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Design and Implementation of a Non-Invasive Blood Sugar Monitoring System Using Infrared Optical Sensing Technology

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Abstract: Diabetes is an increasingly prevalent health concern that significantly contributes to renal and cardiovascular diseases. Consequently, effective diabetes management necessitates consistent monitoring of glucose levels. One promising technological advancement in this area is the development of non-invasive glucometer monitoring. This study focuses on creating a user-friendly glucose monitoring system based on near-infrared sensors, which correlates variations in sensor output voltage with glucose concentrations, thereby facilitating accurate and convenient glucose monitoring for diabetes management. The primary goal is to assess the system's accuracy in comparison to traditional fingerstick methods and to evaluate its performance across various age demographics and dietary conditions through experimental testing and Clarke grid analysis. Our research introduces a non-invasive glucose monitoring technique utilizing near-infrared sensors, designed to be user-friendly. The experimental framework and prototype system have been developed to measure glucose level variations in relation to sensor output voltage. By applying Beer-Lambert's law, we established a correlation between light absorbance properties and sample concentration levels. Testing was conducted on individuals of different ages under various dietary conditions. The results obtained were systematically recorded and validated against the traditional fingerstick method, achieving an accuracy rate of 97.8%. Additionally, Clarke grid analysis was performed to illustrate the patterns observed.

Keywords: Blood Glucose Monitoring-Invasive Technologies. Infrared Sensing. Ultraviolet Sensing. Glucose Measurement.

Introduction:

In today's society, diabetes has emerged as a prevalent metabolic disorder characterized by abnormal blood glucose levels. This condition arises when the body fails to produce sufficient insulin. It is estimated that over half of the Indian population is affected by diabetes, with smillion by 2050. The current trend of urbanization and increasingly sedentary lifestyles contributes to heightened social stress, which in turn elevates the risk of developing diabetes. Consequently, diabetes represents a growing medical concern with significant life-threatening implications, necessitating serious attention and ongoing research to address its complications.

Diabetes is classified into three main types: Type 1, Type 2, and gestational diabetes. Type 1 diabetes is typically caused by an autoimmune response that leads to the destruction of insulin-secreting beta cells in the pancreas. Type 2 diabetes, on the other hand, is characterized by insulin resistance, resulting in elevated blood sugar levels. Both genetic predispositions and lifestyle choices play a crucial role in the development of Type 2 diabetes. Gestational diabetes occurs during pregnancy when the placenta produces hormones that interfere with insulin, causing increased blood sugar levels. The complications associated with diabetes can be severe, including cardiovascular issues, neurological disorders, and retinopathy. Additionally, diabetes may lead to hearing impairment, foot infections, skin infections, as well as mental health challenges such as depression and dementia.

A variety of medications are available for the management of diabetes, including insulin injections, dietary plans, and exercise regimens. Once a diabetes diagnosis is made, routine health care monitoring becomes essential, particularly the self-testing of blood sugar levels multiple times throughout the day, which is necessary for tracking treatment progress, regardless of the patient's age or type of diabetes. Traditionally, blood sugar levels are assessed through invasive methods, such as the Blood Drawn Test (BDT) or fingerstick blood tests. The BDT involves collecting a significant volume of blood from the patient using a syringe in a laboratory setting, followed by the addition of a reagent to measure blood glucose concentration. In contrast, the fingerstick method involves pricking the finger to obtain a blood sample for glucose level determination. This frequent finger pricking can lead to pain, tissue damage, and skin punctures for the patient.

The Continuous Glucose Monitoring (CGM) system utilizes a sensor with a transmitter and receiver to measure interstitial fluid rather than blood directly. However, it still necessitates two finger pricks daily to ensure accurate CGM readings. Invasive methods present several challenges, including stress prior to blood collection, pain experienced by patients, the risk of external infections, and skin irritation. Additionally, the accuracy of results from the fingerstick method can be compromised due to improper storage of test strips or exposure to environmental factors. In many underdeveloped countries, the high cost of needles leads to the reuse of disposable needles.

Research efforts are concentrated on non-invasive techniques for measuring glucose levels while minimizing harm to human tissues. Several non-invasive approaches are being explored, including optical glucose monitoring, fluid sampling, microwave techniques, as well as minimally invasive and electrochemical methods. Among these, optical methods that operate in the near-infrared (NIR) spectrum (680–2500 nm) play a significant role in blood glucose detection. These methods utilize light that can penetrate body fluids and soft tissues to a depth of less than 0.05 cm, exhibiting lower scattering properties compared to ultraviolet or visible light, and can be assessed through both reflection and transmission sensing mechanisms.

