ORIGINAL ARTICLE

Non-Invasive Human Blood Glucose Measurement Using Near-Infrared Sensor

Ahmed Ibrahim Alroud, Fazrena A. Hamid, Jehana E. Jamaluddin

Department of Electrical & Electronic Engineering, College of Engineering,Universiti Tenaga National (UNITEN), Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia

ABSTRACT

Introduction: Non-invasive glucose monitoring remains an important challenge in diabetes management due to limitations of traditional invasive approaches. This study explores the feasibility of using a low-cost reflective opto-electronic sensor (TCRT5000, 950 nm near-infrared LED) for preliminary glucose estimation. **Materials and methods:** A study was conducted with 30 adult participants, where fingertip measurements were obtained using the TCRT5000 sensor integrated into a simple circuit. For each subject, sensor output voltage was recorded and compared against blood glucose levels measured by a commercial glucometer. Multiple readings per subject were taken to reduce random error. **Results:** The pooled dataset showed a strong linear relationship between sensor voltage and reference glucose values (R^2 = 0.996). Clarke Grid Error (CGE) analysis showed that 100% of points were in Zone A, and the Mean Absolute Relative Difference (MARD) was 3.11%. However, variability due to finger placement, skin thickness, and potential optical interferences was observed. **Conclusion:** These findings suggest that the TCRT5000 sensor has potential for non-invasive glucose estimation, though further studies with larger and more diverse cohorts are recommended to validate clinical applicability.
Malaysian Journal of Medicine and Health Sciences (2025) 21(SUPP11): 88-94.doi:10.47836/mjmhs.21.s11.13

Keywords: Non-invasive glucose monitoring, Near-infrared (NIR) spectroscopy, TCRT5000 sensor, Diabetes management, Proof-of-concept study

Corresponding Author:
Ahmed Ibrahim Alroud, Master
Email: ahmad.ir1970@gmail.com
Tel : +962772114949

INTRODUCTION

Diabetes mellitus is a major global health challenge, affecting an estimated 422 million people worldwide in 2014, with projections indicating a continued rise. According to the World Health Organization (WHO), diabetes will be one of the top ten causes of death in 2021, with a 95% rise since 2000(1). Conventional glucose monitoring relies on invasive finger-prick methods, which are accurate but inconvenient and painful, leading to reduced patient compliance. This has motivated extensive research into non-invasive glucose monitoring (NIGM) techniques that can provide reliable, real-time, and pain-free alternatives.

Several approaches to NIGM have been explored, including optical, electromagnetic, and biochemical methods. Optical methods, particularly near-infrared (NIR) spectroscopy, have attracted significant interest due to their ability to probe glucose-related absorption in tissue (2,3). Research has demonstrated that wavelengths in the range of 940–2500 nm can provide glucose-sensitive spectral features, though the accuracy depends heavily on sensor design, wavelength selection, and calibration algorithms (4,5). For instance, commercial-grade NIR spectrometers and custom-built devices have achieved 82–95% accuracy in CGE analysis when tested on larger cohorts (6,7).

Electromagnetic and impedance-based methods have also been investigated, though these often suffer from variability due to skin hydration, temperature, and electrode placement (8). Similarly, optical coherence tomography and Raman spectroscopy show high sensitivity but remain impractical for widespread use due to cost and complexity(9) .

Despite these advances, no commercially available non-invasive glucose monitoring system has yet replaced conventional glucometers in clinical use. High device costs, complex calibration requirements, and interference from physiological factors remain major barriers (10,11). In this context, low-cost and widely available optoelectronic sensors present an attractive alternative for preliminary investigations into NIGM feasibility.

This study investigates the TCRT5000 reflective infrared sensor, a simple and inexpensive optoelectronic device

with an emission wavelength of approximately 950 nm. From the literature review, the shorter-region wavebands of NIR are most suitable for skin penetration and, hence, most appropriate for glucose detection. Prior work investigating NIR spectroscopy for detecting blood glucose levels is within the range of 750 to 1550 nm(11). Although not specifically designed for biomedical use, the sensor's spectral properties overlap with absorption bands of glucose and other tissue constituents, making it a potential candidate for low-cost NIGM research. The objective is to evaluate whether the sensor's output voltage correlates with reference glucometer readings in a sample of 30 subjects, thereby providing a proof-of-concept foundation for further refinement.

