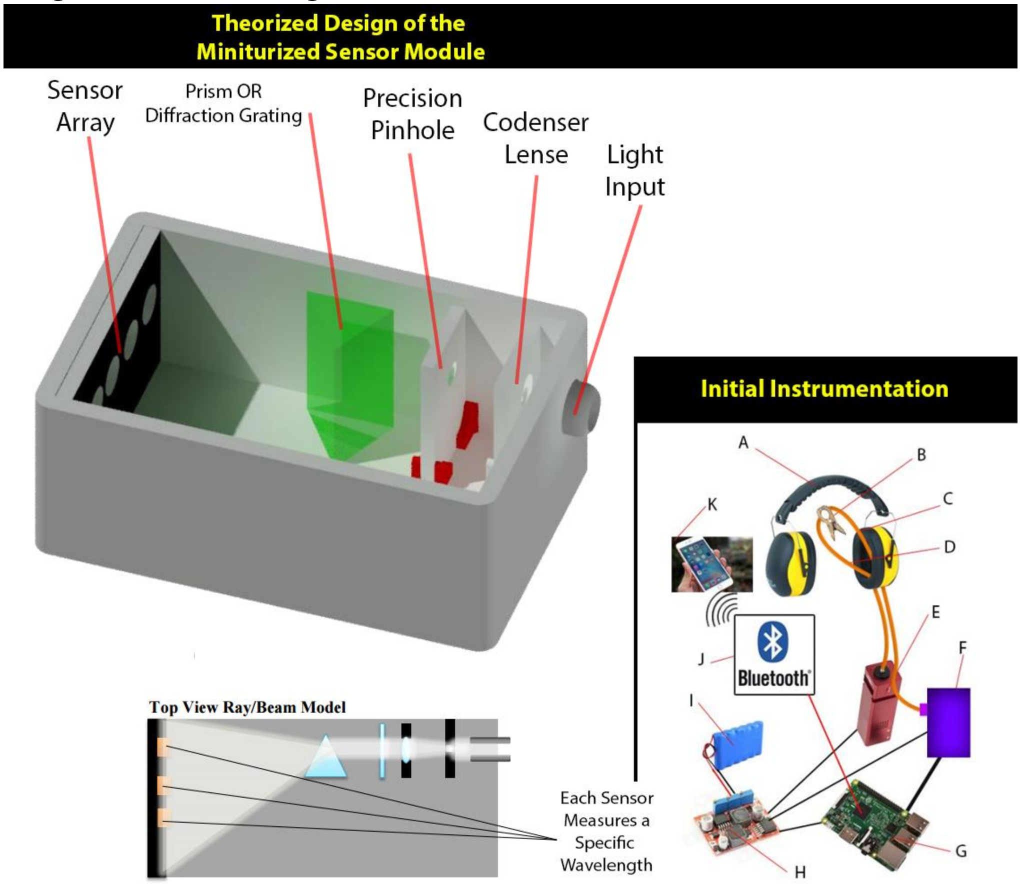

Fig. 2. Initial Design of the Contraption

Each labelled part and its functionality is stated below.

A – Hearing protection headphones used to create a darkroom for the transmission/absorption spectroscopy to be performed on the patient's earlobe.

B – An ordinary clip to clamp onto the earlobe. This part will be modified to allow two optical fibers to be mounted on it. This part is responsible to hold the tips of two wideband multimode optical fibers, in contact with the opposite walls of the earlobe.

C – Receiving optical fiber. Collects the transmitted NIR light and guides it to a photo spectrometer.

D – Incidence optical fiber. Carries light from a light source to the earlobe.

E – Wide band regulated tungsten filament light source. Produces a constant power beam of light with a wide span of wavelengths. An optical high pass filter with a corner frequency of 700 nm is added to filter out the UV and most of the visible spectrum.

F – NIR spectrometer used to detect the intensity of the different transmitted wavelengths through the earlobe.

G – Raspberry PI 3 portable computer. Collects the spectral data from the NIR photo spectrometer and calculates the blood glucose reading by curve fitting the received data.

H – Miniature switch mode power supply to power the Raspberry Pi, Spectrometer, and the light source.

I – Battery Pack to power the unit.

