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Remote Monitoring of Non-Invasive Blood Glucose and ECG

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Abstract— *As the prevalence of diabetes and cardiac issues has increased worldwide in recent years, an increasing number of patients are experiencing pain and infections because of the invasive design of most commercial glucose meters and access to ECG measurement systems at hand. Technology for non-invasive blood glucose monitoring has drawn attention from researchers around the world and is a new approach that may help a lot of patients. The development of noninvasive techniques to replace the traditional method of measuring blood glucose concentration by finger pricking is progressing quickly. This research was done to determine which near-infrared (NIR) sensor wavelengths would be most effective at measuring the prepared samples of glucose concentration of different persons.*

ECG is very important to know the hearts working condition therefore the remote measuring of ECG has been executed successfully. Using non-invasive sensors the blood glucose levels can be measured. It has been executed and the results are accurate and promising. These health parameters can be measured from a distance remotely and accurately as expected.

Keywords: *Non-invasive, biosensor, near-infrared rays (NIR), ECG, Electrocardiogram, Blood glucose level.*

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I. INTRODUCTION

Diabetes is becoming a serious and intimidating illness. There are 415 million grown-ups that have diabetes, and this number is anticipated to rise to 642 million by 2040. Diabetes is the most probable cause of one in ten deaths among people 20- 59 years old. In the U.K, three people get diagnosed with Diabetes every ten seconds, and the most disturbing fact is that about 500,000 people have diabetes and are still undiagnosed. Diabetes is also known as Diabetes Mellitus (DM). It's a medical condition which occurs when the body is unfit to regulate blood sugar situations. There are two types of Diabetes, type-1 and type-2. Diabetes type- 1 is a condition when the body is unfit to produce any insulin which is used to regulate blood sugar situations. Insulin is essential for the body to convert glucose into energy. Diabetes type- 2 occurs when the body isn't making enough insulin or is making insulin which is repelled by the body. This generally occurs in people 40 years of age. Diabetes type- 2 is spreading worldwide more fleetly than type- 1.

Diabetes affects the body in different ways. It leads to numerous serious ails similar to cardiovascular conditions, eye problems, order problems, brain dysfunction and unseasonable mortality. It has also become one of the common causes of amputations which lead to disability. Heart conditions which are caused by Diabetes are adding at an intimidating rate and claiming thousands of lives every minute. About 50 of the Diabetes cases are anticipated to be suffering from nervous damage. Wearable body detectors have lately provided increasingly expansive attention in healthcare operations for nonstop and real-time monitoring of physiological parameters and particular health of cases and non-patients. These detectors are stationed to measure body temperature and glucose levels from sweat. In this regard, it's important to develop non-invasive wearable detectors and systems that determine and cover the glucose situations in blood in real-time. Traditional invasive styles of examination of the glucose situations of the body bears a case to puncture the skin to collect a blood sample to determine the blood glucose situation. This system poses difficulty for cases with Diabetes because they need to prick the skin several times a day to control the glucose situations, and this system causes pain. Patients feel discomfort and agony, depending on the inflexibility of puncturing the skin. Occasionally this invasive system can damage the skin. Also, the needle can induce fatal body infections into the bloodstream. In other words, the most common commercially available glucose monitoring systems are invasive that bear a blood sample to determine the glucose levels in the blood. Non-stop Glucose Monitoring (CGM) or implantable systems are well known in the healthcare industry but they are invasive and bear relief for a couple of days and carry limitations similar to limited battery life. Thus, there's a critical need to develop non-invasive glucose monitoring systems that are easy to use, low cost, and portable and don't pose any hazards to patients.

Based on the detection principle, non-invasive blood glucose detection technology can be categorized into three categories: optics, microwave, and electrochemistry, and reviews recent research developments and significant challenges. The technology includes areas related to medicine, materials, optics, electromagnetic waves, chemistry, biology, and computational science. Horizontal comparisons are made between the benefits and drawbacks of non-invasive and invasive technologies, as well as electrochemistry and optics in non-invasives. . To discuss the development trend in future research, the current research successes and limitations of non-invasive electrochemical glucose sensing systems in continuous monitoring, point-of-care, and clinical settings are also highlighted. The market for non-invasive blood glucose monitoring will become more competitive as wearable technology and transdermal biosensors continue to advance quickly.