1. Related work:

In this study, the researchers employed a light-emitting diode operating at approximately 940 nm in conjunction with a photodiode to develop a non-invasive measurement technique. To assess the device's sensitivity, in vitro tests were conducted across various glucose concentrations, utilizing an Easy Touch GCHb glucometer for measurement. The findings indicate that as glucose levels increase, the voltage decreases, which is attributed to the absorption of light intensity. The authors propose the use of near-infrared (NIR) transmittance spectroscopy for quantifying glucose levels in the bloodstream. An artificial mixture of sugar dissolved in distilled water was used to simulate the body's glucose concentration. The implementation of a notch filter effectively reduced noise power levels, thereby enhancing measurement accuracy. The collective optical signals are employed to estimate glucose levels, with predictions made regarding tissue glucose concentration at the fingertip based on data from a color image sensor. Predicted the blood glucose from the subject's wrist using a visible and near-infrared (Vis-NIR) optical-based wearable sensor .The voltage value is computed for four different channels of wavelength (950 nm, 850 nm, 660 nm, and 535 nm) for analysing the average corre- lation coefficient. The in vivo experiment was done using a limited number of 12 different subjects. The sensitivity and correlation coefficient for the different subjects is around 6.16 mg/dL and 0.86. In the research work [13], they conducted in- vitro experiments and in-vivo testing for glucose concentration identification. An infrared source of 940 nm is an illuminated ray of light with a PIN photodiode onto the human fingertip to detect the light transmitted. It has been evaluated by obtaining the correlation between output potential and glucose level.

This paper proposes the utilization of a dual-channel near-infrared sensor operating between 1200 nm and 1900 nm to assess the responsivity of the epidermis and dermis, which are the top and middle layers of the skin, respectively. The primary objective of this analysis is to mitigate the interference caused by noisy signals from the skin's surface layer, thereby enabling precise detection of glucose levels in the bloodstream. A consumer-oriented, non-invasive wearable device, referred to as iGLU 2.0, was employed to measure serum glucose levels. For the prediction of serum glucose, both polynomial regression and neural network methodologies were utilized. This innovative healthcare approach integrates the Internet of Medical Things framework with end users. In the study conducted by Li and Li (2015), a monitoring system was proposed that utilized glucose aqueous solutions, where a laser diode served as the transmitter and a light power probe (S302C) acted as the detector. The findings indicated a strong correlation between glucose concentration and output power. In vitro testing was conducted using a diluted glucose solution, while in vivo experiments were carried out with a sensor patch placed on the forearm. The glucose concentration was derived from the collected data through the application of an appropriate signal-processing technique, albeit with a limited number of subjects.

This review of various studies highlights the significant influence of the signal-to-noise ratio on near-infrared glucose detection methods, emphasizing the critical role of the measurement site, which can be easily influenced by external factors. It has been concluded that measurement instruments must be meticulously designed to ensure high accuracy and appropriate sensitivity, thereby achieving an optimal signal-to-noise ratio. Additionally, filtering techniques can be employed to remove frequency-sensitive noise from the baseband optical signal. A major challenge remains in the design of wearable devices capable of accurately measuring blood serum glucose, which must also be adaptable to different diabetic conditions. From all the observed flaws and challenges, to tackle the problems stated, we propose a non-invasive measurement device to measure blood serum glucose by continuous means to provide data accurately. The process has been explained in detail in the following sections.

2. Experimental setup:

The comprehensive workflow diagram for the experimental arrangement involving glucose samples is illustrated in Figure 1. When light strikes a material, a specific quantity of the transmitted beam is absorbed, which is contingent upon the concentration of the material in question. In the proposed approach, the artificial combination of distilled water with sugar facilitates the determination of glucose concentration by simulating a biological environment. An electrical circuit has been designed, featuring a near-infrared (NIR) LED operating at a wavelength of 940 nm as the transmitter, while the receiver is an avalanche photodiode (FGA015) also at 940 nm. Positioned between the NIR LED and the photodiode is a glucose solution. As the NIR LED emits light, a fraction of it is absorbed by the liquid phantom. The photodiode detects the amount of light that has been transmitted and generates a corresponding electrical current that reflects the concentration of the glucose solution. The correlation between glucose concentration and current is examined and analyzed. The precise weight of the sugar is measured using accurate weighing equipment (ELB300 PLATFORM BALANCE), as depicted in Figure 1. The entire experimental setup for measuring the current and its corresponding voltage flow resulting from the light absorbed by the sample is presented in Figure 2.

