IJAAR PUBLISHING®

International Journal of Advanced Academic Research | ISSN: 2488-9849
Vol. 10, Issue 2 (February, 2024) | www.ijaar.org

Implementation of a real-time Arduino Based Non-Invasive Blood Glucose Monitoring System

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Abstract

Diabetes mellitus is an acute metabolic disease that can cause damage to the body system and lead to complications if not properly managed. The disease has been classified as one of the world's killer diseases by the World Health Organization (WHO). Implementing a non-invasive near-infrared monitoring device will make diagnosing and monitoring the diseases highly convenient without causing damage to any body tissue or inflicting pain. This paper presents the development of an optically-based glucose sensor using near-infrared spectroscopy to develop a non-invasive blood glucose monitor. The developed near-infrared spectroscopy device was implemented using an Arduino microcontroller, a 940nm LED, a photodiode, a noise filter, an amplifier circuit, and an LED display screen. An invitro experiment of output voltage against infused glucose solution in water placed within the sensor and photodiode is measured for calibration of the device. Twelve people were randomly selected, and the fasting blood glucose level was monitored by measuring it twice (the second measurement was taken after two hours of the first measurement) to get the mean fasting glucose level. The linear regression model was applied, and a correlation coefficient (R2) of 0.9369 was obtained. The high regression coefficient indicates a high correlation between the device's measurements and actual blood glucose levels. This implies that the device's readings are highly predictive of the true glucose concentration.

Keywords: Non-invasive, near infrared spectroscopy, blood glucose, diabetes mellitus

1.0 Introduction

Diabetes has been identified by the World Health Organization as a chronic and non-communicable disease in 2008 and has been proposed as the leading cause of death ranking between fourth and seventh around the world come 2030 (Gregory, 2012). Diabetes mellitus also referred to simply as diabetes is an auto immune disorder that is caused by the inability of the body to regulate sugar or glucose in the body. Persistent untreated diabetes leads to damage and dysfunction of other sensitive organs in the body (Chaudhary & Tyagi, 2022). The insulin produced by the pancreas helps to balance sugar or glucose in the system, but it becomes a health challenge when the pancreas produces less insulin than required or the body has become unable to utilize the produced insulin. There are basically two types of diabetes: Type 1 and Type 2 diabetes mellitus (Matthew & Tadi, 2022).

The absence of pain, piercing, cutting, or bruising to obtain intestinal fluids or blood is known as non-invasive. Several non-invasive techniques have been developed and have been classified according to the material used. The techniques for measuring blood glucose levels that are non-invasive can make use of either tissue or biofluids. Blood glucose measurement requires that a small amount of blood be extracted from the body through invasive methods or through the minimally invasive method, where biosensors are implanted beneath the skin to obtain interstitial fluid. These aforementioned methods are hurtful and sometimes inconvenient, but they are the most precise measurement method for detecting the level of sugar or glucose in the body (Ogunniyi et al., 2021). Its recurrent disadvantage has caused researchers to seek alternate measurement methods that will not cause pain, anxiety, or damage body tissues.

These methods use transducers (sensors) to convert the physical quantities (tissues and fluids) into electrical quantities like current, voltage, and impedance for analysis using electrochemical, electro-mechanical, optical, and other techniques (Ionescu, 2018).A non-invasive method of monitoring the blood glucose level of diabetic patients was actualized by the use of transducers (biosensors) that detect blood glucose levels without inflicting pain on the body. Non-invasive methods can employ the use of tissue or fluids in detecting of blood sugar levels in the body (Alarcon-Paredes et al., 2019). Tissues like the skin, the aqueous humor of the eye, the ear lobe, and the nose, or bio-fluids (tears, saliva, sweat, or urine) other than the blood, are used to analyze the level of glucose present in the bloodstream (Lin et al., 2022; Zhao et al., 2019).

The management of blood glucose levels in a diabetic patient requires constant diagnosis and monitoring. The need to constantly monitor the blood glucose level in diabetic people is necessary since diabetes mellitus (an autoimmune disorder) can cause great damage to the body to the point where the body cannot properly utilize the insulin produced or produce enough insulin. This imbalance of insulin in the body (a hormone produced in the pancreas) leads to the accumulation of sugar in the body, which can also destroy the pancreas (Vashist, 2012). Unfortunately, no known cure has been found for diabetes mellitus, though it can be managed to prevent complications (Alsunaidi et al., 2021).