Several optic technologies like, Electromagnetic Sensing, Reverse Iontophoresis, Near Infrared spectroscopy, Raman spectroscopy and Fourier transfigure Infrared (FTIR) spectroscopy have been used to develop non-invasive glucose monitoring detector systems. Near Infrared (NIR) spectroscopy has gained attention because of its capability to get samples of blood without being invasive. There are several non-invasive styles used to get and cover the glucose position in the body. The GlucoWatch detector is used to measure glucose and brings interstitial fluid through the skin to the external logical platform using iontophoresis. The strike of this detector is that it has caused vexation problems in cases, thus it has been withdrawn from use. Pleitez et al have reported a non-invasive detector system grounded on resonance-enhanced palpitated photoacoustic spectroscopy with a windowless resonator cell deposited on the skin of the fingertip. This detector system configuration is complex and needs further advancements of the cell and its integration into a movable miniaturized device is still necessary. Dachao et al also reported a non-invasive detector device that uses ultrasonic energy at the skin position to determine the glucose situations, still, the detector has also not been miniaturized to be considered a wearable detector, and it uses a marketable biosensor which is veritably precious and complex to be fabricated. A prototype of a non-invasive wearable glucose monitoring system is developed and demonstrated experimentally which is grounded on the optic spectroscopy that quantifies the glucose position in the blood. The proposed device prototype has been tested on a real body for determining the glucose position in the blood.

Persistent blood glucose (BG) checking is important to stay away from the unexpected problems from diabetes mellitus. The regular technique for estimating and observing BG is by pricking the finger which makes agony and inconvenience patients. To handle this issue, there are research zeroing in on physiological signs, like an electrocardiogram (ECG) to make a model fit for consistent glucose estimation. In any case, there are ECG portions that poor person been viewed as that have the chance of working on the presentation for painless BG checking. An elective methodology will be the utilization of physiological signs, like an electrocardiogram (ECG). The progressions in BG influences the action of the heart, examination of ECG subtleties gives a finding of diabetes.

Previously, various techniques have saddled at least one fragment of ECG for BG observing. QT stretch portion in ECG must be subject of extraordinary quest for observing BG. ST portion is the span between ventricular depolarization and repolarization of the ECG signal applied to the baby of diabetic moms for BG status. Another section is pulse (HR) fluctuation is a sign which records contrasts between two sequential pulses was inspected for anticipating hypoglycemia. Right now, a few strategies join a few ECG sections for BG checking like examining hypoglycemic circumstances HR and QT. ID of hypoglycemia and hyperglycemia in type 1 with HR, QT, RT, PR span. Nonetheless, there are ECG portions that poor person been considered as well as the blend of these fragments are important to build the chance of accomplishing improved results.

II. LITERATURE REVIEW

K A Unnikrishna Menon et.al created a self-monitoring glucose meter for determining blood glucose levels. In this procedure, a finger is pricked, blood is drawn from the forearm and disposable test strips are used to do a chemical analysis of the blood. Based on the results of the survey, a noninvasive method of measuring has been developed due to the pain, discomfort, and difficulties this technique causes. This method transmits and receives light from the fingertip using a near-infrared sensor. NIR is transmitted through the fingertip both before and after the blood flow is blocked. [1]

B Lakshmi Priya et.al has recently concentrated more on using near-infrared (NIR) photons to make BGM non-invasive. The present methods of blood glucose monitoring (BGM) are intrusive because blood samples are taken by painful finger pricks, which makes the procedure invasive with the potential for infection. However, the NIR approach has some drawbacks, including increased SNR (signal-to-noise ratio) and low accuracy due to the absorption of light by human tissue. Since then, these flaws have hindered the use of NIR-based blood glucose monitoring in the healthcare industry. This work suggests BGM using laser light to address these shortcomings.[2]

Eko Agus Suprayitno et.al has done a non-invasive instrumentation investigation to measure blood sugar levels which does not hurt the body. The MAX30100 sensor is used in this study to detect blood sugar levels non-invasively because it only requires the index finger to be attached to the sensor to assess blood sugar levels. The MAX30100 sensor is used in this study as a non-invasive way to detect blood sugar levels because doing so simply requires you to attach your index finger to the sensor and does not harm your fingertips. On LCD screens and Android devices, this instrumentation displays the value of blood sugar levels. IoT is used for serial communication in instrumentation with Android smartphones to make it simpler for medical professionals to check on diabetic patients from a distance using Android smartphones. The accuracy of blood sugar readings was 90.3% with a variance of 1.2 - 39.6 mg/dL based on evaluating non-invasive blood sugar detection instrumentation with industry-standard blood sugar measurement (invasive).[3]