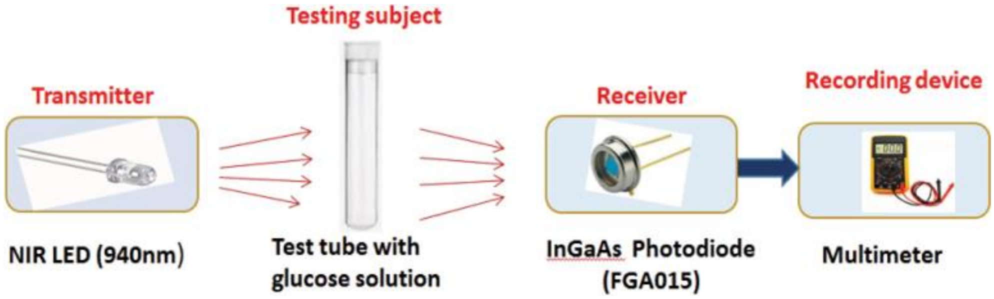


Figure 1. Experimental setup workflow diagram.

4. Prototype system:

The complete workflow diagram for the blood glucose level mon- itoring system using the prototype system is shown in Figure 3.

4.1. Transmitter section:

The initial phase of source identification is crucial, as the light directed at the subject must maintain adequate contact with the fingertip. It is recommended to employ lightweight and compact light sources to achieve effective illumination. The near-infrared wavelength of 940 nm has been determined to be ideal, as it can penetrate organic tissue with minimal absorption by other biological components present in human membranes, including water, lipids, and proteins. The compound semiconductor AlGaAs is suggested as the most appropriate material for the light source, capable of emitting at the optimal wavelength within a power range of 20 mW to 30 mW. To ensure accurate coverage in the targeted penetration area, the LED should be oriented perpendicularly to the fingertip.

4.2. Receiver section:

The light that is transmitted can penetrate the dermis layer to a depth ranging from 0.4 to 0.8 inches, which requires the detector to possess adequate sensitivity to identify the absorption of near-infrared light by glucose molecules in the blood. The detector, located beneath the fingertip, utilizes the OPT101 sensor. This sensor is of the optoelectronic variety and features current-to-voltage converters and operational amplifiers, all contained within a single integrated circuit, as illustrated in Figure 4. The OPT101 demonstrates remarkable sensitivity to the 940 nm wavelength being transmitted and provides numerous benefits, such as a compact design, affordability, a high responsivity of 0.57 V/μW, minimal leakage error, and improved compatibility with wearable devices.

4.3. Data acquisition system:

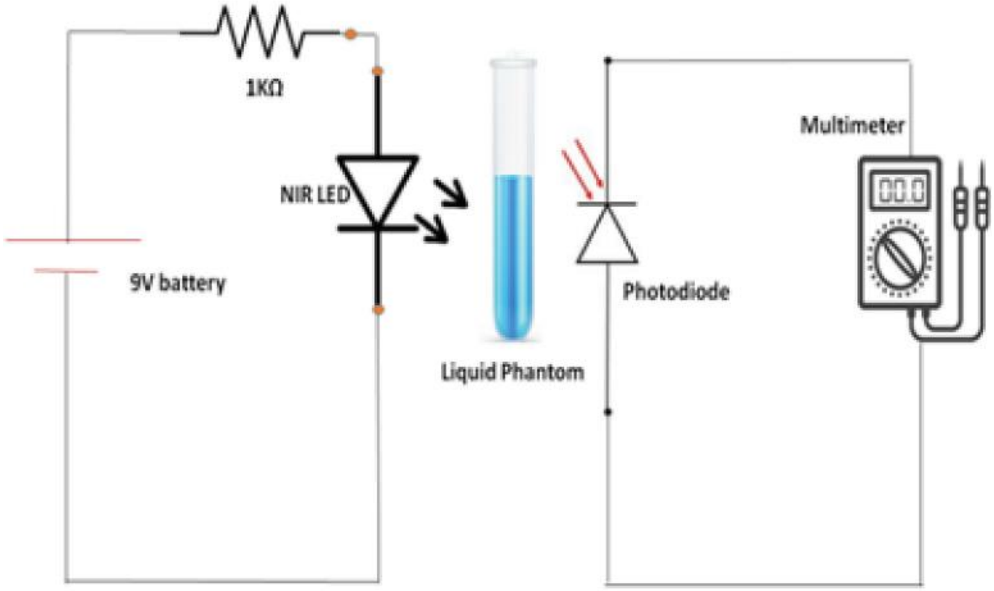
The data acquisition system consists of a data sensing unit and an analog-to-digital converter (ADC) unit. This system integrates an Arduino with MATLAB, enabling the transfer of output from the OPT101 sensor to a laptop via a USB connection. The sensor data collected is analyzed, and the obtained voltage values are processed by considering attenuation to ascertain their corresponding wavelengths. MATLAB then saves this information as variables in text files. The Arduino program is designed to process each sample with a delay of 0.5 seconds, leading to an estimation of 120 data units per minute. The ADC is tasked with converting the analog voltage output from the sensor into digital values that range from 0 to 1023.