J – Bluetooth transmitter to send the data and the results to a smartphone

K – Smartphone to track and display the results plus notification services.

Though, due to a lack of information regarding wavelengths that are significant to blood glucometry, the following investigation was carried out.

Fig. 3. Prepared Phantoms for Data Collection

In the beginning, when the project members first came together it was thought that the best approach in creating a prototype was to use 3D printing. The mold printed would house the circuitry and the infrared light source. The output light that exited the body would be collected by a spectrometer and the data could then be filtered to view points of interest along the desired wavelengths (1319nm and 1650nm). These wavelengths were discovered to have a linear absorbance pattern, when the glucose concentration was varied. As seen in figure 2, flesh emulating phantoms were made in plastic cuvettes and the glucose concentration was linearly varied amount them. More specifically, the first phantom had no glucose and the last phantom had 380 mg of Glucose. There were 20 cuvettes in total. Each cuvette was scanned for transmission spectra, from 800 nm to 2200 nm wavelengths, using the Agilent Cary 6000i Spectrometer. The correlation analysis between the increasing glucose concentration and light transmission spectra showed that the 1319 and 1650 nm wavelengths, showed the most linear correlations. These wavelengths were then tested for, when running scans on human subjects. The transmission spectra of the phantoms are illustrated below:

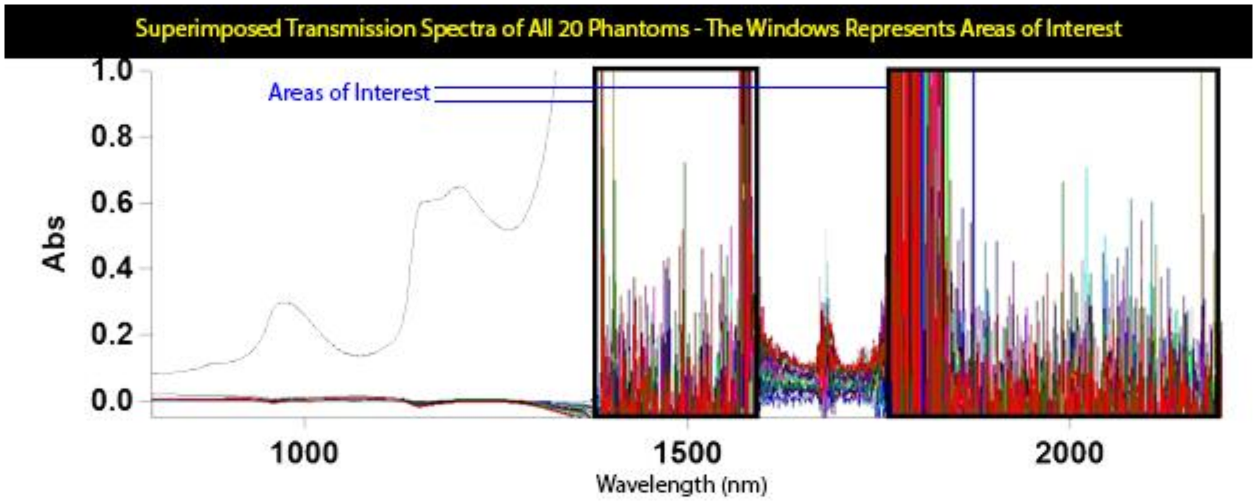

Fig. 4. Transmission Spectra of the Phantoms and the Areas of Interest

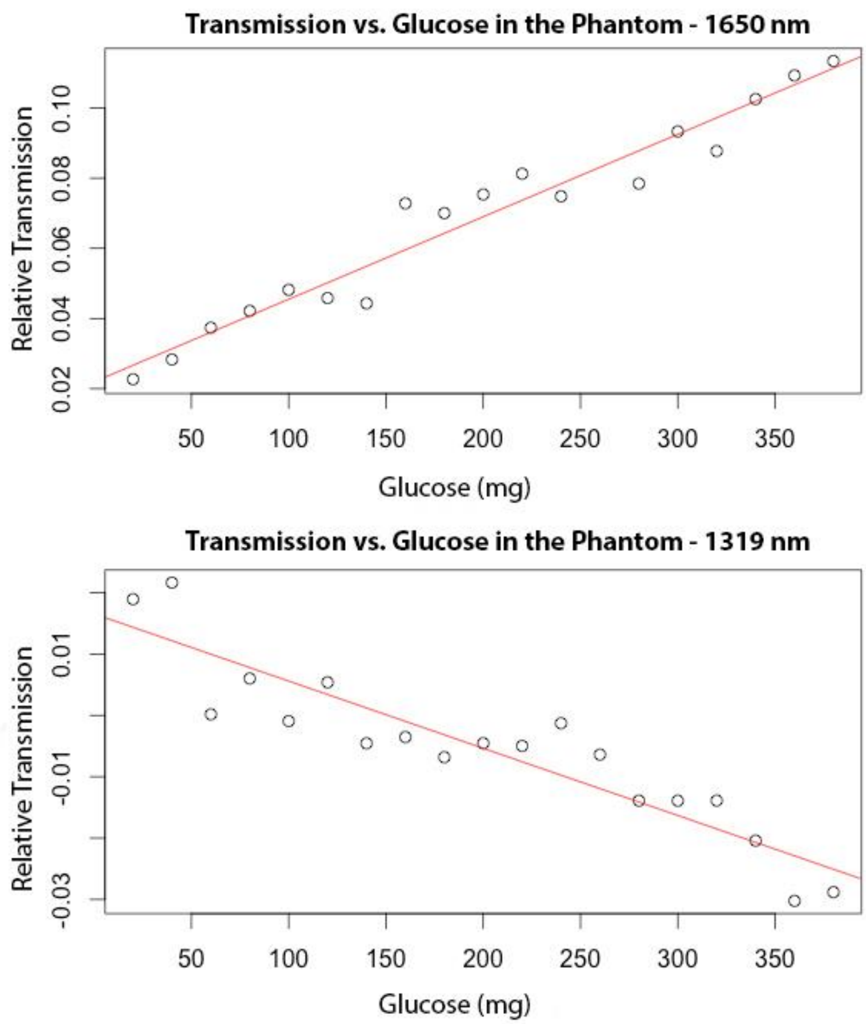

Fig. 5. Transmission Verse Glucose – 1319 nm and 1650 nm