The earlier traditional method of diagnosing people suffering from diabetes was through an invasive method of drawing blood with injections. Presently, the invasive method is done by finger pricks, and a few droplets of blood are used as a sample. Minimal invasion was also introduced, where interstitial fluids are used for glucose measurement and detection by implanting a biosensor beneath the skin (Chen, 2018). This causes pain and discomfort with

use over time. Patients suffering from diabetes mellitus need to continuously monitor their blood glucose level, which can be done more than once if a sufficient blood sample is not obtained. Diabetic patients with very high glucose levels need to constantly observe the glucose in their body more than once a day to prevent a system collapse. This invasive method causes body discomfort, anxiety, and bruises on the finger from multiple piercings of the fingertips, and it inflicts pain on the patient.

In previous studies, different methods have been used, including optical spectroscopy, transdermal techniques using sonophoresis to reverse iontophoresis, and a thermal approach using the absorption effects of glucose by estimating glucose concentration by measuring the behavior in relation to thermal emissions (Alarcon-Paredes et al., 2019). There has been a great deal of scientific investigation into the development of glucose monitoring devices and meters using different methods; one such method is optical spectroscopy. Infrared spectroscopy includes near-infrared (NIR), mid-infrared (MIR), Fourier transform infrared (FTIR), and Raman spectroscopy, where there is a light beam of a particular wavelength that is incident on the part of the body (fingertip or the lobe of the ear or nose) that is reflected, absorbed, or refracted and transmitted, then transformed into an electrical quantity that can be measured (Lin et al., 2022).

2.0 Glucose Monitoring

Monitoring of glucose concentration in the body is done to prevent complications that arise from the accumulation of glucose or sugar in the blood that can destroy the pancreas and, if untreated, can lead to death. The accumulation of excess or unregulated glucose in the body poses a need for measurement to prevent complications such as glaucoma, kidney damage, heart disease, stroke, birth defects, and cataracts. It can lead to a coma and sudden death. The measurement and detection of glucose concentration in the body fluid also started during its era of detection in the early 19th century with glucose in urine. Whenever there is very high glucose in the bloodstream, the excess glucose can be noticed in the urine, which was adopted as a non-invasive method. The detection of the glucose concentrate in urine was done by adding a copper reagent to the urine. The patient's urine was dropped into the reagent and placed in boiling water for a few minutes. The color displayed after the process is an indication of the amount of glucosuria detected. The colors could be either orange/red, yellowish, or green, which correspond to high, moderate, and very light concentrations of sugar levels in the body, respectively (Olczuk & Priefer, 2018).

By the 20th century, the use of blood testing by strip to detect the concentration level of sugar in the body was done using glucose oxidase strips. The blood is dropped on a strip and washed after a minute. The color detected, corresponding to the color chart, is observed to determine the level of glucose in the body. By 1980, the concept of commercializing and making the glucose meter available for personal use at home was launched with the introduction of the Dextrometer. It was not accurate in measurement, but it started the era of commercialization of the glucose meter.

Due to the invasive method of measurement that causes pain inflicted by pricking the tissues of the fingers, Researchers worked to ensure that the pain and amount of blood were reduced to the barest minimum. This led to the use of electrochemical strips for the measurement and detection of sugar levels. The introduction of the enzymatic test was developed and improved upon, which led to the launch of the minimally invasive method of detection of sugar levels.

Min et al. (2017) described the first reported research in non-invasive techniques by Robinson using near-infrared transmission spectra of 800–1300 nm on the finger for meal tolerance level (Min et al., 2017). By 1999 different products emerged for use as a non-invasive device that will not inflict pain, infection, or skin ulcers. The emergence of implemented non-invasive technology has opened up a highly competitive market for the production of an effective, accurate and high-precision device for non-invasive measurement and detection of the blood glucose level in the human body (Hirsch, 2018).

3.0 Optical Techniques for Non-Invasive Methods

There are various sensor technologies for measuring blood glucose concentrations, including invasive, minimal, and non-invasive methods. Optical sensor systems, such as near-infrared vibrational spectroscopy, Raman spectroscopy, and photoacoustic detection, are the most promising, but there are also other techniques like bioimpedance and refractive index changes. The target site for testing varies between technologies, with potential sites including the skin and easily accessible body fluids (tears and sweat). The development of non-invasive glucose measurement technologies is still in the early stages, with challenges in calibration and effectiveness.