4.4. FFT:

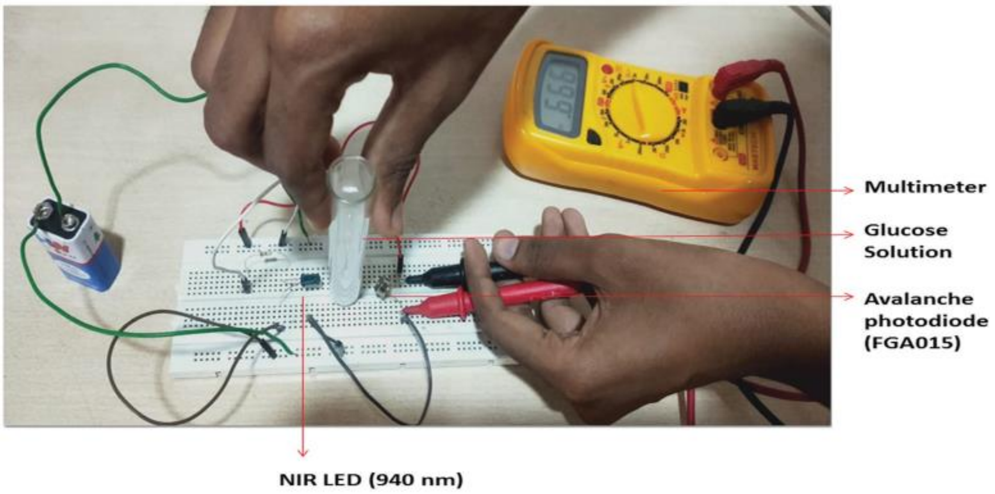
The digital data collected from the data acquisition system, initially represented in the time domain, is transformed into the frequency domain through the application of FFT algorithms prior to undergoing a filtering process. The FFT facilitates the analysis of both spectral content and phase information.

4.5. Blackman filter:

The digitalised data is then filtered to remove the noise due to environmental effects such as water, fat, protein and so on present in the blood (Ingle and Crouch 1988). In the proposed system, the Blackman filter is used to remove the low-fre- quency and high-frequency tones ranging from 2.34 Hz to1.59 kHz.



(a)



(b)

Figure 2. Experimental setup (a) circuit diagram (b) experimental setup.

Blackman window equation for the length N is

$$w(n) = 0.42 - 0.5cos(2\pi nL - 1) + 0.08\cos(4\pi nL - \quad 0 \le n \le M - 1 \qquad (1)$$

where M is $\frac{N}{2}$ when N is even and $\frac{N+1}{2}$ when N is odd

4.6. Estimating glucose concentration:

Beer-Lambert's law articulates the absorbance characteristics of materials across various samples. This law considers factors such as the concentration of the sample, the thickness of the medium, the temperature of the platform, and the wavelength of the radiation. It is defined as the quantity of light absorbed in a uniform medium, which is directly proportional to both the concentration and the thickness of the medium.

of the sample as shown in Figures 5 and 6. When a light beam passes over a uniform sample, the intensity of the transmitted radiation declines with the increase in thick- ness and concentration of the liquid phantom.

The transmittance of the liquid phantom is based on absor- bance (A) and the optical depth

$$A = \epsilon c l \quad (2) \qquad T = \left(\frac{(I)_e^t}{(I)_e^i}\right) = e^{-\tau} = 10^{-A} \quad (3)$$

Or

$$A = \log_{10}(T) = \log_{10}\left(\frac{I_T}{I_T}\right) = \epsilon c l \quad (4)$$