Now that we had the wavelengths of significance, we were required to first produce this wavelength and then detect it. We did find lasers at these wavelengths, as sources, but due to budgeting limits, we passed on the idea. Lasers and LEDs would be ideal for the job, due to their monoenergic spectrum. Lasers and LEDs would make it possible for us to produce a very narrow wavelength band of light and then detect it, using broadband detectors. Our next solution was to use a broadband light source such as a Tungsten filament light bulb. For the detection apparatus, we used the SIR-3400 IR spectrometer. As the light source, we initially used a broadband 15 W Tungsten bulb and isolated the 1319 nm and 1650 nm wavelengths, using FB1320 and FB1650 optical bandpass filters from Thorlabs Inc. At this point, we faced the problem of not being able to detect any light, using our new spectrometer. More specifically, all the collected data was purely composed of noise. We either needed a brighter light source or a more sensitive spectrometer. Something we noticed was that our spectrometer was very insensitive to low levels of light. Specifically, this means that it could not detect light that was not of high intensity. The cause of the problem was unknown, however, due to the age of the device it is possible that a higher intensity light source would allow for a better experimental setup. After some analysis, the next feasible step was to build a new light source. We hypothesized to build a 650 W light source that has enough power at the desired wavelengths to penetrate human flesh and be detected by our spectrometer.

We were proposed to use the flash LED of a smartphone. Though after measuring the spectra of the LED, we noticed the spectra dying off way before the NIR region and thus the idea was dismissed. The following is the spectra that was collected:

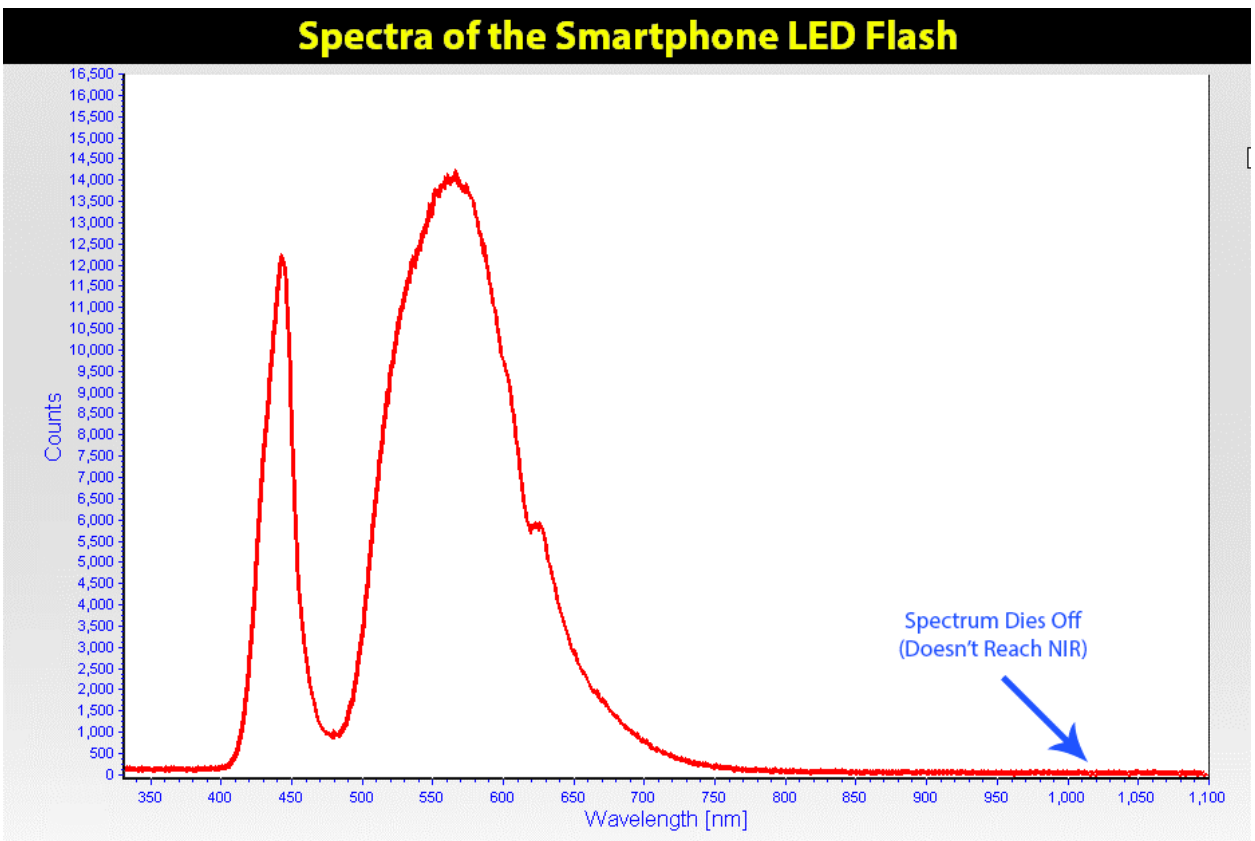

Fig. 6. Spectra of the Smartphone Flash LED

Thus we built the following contraption.