Jyoti Yadav et.al has created a non-invasive blood glucose measurement sensor system employing near-infrared (NIR) technology is the main goal of the current effort. First, a continuous wave (CW) from a NIR LED (940 nm) is used to construct an in-vitro glucose measuring prototype to test the system's sensitivity for various glucose concentrations. A sensor patch was later created to observe the diffused reflectance spectra of blood from a human forearm using an LED and a photodiode. This technique's measurement of the individuals' diffuse reflectance spectra was contrasted with invasive finger-tip glucose meters that are commercially available.[4]

Anas et.al wants to tackle currently implemented invasive procedures which are used in clinical practice to monitor blood glucose, and this is inappropriate and puts patients at risk for infection because the finger is punctured three to five times a day. Near-infrared optical measuring is used in this work to get over the intrusive problems. The instrument they developed uses an infrared emitter that is positioned over the fingertip to monitor blood sugar visually. The photodiode, which has a certain wavelength, will detect near-infrared light. The glucose molecules in the blood determine how much light is received. During the experiment, ten participants were employed. The preliminary findings show that during non-fasting normal conditions, the voltage measured from the design device ranges from 1.4 to 1.66 volts, and during fasting, the voltage ranges from roughly 1.38 to 1.61 volts with readings of 4.7 to 5.5 mol/L. [5]

The author A. Stojmenski et al. proposed the potential correlation between Heart Rate Variability (HRV) parameters and glucose levels in order to develop a non-invasive glucose monitoring methodology. The study is based on a dataset from the Glucose project, which includes ECG data from 143 patients. The paper focuses on extracting HRV parameters from the ECG data, and investigates whether 30-minute ECG measurements can provide an accurate estimation of the body's regulation ability, as compared to 24-hour measurements. This covers several aspects of the study, including outlier handling, statistical measures, and HRV distribution charts. The authors note that their previous results suggest that 24-hour ECG measurements are more relevant for determining HRV parameters. However, in this paper, they aim to investigate whether 30-minute measurements can provide a comparable estimate of the body's regulation ability. The hypothesis being tested in the study is whether 30-minute ECG measurements are relevant for estimating the body's regulation ability. The authors use statistical analysis to compare HRV parameters extracted from 30-minute ECG measurements to those extracted from 24-hour measurements. They also examine the correlation between HRV parameters and glucose levels. [6]

J.Misek et al. presented a design for a remote electrocardiogram (ECG) data collection system that can be used with an Android-based smartphone. The system includes a one-lead ECG sensor that is designed as a USB dongle, as well as a smartphone application that manages the data acquisition process. The main focus is on the hardware design and implementation of the ECG sensor component. During the ECG acquisition process, the data are stored on the smartphone's internal or external storage and then transmitted to a remote biobank server for archiving and subsequent processing at predefined intervals. The article does not provide details on the specific processing methods that are used for the ECG data, but it is suggested that the data could be used for various applications, such as heart rate monitoring and arrhythmia detection.[7]

Tobore Igbe et al. used physiological signals, specifically electrocardiogram (ECG) segments, to create a model for continuous blood glucose monitoring. The conventional method of measuring BG involves pricking the finger, which causes pain and discomfort to patients. The authors performed an oral glucose tolerance test (OGTT) on thirteen adults while continuously recording the ECG signal, and extracted 9 ECG segments. Boxplot and correlation coefficient analysis were performed on the extracted segments to observe the changes in BG. The study found that QT, ST, and QTC segments showed a consistent pattern among participants, and HR and RR-I segments had dominant inverse behavior with a 92% correlation with the QT segment. The PRQ and QRS segments also showed potential with an 85% and 77% correlation respectively with QTC segments. The R-H and P-H segments had weak results with most of their values below 50%. These findings suggest that certain ECG segments could be useful for non-invasive continuous BG monitoring and warrant further investigation. [8]

III. PROPOSED METHOD & EXECUTION

This study describes a noninvasive glucose monitoring system that uses near-infrared transmission spectroscopy to measure glucose concentration. Both, in-vitro and in-vivo experiments were conducted to evaluate the system's performance.