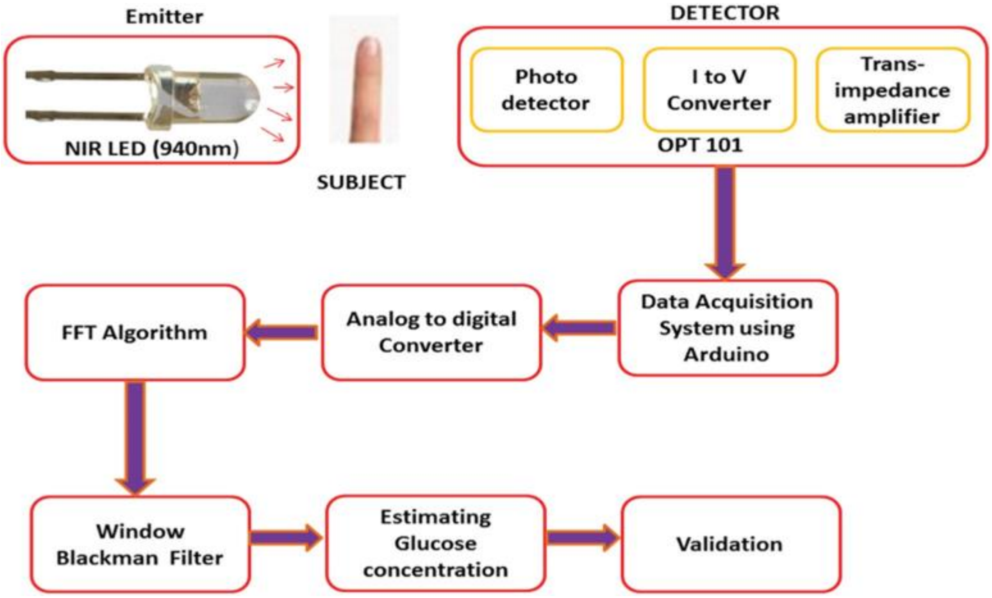


Figure 3. Workflow diagram for the blood glucose monitoring system.

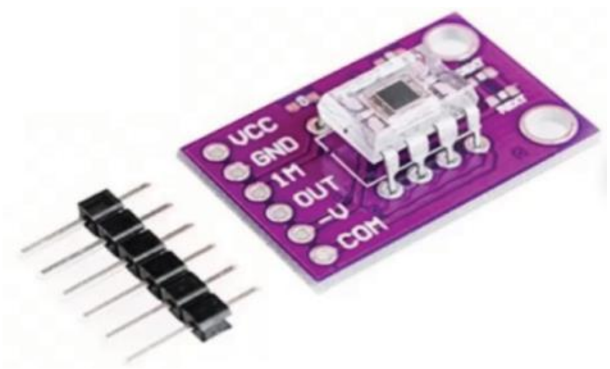


Figure 4. OPT101 light intensity sensor

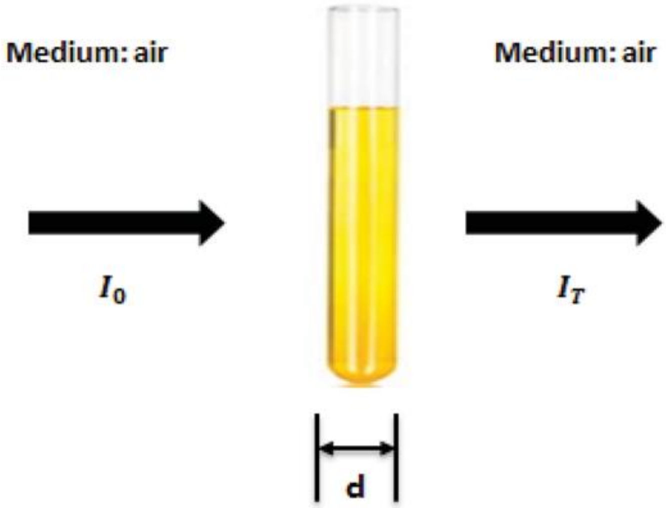


Figure 5. Passing of light beam in liquid phantom

where, T. A and t is the term of transmittance, absorbance, and optical depth, tporresponds to transmitted radiant flux, i js the received radiant flux, the intensity of light entering the liquid sample is a whereas leaving the sample is fra As per the Beer-Lambert law

$$T = e^{-\sigma \int_0^l N(z)dz} = 10^{-\in \int_0^l C(z)dz} \quad (5)$$

Or equivalently

$$\tau = \sigma \int_0^l N(z)dz \quad (6)$$

$$A = \in \int_0^l C(z)dz \quad (7)$$

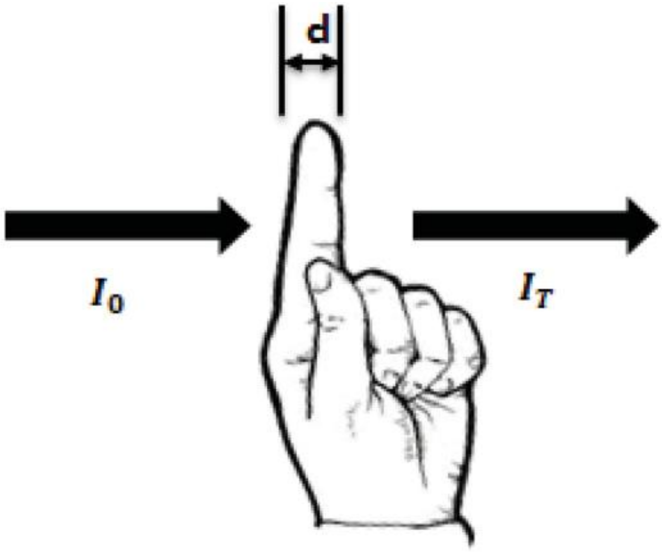


Figure 6. Passing of light beam in human fingertip.