The general principle for this study depends on detecting the reflected infrared rays from glucose compounds to measure their level in the blood. Figure 1 shows the behavior of IR rays when reflected from blood contents. The relationship between blood glucose levels and reflected infrared (IR) light is that the intensity of the reflected light correlates with the concentration of glucose in the blood. This allows for accurate measurements of glucose levels without the need for pricking or drawing blood. This principle is the working mechanism of the TCRT5000 sensor, which sends rays from the photodiode transmitter. These rays collide with glucose molecules and are then reflected to the receiver, which is a phototransistor. The wavelength of the TRCT5000 sensor is 950 nm, which is in the shorter range of NIR.

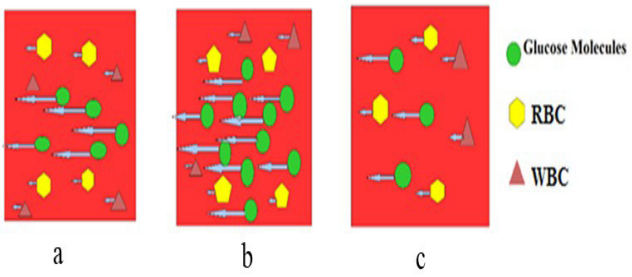

Figure 1: (a) IR ray (blue arrows) reflected by glucose molecules in the blood (b) increased glucose molecules increase the intensity of reflected ray (c) decreasing glucose molecules reduces the amount of reflection.

MATERIALS AND METHODS

This experiment was conducted at Universiti Tenaga Nasional, Malaysia, with patient tests performed at the Department of Medical Equipment at Prince Zaid Military Hospital in Tafila City, Jordan. The flowchart in Figure 2 below shows the project methodology for glucose measurement in patients using both the non-invasive sensor device and the invasive device, i.e., glucometer.

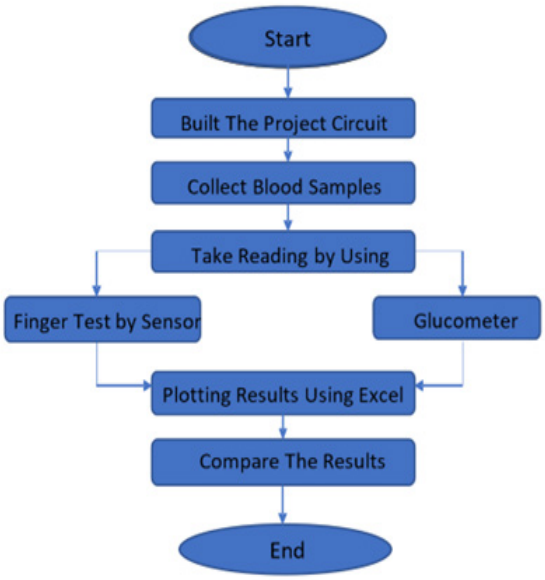

Figure 2: Methodology Flowchart of this study.

Thirty adult participants (both diabetic and non-diabetic) were recruited. Inclusion criteria required participants to be over 18 years of age and able to provide consent. Exclusion criteria included skin lesions, severe circulatory problems, or recent hand injury, as these may affect sensor readings. For each subject, three consecutive voltage readings were recorded and averaged. Immediately afterward, a blood sample was collected and analyzed using a commercial glucometer (Gluco Check). Both the non-invasive voltage readings (Vout) and the reference glucose levels (mg/dL) were documented.

The patients place their finger on the TCRT5000 sensor, as shown in Figure 3, where the fingertip is placed directly above the sensor module, allowing emitted IR light to be partially absorbed and partially reflected back to the phototransistor.and a voltage reading is obtained using a digital multimeter (Vout). Then, a blood sample is taken from the same patient and analyzed with a Gluco Check device to measure the blood sugar level(mg/dL). The voltage value from the sensor and the corresponding blood sugar reading are recorded in a table for comparison.