In vitro Experiment:

The in-vitro test set-up described is used to investigate the relationship between glucose concentration and the attenuation of near-infrared (NIR) light. The prototype uses a photodiode and an LED operating at 940 nm. The photodiode is positioned opposite the LED to receive the transmitted signal. The set-up is enclosed in a box to stabilize the photodiode. This in-vitro test aims to study the effect of glucose concentration on the NIR light attenuation in a controlled environment.

Additionally, the setup aims to reduce volatility in the output voltage by maintaining a consistent LED supply current. The in-vitro experiments use glucose samples with concentrations ranging from 40 mg/dl to 400 mg/dl, which are created by diluting a 40 mg/dl dextrose glucose solution in incremental steps. This allows the system to measure the changes in NIR light attenuation as the glucose concentration changes.

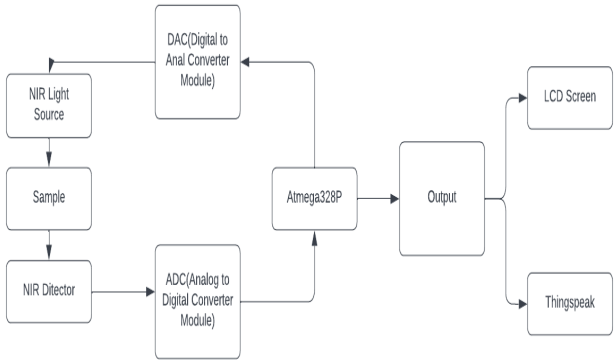
To understand how changes in glucose concentration affect NIR radiation, the in-vitro measurement takes ten readings for each glucose concentration. This allows for the collection of multiple data points to determine the system's accuracy and reproducibility at different glucose levels.

In vivo Experiment:

The goal of the in-vivo sensor patch is to measure the diffuse reflectance spectrum of the forearm, which can be used to monitor glucose concentration. The sensor patch is constructed by placing a photodiode and a NIR LED (950 nm) 4mm apart. During the experiment, subjects are instructed to sit still and not move during the optical measurement. The sensor patch is applied to the inside of the forearm and the diffuse reflectance spectra are collected to measure glucose concentration.

Non-invasive glucose measurement is a challenging task because glucose is present in very low concentrations in the interstitial fluid, which is the fluid that surrounds the cells of the body. Therefore, several optical non-invasive techniques have been proposed to measure glucose levels. One of the most promising is near-infrared (NIR) spectroscopy. This method uses light in the NIR range, which has strong penetration through the skin and other tissues. This allows the light to reach the interstitial fluid and measure glucose levels. NIR spectroscopy has been used on various body areas, including the finger, palm, arm, forearm, earlobe, and cheek, with varying levels of success.

The proposed model aims to overcome the problems associated with invasive methods, such as finger puncturing, by using a non-invasive technique based on near-infrared (NIR) spectroscopy. This technique utilizes light in the NIR range, which has strong penetration through the skin and other tissues, to measure glucose levels in the interstitial fluid. NIR spectroscopy works by analysing the absorption of light by different molecules in the body. The absorption of NIR light by glucose is due to the presence of C-H, O-H, and C=O bonds in the glucose molecule. These bonds cause glucose to absorb light in the NIR range, which can be used to measure glucose levels. The NIR spectrum used for glucose measurement typically ranges from 750 to 2500 nm in wavelength.



Block Diagram 1: Non-invasive Glucometer

In NIR spectroscopy, test samples are exposed to an infrared laser beam, which is then detected by a sensitive infrared detector. Different body parts can be examined using different techniques. For example, NIR transmittance spectroscopy can be used to examine the fingertips and earlobes, as these areas have a relatively high penetration power of NIR light. Reflective spectroscopy is used for the forearms and cheekbones, as the penetration power of NIR light is low in these areas. This allows glucose to be detected by measuring the amount of NIR light that is reflected or transmitted through the tissue. It should be noted that NIR spectroscopy is a well-established technique for glucose measurement due to its applicability and simple concept. Near-infrared spectroscopy (NIRS) is a non-invasive technique that uses light in the 750-2500 nm range to probe the tissue. The low-energy radiation used in NIRS allows for the detection of glucose levels up to a few millimetres beneath the skin. One of the advantages of NIRS is that it does not require any special reagents, which allows for repetitive analysis at a reasonable cost. The NIR radiation range between 700-1100 nm is considered as a therapeutic window for glucose detection. This specific range is most effective in detecting glucose beneath the skin.