Where l represents path length; N represents attenuating mate- rial number density; represents attenuation coefficient; σ is the cross-section of the attenuation material; c represents attenuating material molar concentration.

Under consistent attenuation, the equation follows as

$$T = e^{-\sigma Nl} = 10^{-\in cl} \quad (8)$$

$$\tau = \sigma Nl \quad (9)$$

$$A = \in cl \quad (10)$$

The Beer-Lambert law illustrates the relationship between a sample's concentration and its light absorbance.

5. Results and discussion:

In this section, a comprehensive presentation and explanation of the results obtained from both the experimental approach and the prototype system are provided.

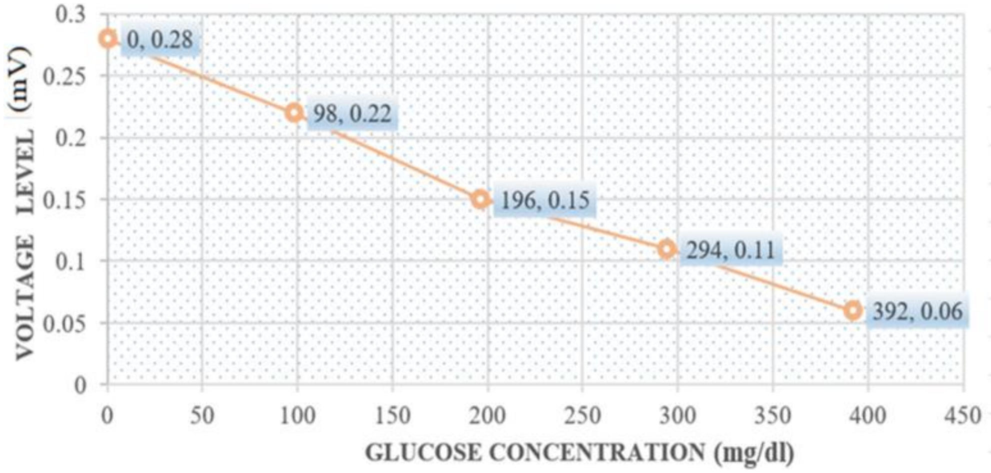


Figure 7. Voltage flow variation corresponding to glucose concentration levels.

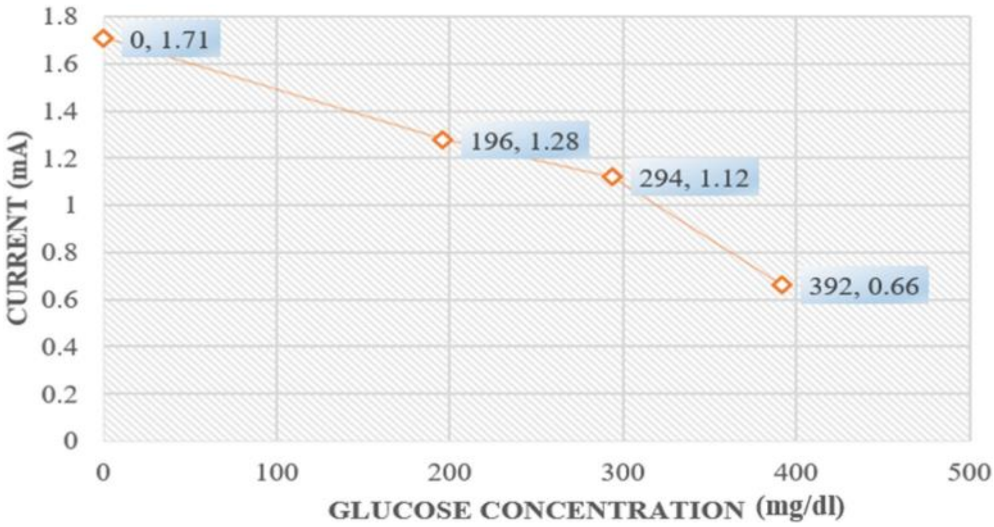


Figure 8. Variation in the flow of current relative to the specific concentration of glucose.