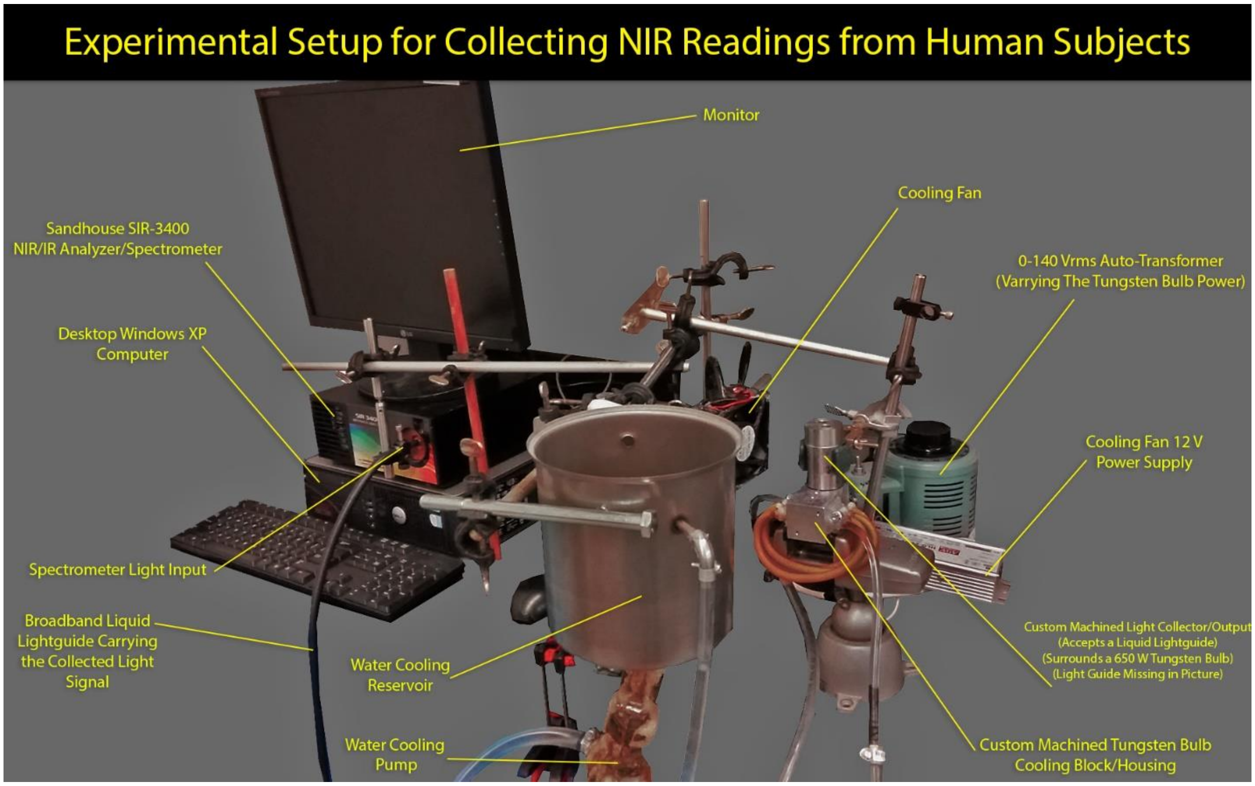

Fig. 7. Light Source and Spectrometer Contraption

The first challenge was to collect the light given by the bulb, so it can be directed to illuminate and penetrate the human flesh. Initially, we planned to use a series of condenser lenses to focus and couple the light into a Ø1 mm core multimode fiber but the time limit and resource limit forced us to go for a simpler design. One other concern was the immense heat given off by the Tungsten light bulb, which could damage the contraption. The lightbulb was a 650 W bulb that is used for photography purposes. This means that it is not only very bright but also produces a great deal of heat. The average lifespan is 6h of on-time and it cannot be left on for more than 30 minutes a time. To combat this issue, it was decided that a metal component would be fabricated from aluminum and a cooling system would be incorporated into the housing of this component to reduce the temperature of the device, during operation.

In addition, a secondary component had to be specially manufactured and to be used in conjunction with the main component so that the light emitted from the 650 W light source wasn't too bright for participants that underwent experiments with the prototype. More specifically, the custom piece surrounded the lightbulb to contain the emitted light while controlling the location at which the light would enter the liquid light guide.