The experiment's findings suggest that it is possible to predict blood glucose levels using NIR spectroscopy by analyzing the correlation between the measured voltages and glucose concentrations. The study found that the voltage differences between fasting and non-fasting states can be distinguished. However, there may be room for improvement in the device's accuracy and precision of measurement. The in-vitro experiment was conducted by generating different concentrations of glucose in distilled water and adding 40 mg/dl of glucose. The sensor was placed on the wall of the test tube to observe the glucose and the attenuation of NIR light.

In NIR spectroscopy, the photodiode output typically falls as the glucose concentration rises. This is because as the glucose concentration increases, more NIR radiation is absorbed by the glucose molecules, resulting in less light being transmitted through the tissue. This relationship between the optically detected signal and the actual glucose level is demonstrated by in-vitro research. The in-vitro experiments are done by exposing samples with different glucose concentrations to NIR radiation, measuring the amount of light transmitted through the samples, and comparing the results to the known glucose concentrations. These experiments confirm that the NIR spectroscopy technique has a good correlation between the optically detected signal and the actual glucose level.

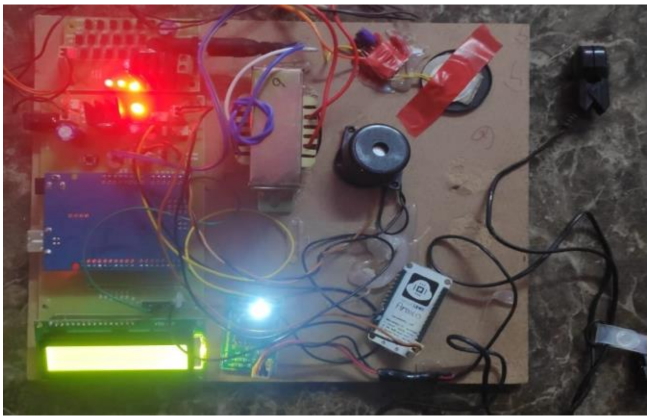


Fig 1: Circuit of Non-invasive Glucometer

Fig 1 represents the circuit model of the non-invasive glucose monitoring system.

The next step after validating the performance of the device in-vitro is to conduct in-vivo experiments to test the device on human subjects. The planned in-vivo experiment is to collect diffused reflectance spectra using a sensor patch placed on the inside of the forearm and a signal conditioning device.

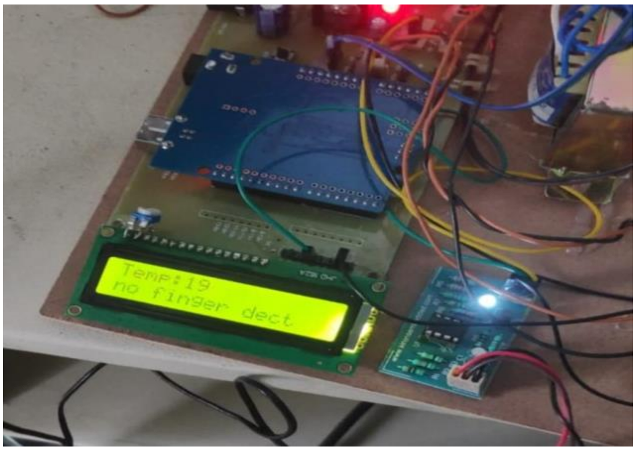


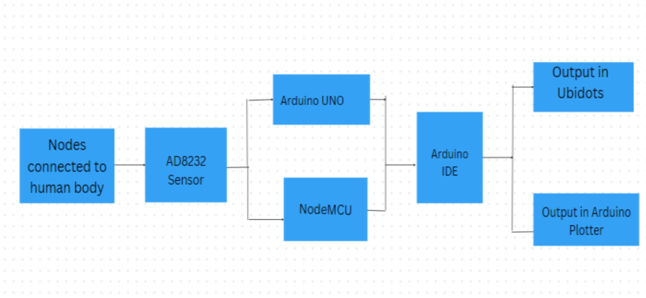
Fig 2: Circuit of Non-invasive Glucometer

Fig 2 shows the temperature when no finger is detected by the sensor. The results that the present sensor prototype has produced are promising which are shown below in Table 1. The results demonstrate the potential for a non-invasive blood glucose testing method based on diffused reflectance via the forearm. Minimizing the inaccuracy brought on by the placement of the sensor patch on the forearm during each measurement can increase the performance of the suggested method.