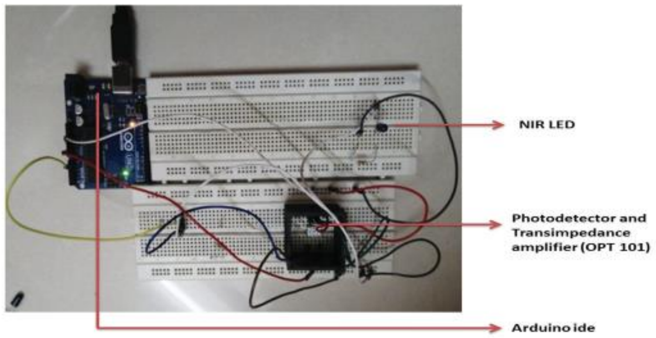
5.1. Results of the Experimental Approach:

The exact weight of the sugar is determined using specialized apparatus, namely the ELB300 PLATFORM BALANCE, as shown in Figure 2. In the course of the experimental procedure, a liquid phantom or sample is created by mixing 30 ml of distilled water with sugar.

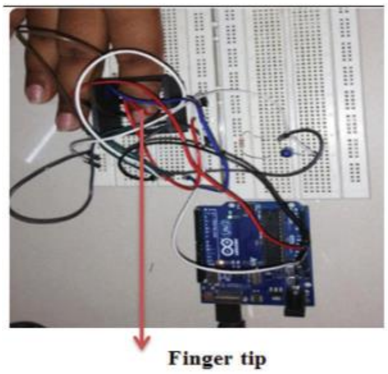
The findings derived from the experimental configuration illustrated in Figure 2, which demonstrate the correlation between current and the associated voltage flow resulting from light absorption by the sample, are graphically represented in Figure 7. The data distinctly reveal that the current recorded at the photodetector diminishes as the concentration of glucose in the liquid phantom increases.

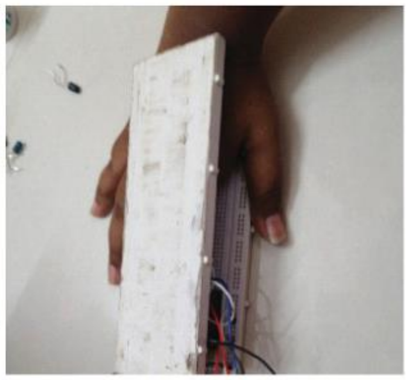
As a result, Figure 8 illustrates a decreasing trend, reinforcing the assertion that blood glucose concentration (mg/dl) is inversely correlated with the current generated by the photodetector.

Similarly, the voltage output from the photodetector decreases as glucose concentration increases, which is due to the glucose molecules in the liquid phantom absorbing light intensity. This leads to a decline in voltage, as depicted in Figure 7. Hence, it can be inferred that the concentration of glucose (mg/dl) in the blood is inversely related to the voltage produced by the photodetector.

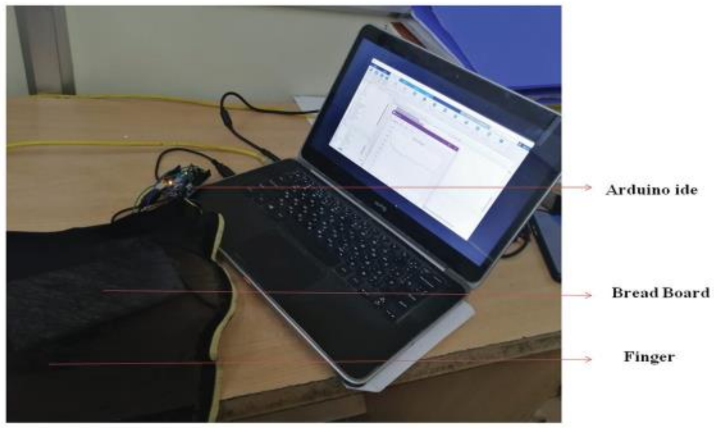


(a)





(b) (c)



(d)

Figure 9. Prototype of the complete glucose estimation system (a) prototype setup (b) fingertip subject placed over OPT101 (c) transmission and reception of optical. light (d) entire set-up covered with black cloth.