Optical measurement techniques use electromagnetic wave radiation to evaluate the concentration of glucose in the tissue used for non-invasive methods. The optical technology explores the properties of electromagnetic waves of a wavelength of 0.75nm (the infrared wavelength) when they are incident on a medium to reflect, refract, diffract, absorb, and scatter the light wave (Ogunsaya & Daramola, 2022). One such optical methodology is optical spectroscopy, which uses the effect of light and has its incidence on a medium like the skin, fingertip, and earlobe. It has three regions that can be utilized: mid-infrared, near-infrared, and far-infrared spectroscopy (El-Azazy, 2018). The optical measurement of blood glucose level is used to overcome the physiological lag in interstitial fluid-based detection.

Near-infrared spectroscopy is a technique that uses the transmittance and reflectance of light of a wavelength between 700 and 2500 nm, relying on molecular vibrations and the bond rotation of glucose molecules. This can be classified further into its first overtone (1400–2000 nm), the second overtone (750–1400 nm), and its band between the first band and 2500nm; the combinational spectra (Hina & Saadeh, 2022) and (Laha et al., 2022). It detects changes in light intensity caused by the absorption or scattering of wavelengths during glucose molecule detection, though it scatters less than ultraviolet. The second overtone has spectra that have minimal interactions with water, hemoglobin, and lipids (Delbeck et al., 2018).

Near Infrared Spectroscopy is used for the identification and chemical characterization of molecules and compounds. The infrared interacts with the chemical polarity of the molecule or compound due to its electromagnetic property of light waves. In cases where there is no polarity in the compound, no infrared radiation is given off (Oloyo, 2020).

According to Yaacob et al. (2021) and Saad et al. (2017), the infrared wavelength of 940nm has the best absorption correlation to glucose concentration with the chemical formula $C_6H_{12}O_6$ in the body tissue. The most commonly used wavelength for NIR is 940nm in the second overtone of O-H and C-H stretching, and it has been used in the implementation of a non-invasive device using the absorption of light with an operational amplifier to detect glucose in the blood. It is cost-effective as compared to the other spectra.

According to Laha et al. (2022), there have been researchers that have compared the long and shorter wavelengths of NIR spectra for the best glucose estimation. The short wavelength has been able to penetrate through the finger tissues and has a better glucose estimation in the blood. The light transmitted through the glucose molecule is inversely proportional to the concentration of glucose in the sample based on the absorbance at the NIR overtones.

$$A = \log I_0 - \log I \quad (1)$$
$$= \log \mathrm{Io}/\, I$$
$$T = I \,/\, I_0 \quad (2)$$

Where A = Absorbance, I *and* I_0= Intensity of transmitted light and intensity of incident light respectively. T=Transmittance of light through the molecule of the sample.

The Beer-Lambert law will be used to calculate the absorption of light waves. Beer-Lambert rule is linear with the formula below:

$$A = \varepsilon C \ell \quad (3)$$

Where ε = molar absorptivity, C = concentration of sample (in mg/dl) and ℓ= pathlength

$$\varepsilon C \ell = \log I \,/\, I_0 \quad (4)$$

It implies that as the glucose concentration increases, causing an increase in light intensity and a corresponding short optical pathlength leading to decrease in effective coefficient

$$A \propto C \quad (5)$$
$$A = log\, T \quad (6)$$

Coefficient of absorptionμa is also a product of Ɛ and C

The effective coefficient is the function of scattering coefficient, μs and absorption coefficient,μa.

$$\mu_{\mathrm{eff}} = \mathrm{f}\,(\mu_{\mathrm{s}}, \mu_a) \quad (7)$$

$$\mu_{\mathrm{eff}} = \sqrt{3\mu_a\,(\mu_a + \mu_{\mathrm{s}}\,(1\text{-}\mathrm{g}))} \quad (8)$$

with g is average cosine angle of scattering.

Narkhede et al. (2016; the authors used the 940nm short wavelength of the NIR, leveraging reflectance techniques, and got a second-order polynomial with regression. It can be improved with the inclusion of a noise filter.

In the journal Noninvasive Blood Glucose Monitoring System based on the near-infrared method by Al-Dhaheri et al. (2020), the authors implored that the other technique of NIR is photoplethysmography (PPG), which uses changes in the volume of circuitry flow of blood with the PPG voltage signal proportional to the flow of blood through the blood vessel. The technique takes note of the heart rate and pulse, and by using a machine learning algorithm, the blood glucose level is calculated. The extraction is based on linear regression with a correlation factor (R^2) of 0.839 and an average root mean square error of 10.44 mg/dl. There is a need to improve noise filtering as well. The challenge of adapting the circumference of the finger and the roughness of the skin is needed by the general person. In Blood glucose detection using 3 LEDs: an analytical model by Pedro et al. (2021) The blood glucose was measured using 3 LEDs with different wavelengths by PPG. In this method, one or two LEDs are used to transmit the infrared spectrum or spectra through the tissue of the finger, earlobe, or forearm before detection by a photodiode (photodetector).