The output could then be examined for any meaningful data that can be linked to the glucose levels of the subject. However, the setup ended up being larger than anticipated due to the addition of components required to allow any experiments performed to run smoothly. The cooling fan for example was used to reduce the temperature of the custom machined light collector due to the temperature the component reached during operation of the device. The custom machined light collector was important as it was responsible for accepting a liquid light guide which carried the emitted light to the patient. A 2-1 branched ratio liquid light guide was used to transmit the light. This fiber was purchased from Edmund Optics. An input of 2 points was used because two inputs provided a larger surface area allowing for more light to enter the liquid light guide. A 2 branched light guide was used to increase the surface area at the input to increase the coupling efficiency which lead to an increase in light intensity at the output. The increase in light intensity at the output of the liquid light guide was required as the SIR-3400 spectrometer had an input that wasn't very sensitive, as mentioned before. For example, if the light entering the spectrometer was not of certain intensity the spectrometer would show data that was noisy and desired values could not be distinguished from undesired values. Of all the components shown above the most important one would be the custom machined tungsten bulb cooling block. This component both houses the light bulb and provides cooling to combat the heat created by the light source. To maintain it at a reasonably cool temperature a water cooling pump was used in conjunction with a water cooling reservoir that stored all the water needed to cycle through the system. Keeping a stable and cool temperature around the light bulb would stabilize its emission spectra, due to the theory of Black Body radiation. In addition, to control the output of the light source a 0-140Vrms Auto-Transformer (Variac) was used as shown in Fig. 9. The Variac allowed for a steady and adjustable power to be supplied to the light source which allowed for variation in light output intensity to exist. During experiments conducted on subjects the data was collected by a program (SandHouse) that came along with the spectrometer. This program provided features that allowed for visualization of desired wavelengths with great resolution. The following represents the design diagram for both the light collector block and the cooling block.

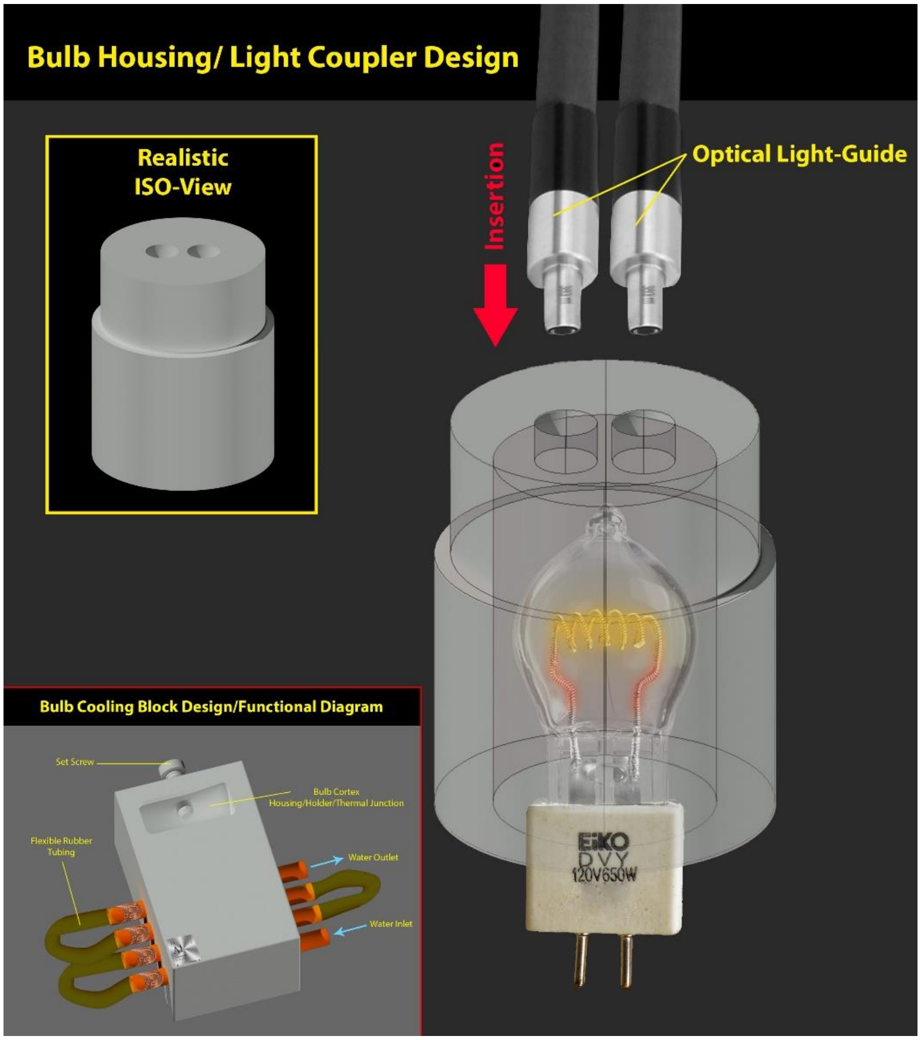

Fig. 8. Design/Functional Diagrams of the Light Collector Block and the Cooling Block