5.2. Prototype results:

A heterogeneous group of participants, representing a range of ages and including both individuals with diabetes and those without, was assembled to assess the effectiveness of the proposed prototype system. The blood glucose levels recorded by this prototype for a 20-year-old female are depicted in Figure 9. The complete configuration of the prototype is illustrated by arranging the optical transmitter and receiver on a breadboard connected to an Arduino, as shown in Figure 9(a). The subject's fingertip is then positioned above the optoelectronic sensor (OPT 101) to evaluate the glucose concentration in the blood sample, as represented in Figure 9(b). Following this, the NIR LED is placed in direct contact with the subject's forefinger to enable light transmission, as indicated in Figure 9(c). To ensure the detector operates at peak efficiency, it is essential to reduce or eliminate ambient light in the surrounding area. Consequently, the entire prototype setup is completely covered with black cloth, as demonstrated in Figure 9(d).

During the initial stage of data collection, a 20-year-old female participant is assessed to observe fluctuations in blood glucose levels. The prototype is first powered on to activate the NIR LED (AlGaAs LED), which emits invisible light. The subject's forefinger is positioned above the optoelectronic sensor (OPT 101) to measure the glucose concentration in the blood sample through optical techniques. The NIR LED is then placed in contact with the forefinger to capture the light that passes through the medium. The subject is tested under four different conditions: fasting, one hour after food intake, one and a half hours after food intake, and two hours following morning food consumption. The estimated values are presented in Figure 10. Initially, the subject, a female, underwent blood glucose testing through an optical method while in a fasting state. During this fasting period, the intensity of light detected between the near-infrared (NIR) LED and the optical receiver was noted to be lower. The recorded blood glucose concentration during fasting was 85 mg/dl. According to Beer-Lambert's law, light that traverses blood will absorb photon molecules. As the glucose concentration increases, the number of photon molecules absorbed by the blood also increases. Therefore, the output of the proposed system indicates fluctuations in blood glucose concentration in relation to the intensity of the transmitted light. Subsequently, the subject ingested a high-carbohydrate meal consisting of bread and milk. The digestion of this meal occurs in the small intestine, where carbohydrates are transformed into glucose and absorbed into the bloodstream. During this process, the intensity of light received by the OPT 101 decreased compared to the initial measurement. After one hour, the estimated blood glucose level increased to 123 mg/dl. Blood glucose levels were similarly evaluated after one and a half hours and two hours following consumption, as illustrated in Figure 10.

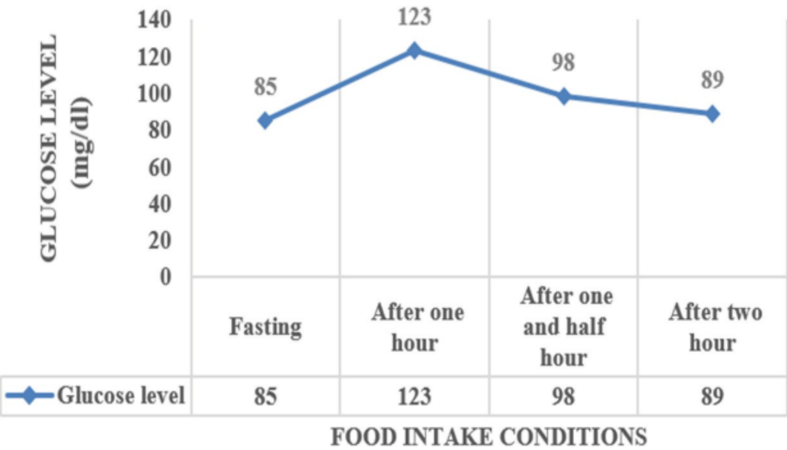


Figure 10. Estimated glucose concentration utilizing a non-invasive method.

Figure 11. Validation of a non-invasive method through the use of an invasive device for an individual.

7. Conclusions:

This research article introduces a novel methodology designed to demonstrate the relationship between glucose concentration and the output voltages of sensors, which are affected by the light intensity emitted from a Near Infrared LED. The findings indicate that an increase in glucose concentration results in a corresponding decrease in sensor voltage. The proposed prototype of the NIR LED-based glucose sensor offers a promising invasive technique for the continuous monitoring of blood glucose levels. Experimental data for this prototype are presented and depicted in Figures 5–7, with test results collected over a span of 50 seconds. The effectiveness of the non-invasive prototype has been compared to traditional invasive methods across four volunteers under three different conditions: fasting, one hour after consumption, and one and a half hours after consumption. The results suggest that the non-invasive method closely mirrors the invasive approach, showing a strong correlation between fluctuations in photon intensity detected by the photodetector and glucose levels. Additionally, analysis through the Clarke grid indicates that the test measurement data points are within an acceptable range, suggesting that the developed non-invasive glucose monitoring system demonstrates enhanced accuracy. Future investigations may aim to explore the impact of skin texture and bodily fluid concentration on sensor performance to improve calibration and system sensitivity.

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