The effects of wavelength on the skin of the human using infrared and light-emitting diodes (LED) using the wavelength between 890nm and 1mm of electromagnetic waves compared to ultraviolet light and visible light from lasers are irradiations that are used for treatment and monitoring of blood glucose levels and have no side effects, making NIR a safe option (Cios et al., 2021).

4.0 Materials and Methodology

The near-infrared spectra with wavelengths of 700nm –2500nm has a light absorption peak to ensure minimal optical signal attenuation, minimal interference with water, and a greater selectivity for glucose concentrate with a high signal-to-noise ratio. The 940nm LED (sensor) falls within the short wavelength and with the wave characteristics was used because it is one of the sensors that is readily available and made the implemented device cost effective (Hirsh, 2018).

The near-infrared (NIR) sensor is connected to the fingertip via the finger clip. The sensors used the absorption of light from the emitted electromagnetic spectrum with a wavelength of 940nm to detect the glucose concentration at the tip of the finger. The NIR sensor and photodiode were interfaced with the Arduino module to convert the spectroscopic wave measurement linearly with the noise filter (low pass filter) and then sent through the amplifier. Figure 1 shows the block diagram of the designed non-invasive system. The amplified output voltage is connected to the ADC embedded in the microcontroller, whose value is transmitted and displayed on the screen. The value displayed will correspond to the calibrated glucose level obtained. The sensor is embedded into the finger clip for detection of the fingertip. Figure 2 shows the flow chart diagram of the implemented device.

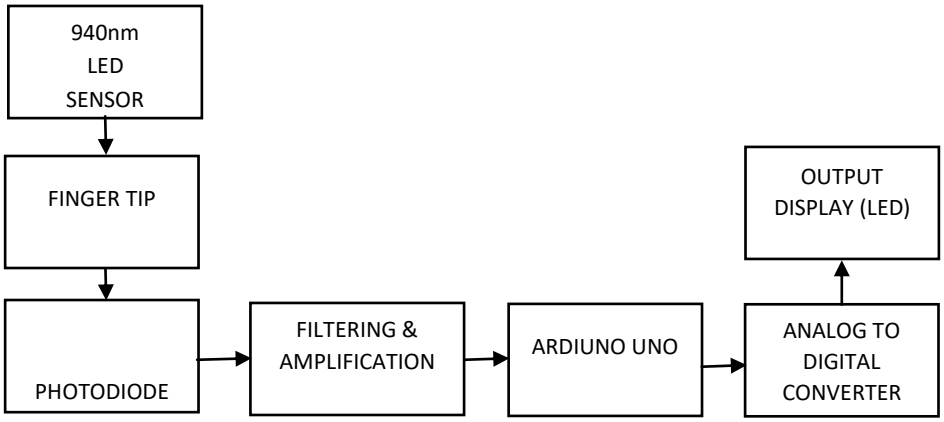


Figure 1: Block diagram of the implemented device

An improvised invitro method was used for the programming of the Arduino microcontroller. The glucose aqueous solution was mixed with water and the glucose concentration was increased gradually from 0mg to 250mg with increment of 50mg of glucose solution per time. The measurement was measured alongside the output voltage of the device. Figure 3 shows the relationship with the transmittance of the spectrum by the solution as it is being varied with the output voltage.