Person 1		Person 2		Person 3	
Invasive	Non-invasive	Invasive	Non-invasive	Invasive	Non-invasive
82	78	74	76	77.5	72
82	76.5	74	76.5	77.5	70
82	76	74	75	77.3	70.2

Table 1: Glucose measurements using invasive and non-invasive methods

Remote sensing electrocardiogram (ECG) refers to the process of recording the electrical activity of the heart from a distance using sensors placed on the body. This technology is commonly used in medical settings to monitor patients' heart rates and detect any irregularities or abnormalities in heart rhythm. With remote sensing ECG, the sensors are placed on the skin of the patient and can be wirelessly connected to a monitor, allowing medical professionals to view the data in real-time. This is particularly useful in situations where continuous monitoring is needed, such as during surgery or in critical care settings.



Block Diagram 2: ECG Classification

Remote sensing ECG technology has also advanced to include wearable devices that allow for continuous heart rate monitoring outside of medical settings. These devices can be used to track physical activity, monitor heart health, and detect potential heart problems. Overall, remote sensing ECG is a valuable tool in modern medicine, providing medical professionals with a non-invasive way to monitor and diagnose heart conditions in patients.

IV. RESULT ANALYSIS

The testing phase of the device was conducted using a group of three people to evaluate its capabilities. A commercial invasive sensor, TRUE result twist, was used as a benchmark to compare the effectiveness of the proposed non-invasive system. The results were also evaluated using the Clarke error grid analysis, which is a commonly used method for evaluating the accuracy of glucose monitoring devices. The Clarke error grid analysis showed that the majority of the readings from the proposed system were in the acceptable range, indicating that the device has good accuracy. Additionally, readings were taken one minute apart, both with the invasive and non-invasive device, to compare the results and validate the results of the non-invasive device.

The testing phase of the device showed that the invasive values ranged from 70 to 105, while the non-invasive values fell between 70 and 110. The collected data points from the test measurements fall within an acceptable range, demonstrating the accuracy of the non-invasive glucose sensor that was developed and proposed. The measurements shown in table 1 were made after the system had completed its calibration. The calibration procedure was completed 24 hours before the equipment was tested in its intended capacity. The calibration process required readings from both the invasive and non-invasive devices to calculate the molar absorptivity coefficient. A variety of measurements were performed on each patient and table 1 includes a unique outcome dataset for each patient.

The proposed non-invasive glucose sensor was tested on three volunteers, and their glucose levels were measured and compared with a commercial invasive sensor as a benchmark. The invasive sensor is a glucose meter that offers simple, precise testing and only needs a small 0.5 microliter sample. Results of the test are shown in as little as 4 seconds. The results of the comparison between the proposed non-invasive sensor and the commercial invasive sensor are presented in table 1, which shows the accuracy of the proposed non-invasive glucose sensor prototype in determining the blood glucose level.

The average values of the three people's blood glucose levels for the proposed non-invasive sensors and the invasive sensors were calculated, and the results were 86.9 mg/dl for the non-invasive sensors and 84.6 mg/dl for the invasive sensors. For most of the test participants, the invasive values were higher than the non-invasive values, but for one test subject, the results were the opposite. However, the data variability for all test participants is comparable. The non-invasive results fall within the acceptable range, using the Clarke error grid analysis. The finger's thickness was measured using a Vernier callipers. The average values for men and women were established by aggregating and filtering the data.

Fig 3: Circuit of Non-invasive Glucometer

Fig 3 shows the normal glucose level of the patient. The study will involve 3 non-diabetic patients between the ages of 25 and 35 (4 male and 3 female subjects) to examine the sensitivity of the sensor patch. The signal will be collected from each subject both before and after a meal to evaluate the device's performance under different glucose levels. The in-vivo experiment will provide more realistic results and help to confirm the device's performance and usefulness for non-invasive glucose monitoring.