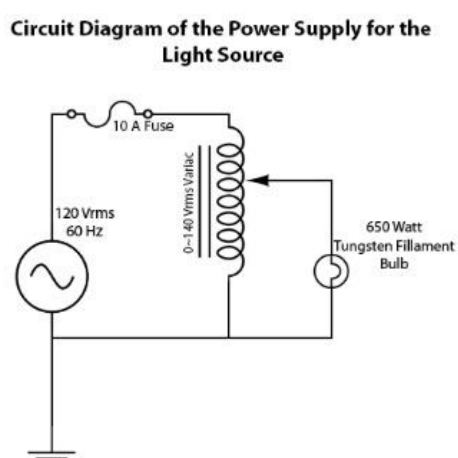

Fig. 9. The Power Control Circuit Schematic of the Bulb

After the design of the contraption shown in Fig. 7, it was time to collect the body measurements from human subjects. I collected data from myself and one other female participant. The experiment went as follows:

Initially, the spectrum sample range was set to 1000 - 1700 nm.

1- The light source was turned on to 83% of the power and was directly fed into the spectrometer to get the maximum collectible data.

2- The light source was then turned on to 83% power and four samples were collected when the participants had an empty stomach (low blood sugar), from the thin web flesh between the index and middle finger of the right hand (Fig. 10.)

3- The participants then consumed a plain timbit (Tim Hortons Sweet/Starchy Pastry) and four samples were collected after 10 minutes of the consumption (allowing the blood sugar to rise).

4- The participants then consumed another timbit and the same process was repeated after 10 minurtes of the consumption.

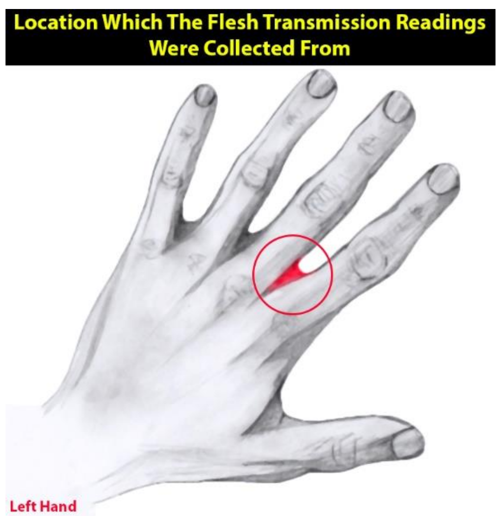

Fig. 10. Location in Which the Flesh Was Illuminated and Data Was Collected From

As it can be seen in Fig. 11, although the input light measured by the spectrometer resulted in a decent signal to noise ratio, the measurements from the body were far too noisy. In addition, the spectra data showed misleading DC offsets which might have also been resulted from the low signal to noise ratio. I did play around with digital Fourier filters but the data was uninterpretable to me, due to my limited knowledge in signal processing.