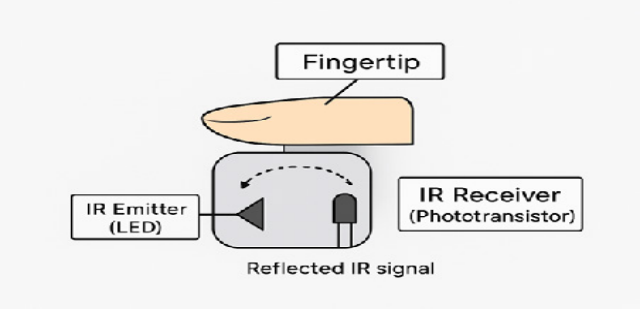

Figure 3: Glucose detection using TCRT5000 Sensor.

The circuit diagram in Figure 4 shows the TCRT5000 infrared sensor (emission peak at 950 nm), two resistors, a 5V DC supply, and a multimeter. The TCRT5000 is an optical sensor that includes both an IR LED and a phototransistor. The TCRT5000 device emits infrared radiation using an IR LED at 950nm, while the phototransistor receives the IR light after reflection(8). When connected to the power supply, the IR diode sends infrared light that is absorbed by the fingertips of patients. This near-infrared (NIR) ray is reflected by the glucose molecules in the blood and is detected by the phototransistor. Resistor R1 (220 Ω) is connected in series with the IR photodiode and is to limit the current through the IR LED. R2 (10 k Ω) acts as a pull-up resistor for the phototransistor, ensuring a stable output signal, as the transistor biasing is mainly controlled by the received IR light. The resulting output voltage due to the reflected light is measured across the phototransistor. As shown in the block diagram of the measurement system, which highlights the functional flow of data. The optical signal from the TCRT5000 was detected and transmitted to the microcontroller, where it was processed and then displayed on an LCD module or transferred to a personal computer for visualization and storage. This representation emphasizes the data path and the system's modular structure.

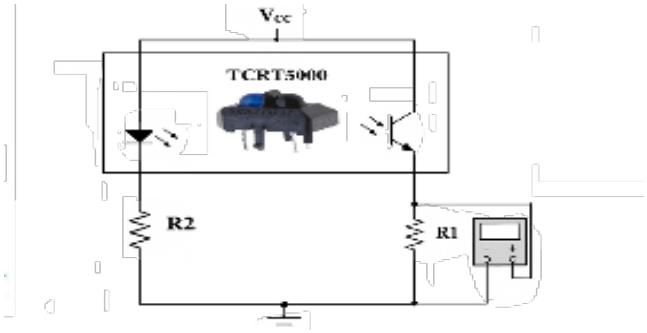

Figure 4: Circuit Diagram

It considers the standard factors for glucose and infrared wavelengths, where the wavelength (λ) for the infrared sensor is 950 nm. These factors ensure that incident light impacts glucose more than other molecules and that glucose reflects more light than other substances. The specific frequency of light acts as a key to detect glucose. It's also important to note the relationship between the two wavelengths: if the wavelength for glucose is much smaller than that for infrared, glucose behaves as a reflective element for near-infrared (NIR) light; however, if the opposite is true, glucose does not reflect NIR (11).

In this work, a TCRT5000 sensor with a wavelength of 950 nm is utilized. Previous studies have determined that the optimal wavelength for estimating glucose molecules in blood ranges from 750 nm to 1400 nm (7). The protocol for measuring blood glucose levels involves using a TCRT5000 sensor alongside a standard glucometer. In this method, the patient first places a finger on the TCRT5000 sensor, which captures a voltage reading displayed on a multimeter (Vout). This non-invasive reading is followed by collecting a blood sample from the same patient, which is then measured using a Gluco Check glucometer to ascertain the blood glucose level(mg/dL). Both the sensor output voltage (Vout) and the corresponding reference glucose level (mg/dL) were documented in a dataset for comparison. For instance, a recorded voltage value of 4.510 V may correspond to a blood glucose concentration of approximately 54 mg/dL. Such comparative data points provide insights into the potential relationship between sensor voltage readings and blood glucose levels, supporting further analysis and calibration. Future advancements could involve integrating a digital electronic control circuit into the sensor setup, enabling the automatic conversion of voltage readings into direct blood glucose values. This integration would enhance the device's functionality, offering a more efficient and user-friendly alternative to noninvasive blood glucose monitoring.