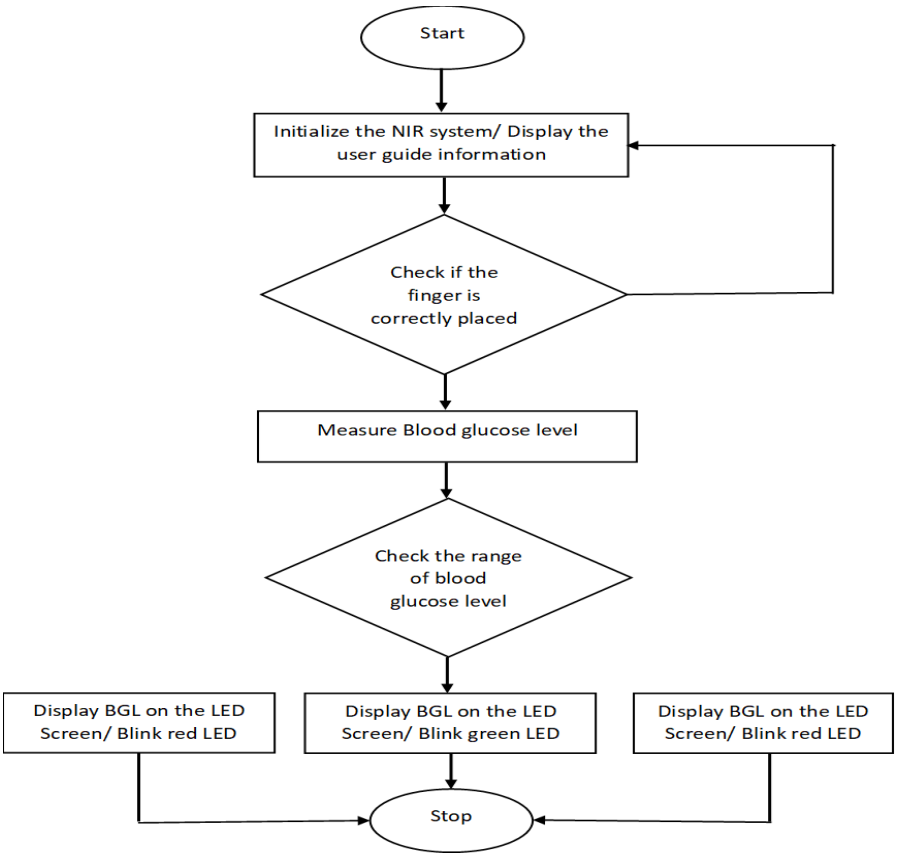


Figure 2: The flowchart of the blood glucose level monitoring device

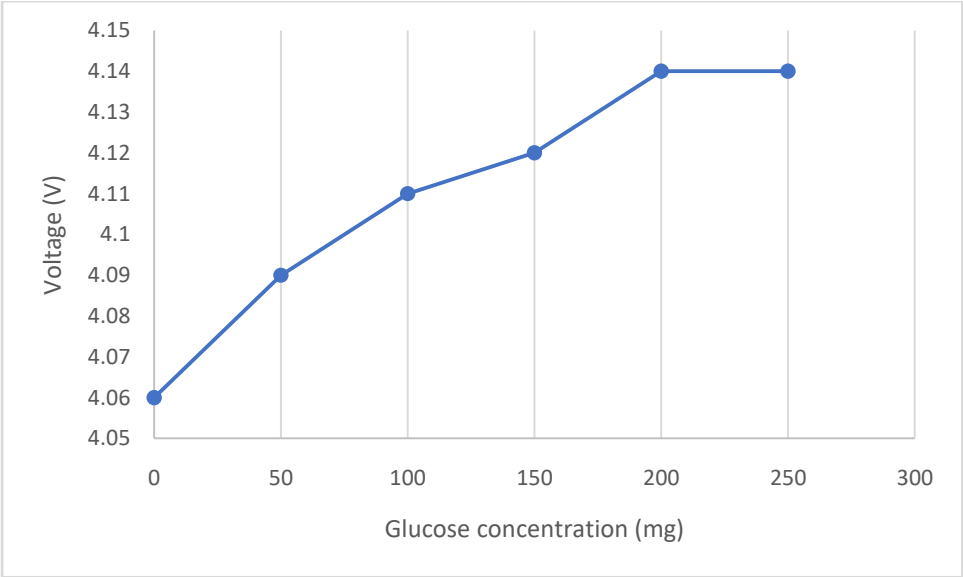


Figure 3: Graph of the concentration of aqueous glucose in water against output voltage

5.0 Result and Discussion

Previous studies and experiment showed that at a temperature of 30^0C and using glucose syrup that the 940-950nm spectra shows that water is least absorb in the NIR region. It also shows that the first overtone and second overtone region which lies in the shorter wavelength of the NIR are highly recommended for blood glucose estimation. The absorption, A is proportional to the glucose concentration, C in equation 5 was used in vitro experiment for initial calibration and programming of the Arduino. Figure 4 below, showed the implementation of the device while measuring the blood sugar level (mmol/L) of one of the individuals used for sample collection. The difference in the referenced value against the measured output value is shown on the graph in figure 5.