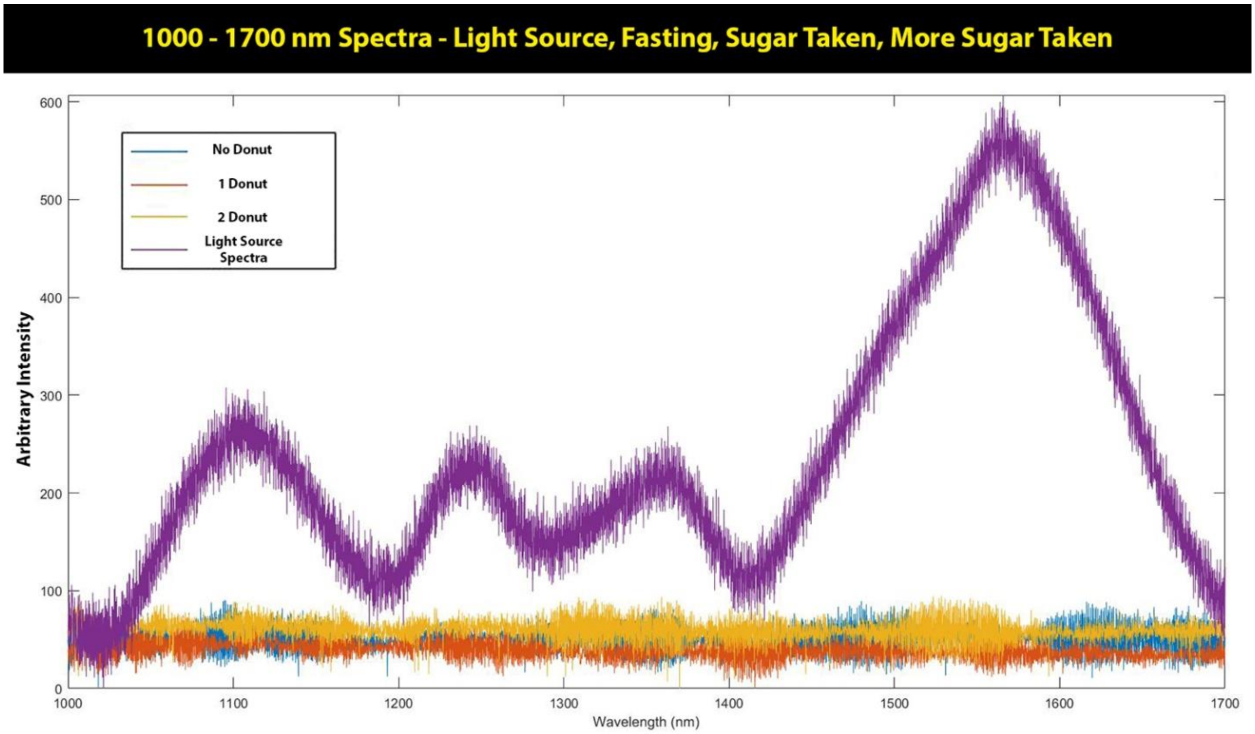

Fig. 11. Light Source Spectra and Ensemble Averages of the Body Spectra, For Each Blood Sugar Scenario

Pros and Cons:

Pros –

The device was flexible in the sense that it allowed for data from multiple different locations in the body. Another location that was tested was the ear lobe. It was thought since the ear lobe is composed of relatively thin tissue, it could be able to attenuate the incoming light just enough for a reading to become possible on the spectrometer. Lastly, another location that could be used is the tip of the finger around the nail plate and cuticle. The reasoning behind such a choice is due to the dermis of the nail bed being very vascularized. However, due to the nail plate artifacts were introduced into the signal that didn't allow for a clear signal to arise at the output leaving out the option of using the nail plate as a region to use. In addition, another pro is the effectiveness of the prototype created. Many experiments were conducted using the prototype created and each time the device showed that it could be used effectively without the need of too much maintenance. The device allowed for data to be acquired in a quick manner allowing for experiments to be conducted under shorter than expected intervals.

Cons –

The limiting factor of the experiment was the measurement tool that we used to. Specifically, the spectrometer. Due to its low sensitivity, lackluster software, and no manufacturer support the project had to be adjusted accordingly. This means that a higher-powered light source had to be purchased, for which a cooling device was devised. The device became larger than anticipated due to all the additions that were required to make a functional prototype. Therefore, the device is no longer portable and fails to meet its initial goal. In order to operate the device a computer is required that runs Windows XP. Without the use of Windows XP, the spectrometer could not be used as its software is designed specifically for the use on that operating system. Another con is the temperature some of the components reach during operation. More specifically, the temperature that is reached by the custom machined light collector. During operation if the device is active for longer than a few minutes the custom machined light collector would reach a temperature that would most likely cause very light burns on anyone who makes contact with the component. Even with the cooling fan the component can not maintain a low temperature during operation. Therefore, a similar water cooling system that is used for the custom machined tungsten bulb cooling block will also have to be used on the custom machined light collector in the future. In addition, another con discovered with the prototype is its ability to produce an desired output in terms of the data collected. Often the experiments on the subjects produced data that was noisy and it made it difficult to distinguish any points of interest from noise observed. Even after filters were applied to the data, using MATLAB, the data was still seen to be noisy with points of interest being slightly distinguishable from noise.