Sensor voltage values (V) were paired with corresponding glucometer readings (mg/dL) for each subject. The dataset was analyzed using Microsoft Excel. Scatter plots and linear regression were applied to establish the correlation between sensor voltage and reference glucose values. The coefficient of determination (R^2) was calculated to quantify the strength of the linear relationship. In addition, clinical accuracy was evaluated using CGE analysis and the Mean Absolute Relative Difference (MARD) metric, as recommended by international standards for glucose monitoring device validation. as shown in Figure 5.

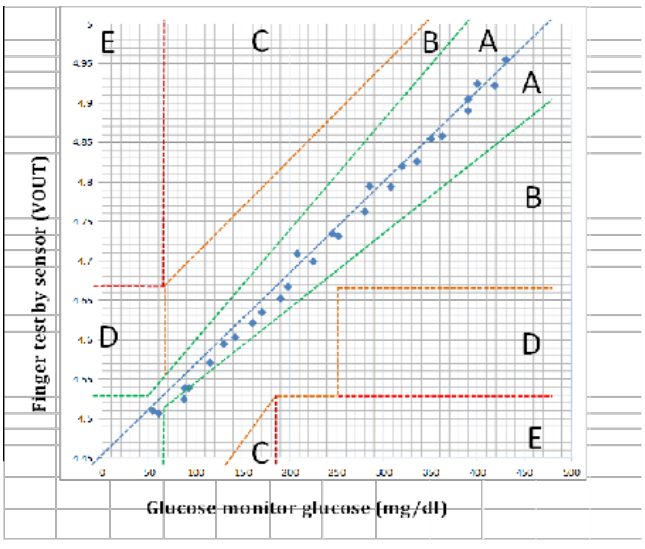

Figure 5: Glucose level versus measured voltage by Clark grid error

For each subject, three consecutive voltage readings were recorded and averaged. Immediately afterward, a blood sample was collected and analyzed using a commercial glucometer (Gluco Check). Voltage readings (Vout) and corresponding blood glucose levels (mg/dL)

were documented. Data analysis included scatter plots, linear regression (R^2), CGE, and Mean Absolute Relative Difference (MARD).

Ethical Clearance

Ethical approval was obtained from the ethics committee of the target institution (reference number: M.T.H/1429). Participants were informed that their involvement is voluntary and that they can withdraw or decline participation at any time without penalty. Additionally, informed consent was obtained from all participants before their involvement.

RESULTS

The study was conducted on 30 participants (both diabetic and non-diabetic). Table I presents the sensor output voltage range from 4.510V to 4.985V alongside corresponding reference glucose values between 54mg/dl and 460mg/dl. A clear trend of increasing voltage with higher glucose concentrations was observed. Linear regression analysis produced the following calibration equation, as shown in Figure 6:
with a coefficient of determination R^2= 0.996, indicating a strong linear relationship between sensor readings

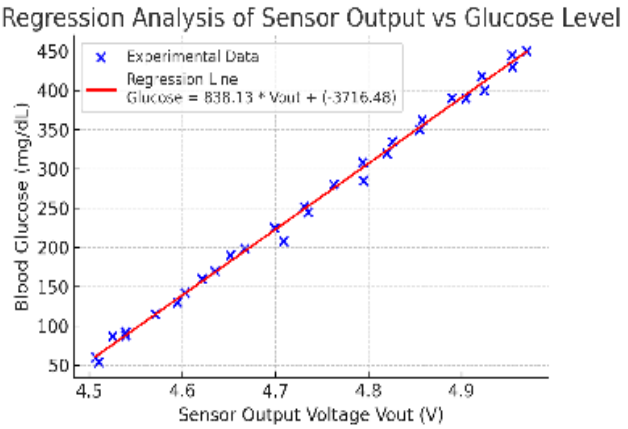

Figure 6: The regression analysis between sensor output voltage (Vout) and reference glucose levels (mg/dL).

$$\text{Glucose (mg/dL)} = 838.13 \times \text{Vout} - 3716.48 \quad (1)$$

and reference measurements. Similar regression-based calibration approaches have also been employed in prior studies on non-invasive glucose monitoring using near-infrared sensors, where glucose concentration was estimated from optical signals through linear or multivariate regression models (11).