The proposed non-invasive glucose sensor system is designed to be affordable and user-friendly. The finger size input during the calibration stage helps account for individual finger thickness variations. Since the most frequent finger sizes for both men and women fall within similar ranges, there is not much variance in the thickness of their fingers. The cost of the 3-D printed housing is included in the sensor's overall price, which makes it more cost-effective and accessible than invasive systems. The system's overall production and maintenance costs are lower than those of currently available invasive systems. However, it should be noted that for glucose in fingers, a homogeneous attenuation is expected. In contrast to other elements in the sample, light mostly interacts with glucose. Other variables such as skin roughness, which can scatter light, various body fluid concentrations, etc. can influence the glucose test results.

It is important to note that there may be variations in non-invasive readings for the same person and the same invasive reading, but the variances should be within an acceptable range. In future work, it would be beneficial to investigate how other factors, such as temperature and finger detection, may affect the accuracy of the proposed sensor. Temperature measurement and finger detection are critical factors that need to be considered when developing a non-invasive glucose sensor system.

Remote ECG monitoring can provide continuous monitoring of heart function, allowing for early detection of arrhythmia or other abnormalities. This can be especially important for patients with heart conditions or those at high risk for cardiovascular disease. Early detection of heart problems through remote ECG monitoring can help healthcare providers intervene quickly to prevent serious complications. For example, if a patient with a history of heart disease experiences an arrhythmia, remote monitoring can alert their healthcare provider who can then adjust their medication or suggest other interventions to prevent a heart attack or stroke.

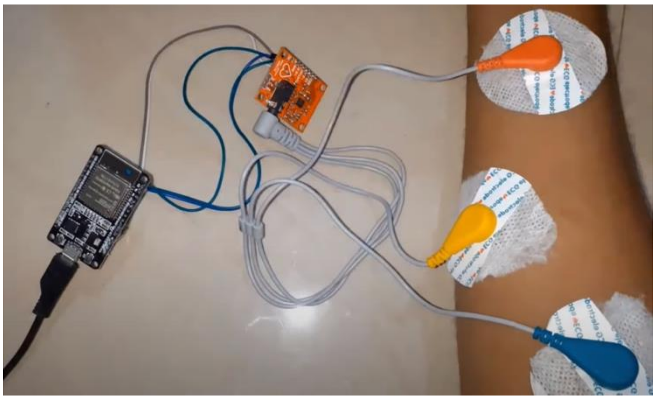


Fig 4: Circuit of ECG Monitoring

Overall, remote ECG monitoring is a valuable tool for the early detection and management of heart conditions, and can help improve outcomes for patients with cardiovascular disease. Combining multiple ECG segments may improve the accuracy of blood glucose monitoring. For example, some studies have combined HR and QT interval analysis to predict hypoglycemic events in individuals with diabetes (Gennaro Gelao, Design of a Dielectric Spectroscopy Sensor for Continuous and Non-Invasive Blood Glucose Monitoring, 2012) (O. Abdallah, Design of a Compact Multi-Sensor System for Non-Invasive Glucose Monitoring Using Optical Spectroscopy, 2012) (E. Hidayanto, Design of Non-Invasive Glucometer using Microcontroller ATMega-8535, 2015). However, it is important to note that further research is needed to determine which ECG segments are most useful for blood glucose monitoring, and to identify the optimal combinations of ECG segments for this purpose.

Fig 5: ECG Waveform in Ubidots software

V. CONCLUSION AND FUTURE SCOPE

To summarize, the proposed non-invasive glucose measuring device uses a near-infrared (NIR) technique to measure glucose levels in various body areas such as the finger, palm, arm, forearm, earlobe and cheek. The device uses NIR light in the 750-2500 nm range to probe the tissue and detects changes in the transmitted signal caused by the absorption of glucose. The device is low-cost and easy to use and has shown promising results in in-vitro experiments. The results of the in-vivo experiments are also encouraging, with the majority of the readings falling within the acceptable range. The device has the potential for continuous, real-time monitoring of blood glucose levels and could be a valuable tool in the biomedical field. However, further studies are needed to investigate how additional factors may affect the device's accuracy.

Investigating the effects of additional variables such as skin roughness and different body fluid concentrations on system performance can help improve the calibration and sensitivity of the system. This can lead to a stronger association between inputs and outputs, and optimize and refine the current model.

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