The linear regression model was used with the equation y = 1.1623x - 0.175 and a correlation coefficient of R^2 = 0.9369 as seen in figure 5. Statistical data gathering was gotten from twelve (12) random sample for validation (taken twice within the interval of two hours to get the mean fasting blood plasm level) and accuracy check.

$$Error, E = \frac{y - y_i}{y_i} \quad (9)$$

where y and y_i measured blood glucose level in mg/dl and referenced level respectively.

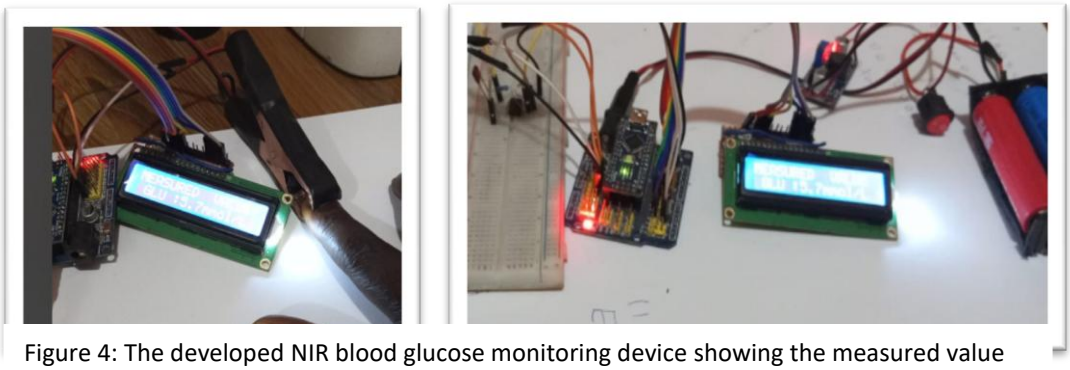


Figure 4: The developed NIR blood glucose monitoring device showing the measured value

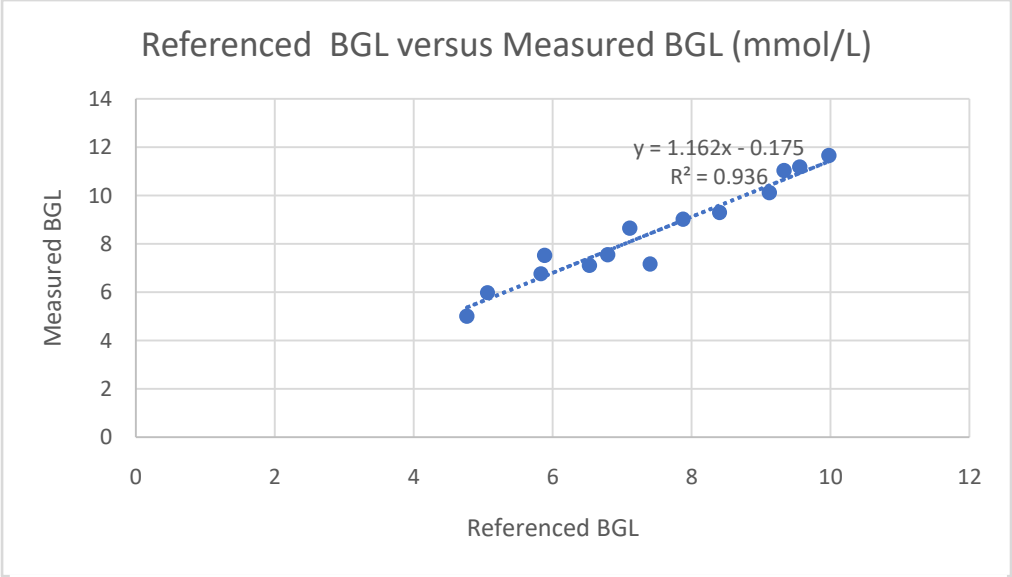


Figure 5: Measured blood glucose level versus referenced blood glucose level

6.0 Conclusion

Utilizing the near infrared technology aligns with a broader trend in the development of the non-invasive device. The developed device allows for a convenient diagnosis and monitoring of blood glucose level without causing any pain or harm to body tissues. The device incorporates an Arduino, a 940nm sensor, a photodiode and a noise filter to increase efficiency, reliability and reduce noise. This study leveraged on the infrared spectroscopy for its implementation using the linear regression model with a correlation coefficient of 0.9369. Further study and future trend can implement this design into smart wearable device.

Acknowledgement: This research is sponsored by the Tertiary Education Trust Fund (Tetfund) under the Institution Based Research Grant Intervention 2022.

Conflicts of Interest: The authors have no clash of interest

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