The TCRT5000 sensor was used to measure fingertip glucose levels, with its output recorded in voltage. These voltage readings were then compared to glucometer readings, which provided actual blood glucose levels in milligrams per deciliter (mg/dL).

To evaluate clinical reliability, CGE analysis confirmed that 100% of the 30 data points fell within Zone A, as shown in Figure 5, showing clinically acceptable accuracy. The Mean Absolute Relative Difference (MARD) was 3.11%, well below the 10% threshold commonly used in glucose monitoring validation, according to Equation (2).

$$\text{MARD} = (1/N) \times \Sigma \, | (\text{CGM-Reference})/\text{Reference} | \times 100\% \quad (2)$$

N: is the total number of paired measurements, CGM: is the value from the continuous glucose monitor, Reference is the value from the comparison method (e.g., SMBG or a clinical blood analyzer), and Σ: denotes the sum of the values(12). In this study, three consecutive readings were obtained for each of the 30 participants using the CGM system, and their average was compared against simultaneous glucometer readings. The calculated MARD was 3.11%, which is considerably lower than the widely accepted clinical threshold of 10%, indicating the potential reliability of the proposed system.

Descriptive Statistics: Voltage readings ranged from 4.510 V to 4.985 V, corresponding to glucose values between 54 mg/dL and 460 mg/dL. The mean glucose level was approximately 255 mg/dL with a standard deviation of ±130 mg/dL.

These findings suggest that the proposed approach demonstrates promising feasibility for low-cost non-invasive glucose estimation despite the small sample size and simplified measurement setup.

DISCUSSION

The regression slope (838.13) indicates that each 1-volt increase in sensor output corresponds to an approximate increase of 838 mg/dL in glucose concentration. The intercept (–3716.48) serves to adjust the calibration line so that the estimated glucose levels align with the reference glucometer readings. The high R^2 value (0.996), obtained from Figure 6, demonstrates that voltage output strongly correlates with actual glucose levels. However, it is important to note that correlation alone does not guarantee specificity for glucose, as external factors such as skin thickness, pigmentation, and finger pressure may also influence infrared reflectance.

In this study, Table I shows the data on glucose levels (mg/dL) and corresponding voltage readings (V) measured from a patient's finger by the TCRT5000 sensor. A clear positive correlation between the glucose level and the voltage reading is shown. For lower glucose levels, i.e., 54 mg/dL, the voltage reading is relatively low at 4.510 V. For higher glucose levels, i.e., 450 mg/dL, the voltage reading is relatively high at 4.970 V. This suggests that the voltage measurement from the finger could potentially be used as a non-invasive indicator of blood glucose levels. However, further analysis and validation are needed to establish the accuracy and reliability of this

method for medical use. Table II shows the descriptive statistics for the experimental results.

Table I: Measured output voltage by finger sensing using TCRT5000 (V), and glucose level measured by glucometer (mg/dl).

Patient Number	Gender	diabetics, non-diabetics	Finger test by the sensor (Vout)	Actual Glucose Level (mg/dl)
1	M	non-diabetic	4.51	54.0
2	M	non-diabetic	4.507	60.0
3	M	non-diabetic	4.525	87.0
4	F	non-diabetic	4.539	88.0
5	M	non-diabetic	4.539	92.0
6	M	non-diabetic	4.571	115.0
7	F	non-diabetic	4.595	130.0
8	M	Diabetic	4.603	142.0
9	M	Diabetic	4.621	160.0
10	F	Diabetic	4.635	170.0
11	F	Diabetic	4.652	190.0
12	M	Diabetic	4.667	198.0
13	F	Diabetic	4.709	208.0
14	M	Diabetic	4.699	225.0
15	M	Diabetic	4.735	245.0
16	F	Diabetic	4.731	252.0
17	M	Diabetic	4.763	280.0
18	M	Diabetic	4.795	285.0
19	M	Diabetic	4.794	308.0
20	F	Diabetic	4.82	320.0
21	F	Diabetic	4.826	335.0
22	M	Diabetic	4.855	350.0
23	M	Diabetic	4.858	362.0
24	F	Diabetic	4.89	390.0
25	F	Diabetic	4.905	390.0
26	M	Diabetic	4.925	400.0
27	M	Diabetic	4.922	418.0
28	M	Diabetic	4.955	430.0
29	M	Diabetic	4.954	445.0
30	M	Diabetic	4.970	450.0

Note. M = Male, F = Female, V= Volt, mg/dl = Milligram/Deciliter

Table II: Descriptive statistics for the experimental results.

Statistic	Voltage Reading (V)	Glucose Level (mg/dL)
Count	30.000	30.000
Mean	4.736	252.63
Standard Deviation	0.15	125.96
Minimum	4.507	54.0
25th Percentile (Q1)	4.608	146.5
Median (Q2)	4.733	248.5
75th Percentile (Q3)	4.857	359.0
Maximum	4.97	450.0

The data can be applied to generate a calibration curve, in which voltage readings are plotted against glucose levels. This curve can then be used to estimate glucose levels based on voltage readings from similar sensors. Then, the CGE analysis (12) may be used to determine the clinical accuracy of the blood glucose monitoring device by comparing the data to reference glucose levels. The grid divides the accuracy of the measurements into five zones (A, B, C, D, and E) according to their potential influence on patient treatment (12,13).

Several significant studies employing NIR for predicting blood glucose levels in the literature show encouraging results for systems created using shorter-region wavelengths similar to the 950nm of the TCRT5000 device in this study.

Several notable studies using NIR for blood glucose prediction systems in the literature indicate promising results for systems developed using shorter-region wavelengths, which are close to the 950nm of the TCRT5000 device in this work. A developed a dual-wavelength system at 940 nm and 1300 nm. They reported 95% accuracy using CGE analysis for predicted blood glucose concentration for 25 subjects, with an R^2 value of 0.9084 (11).

In (13) a system employing NIR at 940 nm is suggested, validated with 200 participants and an R^2 of 0.937, achieving a CGE greater than 95% of predicted glucose readings. In (14) a system was developed using an NIR wavelength of 950 nm, where their CGE validation with 75 subjects shows an accuracy of 82%.

Compared to other approaches in the literature in (7) employed NIR wavelengths in the range of 700 to 2500 nm. The outcome of this study is that while NIR technology shows significant agreement due to its noninvasive nature, there are still challenges related to accuracy, calibration, and individual variables that need to be addressed. The authors recommended that more research and development are essential to overcome these limitations and improve the accuracy and monitoring of NIR-based blood glucose. In (14) NIR wavelengths range from 800 nm to 2500 nm. The results in this study indicate a high correlation between NIR spectra and blood glucose levels, proving the change in the technique. The method successfully measures glucose levels non-invasively, making it easy and less painful. However, this study has some challenges, such as the risk of skin, where NIR light is projected onto the skin, and the reflected light is captured to get spectral data from people with varying glucose levels. Another author (8,9) The NIR wavelength of 1560 nm in their system was 1560 nm. The result is that the system shows high accuracy in glucose measurements, proving effective as a non-invasive monitoring technique. So, the collection of NIR spectroscopy and "Huber's regression model" (9) showed the possibility for practical use in non-invasive glucose monitoring devices. However, this study has significant problems, such as using NIR spectroscopy and Huber's regression model, which are technically demanding and require highly specialized, expensive equipment. Additionally, the initial setup and equipment costs may exceed those of traditional invasive methods.

The strong correlation between TCRT5000 sensor readings and glucometer values highlights the potential of this low-cost infrared sensor for non-invasive glucose monitoring. However, variability due to skin tone, tissue thickness, and finger pressure may influence results. These limitations, along with the small dataset, suggest that findings should be interpreted as proof-of-concept. Prior research using NIR spectroscopy in the 940–950 nm range reported CGE accuracies of 82–95% (13,14), consistent with this study's preliminary outcomes. Future work should validate these findings across larger, more heterogeneous populations and include optical shielding, pressure-control mechanisms, and advanced calibration models to reduce potential interferences. Also, a digital electronic control circuit could be added to the circuit in Fig. 4 to convert the voltage reading to a blood glucose level automatically. This simple prototype can be a low-cost solution to the non-invasive care for patients with diabetes, and is potentially beneficial for use in remote and rural areas, especially in developing nations.

CONCLUSION

This study presented a proof-of-concept non-invasive glucose monitoring system using the low-cost TCRT5000 infrared sensor. The system demonstrated promising accuracy, with all data points within Zone A of the CGE and a low MARD value. Although preliminary, this approach could evolve into a reliable, low-cost, and accessible solution for diabetes management, particularly in resource-limited settings.

ACKNOWLEDGEMENT

We would like to convey our gratitude to all patients who willingly participated in this study, and the Department of Medical Equipment at prince Zaid Hospital in Tafila City, Jordan for providing consent and support for the research.

REFERENCES

1. World Health Organization. The Top 10 Causes of Death. 2024.
2. Kumar, R., Saha, P., Kumar, Y., Sahana, S., Dubey, A. and Prakash O. A review on diabetes mellitus: type1 & Type2. World J Pharm Pharm Sci. 2020;9(10):838–50.DOI: 10.20959/wjpps202010-17336
3. Varadi Z, Szilagyi GA. Applicability of a Gage R&R Study on a Home Blood Glucose Meter. Eurasia Proceedings of Science, Technology, Engineering and Mathematics [Internet]. 2023; Volume: 23, 292 - 299, Available from: www.isres.org.https://doi.org/10.55549/epstem.1368281
4. Van Enter BJ, Von Hauff E. Challenges and perspectives in continuous glucose monitoring. Chemical Communications. 2018;54(40):5032–45. DOI: 10.1039/c8cc01678j
5. Chi-Fuk So, Kup-Sze Choi TKW& JWC. Recent advances in noninvasive glucose monitoring,

Medical Devices: Evidence and Research. ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/dmde20. 2012 Jun 29;5:45–52. https://doi.org/10.2147/MDER.S28134

6. Yasuhiro Uwadaira AI. Noninvasive Blood Glucose Measurement,Nutritional and Therapeutic Interventions for Diabetes and Metabolic Syndrome. In 2018. p. 489–504.
7. Hina A, Saadeh W. Noninvasive Blood Glucose Monitoring Systems Using Near-Infrared Technology—A Review. Sensors. 2022 Jul 1;22(13). https://doi.org/10.3390/s22134855
8. Nadhiya J, Vijayalakshmi M.K, Showbharnikhaa S. A Brief Review on Diabetes Mellitus: Short Communication. Journal of Pharma Insights and Research. 2024;2(1):117–21.DOI: 10.5281/zenodo.10631511
9. Aloraynan A, Rassel S, Xu C, Ban D. A Single Wavelength Mid-Infrared Photoacoustic Spectroscopy for Noninvasive Glucose Detection Using Machine Learning. Biosensors (Basel). 2022 Mar 1;12(3). https://doi.org/10.3390/bios12030166
10. Vishay (2019). Reflective Optical Sensor with Transistor Output, datasheet, 83751, Vishay In-. tertechnology Inc. 2019;
11. Jain P, Maddila R, Joshi AM. A precise non-invasive blood glucose measurement system using NIR spectroscopy and Huber's regression model. Opt Quantum Electron. 2019 Feb 1;51(2).
12. Clarke, W.L., Cox, D., Gonder-Frederick, L.A., Carter, W. and Pohl SL. Evaluating clinical accuracy of systems for self-monitoring of blood glucose. Diabetes Care. 1987;10(5):622–8. DOI: 10.2337/diacare.10.5.622
13. Hina, A. and Saadeh W. Noninvasive Glucose Monitoring SoC Based on Single Wavelength Photoplethysmography. IEEE Trans Biomed Circuits Syst. 2020;14:504–15. DOI: 10.1109/TBCAS.2020.2979514
14. Reddy PSK, Mahesh D, Uday Teja C, Janaki M, Mannem K. Non-Invasive Glucose Monitoring Using NIR Spectroscopy. In: Journal of Physics: Conference Series. Institute of Physics; 2022. DOI 10.1088/1742-6596/2325/1/012021