Comparative Study of Different Near-Infrared (NIR) Wavelengths on Glucose Concentration Detection

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***Abstract*— There are a lot of in-vitro non-invasive techniques to measure a glucose concentration and one of them is by using near-infrared (NIR) spectroscopy. In this study, the main objective is to compare the behaviour on the different wavelengths of NIR transmitter (1050 nm, 1200 nm, 1300 nm, 1450 nm, and 1550 nm) on different glucose concentration solutions (0 to 300 mg/dL) and the measurement indicates a correlation between voltage and glucose concentration. The conditional circuit of NIR transmitter and detector is designed in order for the transmitter to transmit an optimal intensity of light. Besides, it also consists of the filter and amplifier used to filter and amplify the signal from the noise on the detector side. The transmitter and detector are positioned facing each other and the cuvette that filled with glucose solution is located in between. A placeholder casing for the experimental setup is designed to reduce an external error during the data collection. The voltage outputs are recorded for every different glucose concentrations by using different transmitter wavelength. Based on the results, it shows that the voltage output reading is directly proportionate to the glucose concentrations. These behaviours are similar to all different transmitter wavelengths used. The R-square (R^2) and root-mean-square error (RMSE) for every wavelength used are varied. The result of using 1450 nm wavelength shows the best correlation between voltage outputs and glucose concentrations compared to other wavelengths with the highest value of R^2. A linear equation is extracted from the fitted graph and can be used to predict the value of glucose concentrations.**

***Index Terms*— In-vitro; Glucose concentration; Near-infrared (NIR); Non-invasive**

I. INTRODUCTION

Previously, there are many studies and developments had been done with an infrared spectroscopy technique for the biomedical field [1]. This technique is also applied in other applications such as pharmaceutical, agriculture and petroleum field [2]. NIR Spectroscopy is one of the optical techniques that use light properties of NIR on a detection of a blood glucose concentration. This study focuses on the comparison of the NIR transducer response on glucose concentrations. There are three methods to measure blood glucose level as shown in Figure 1.

The non-invasive method is more preferred than an invasive method for measuring a blood glucose concentration since the non-invasive method does not require a blood sample in the measurement. Figure 2 shows how blood glucose is tested by the invasive method.

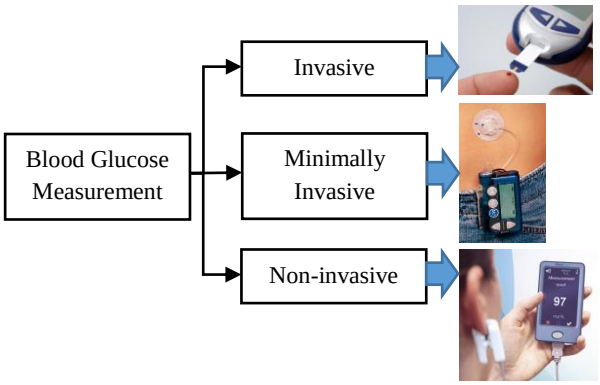


Figure 1: Blood glucose measurement approach.

The non-invasive method can be classified into two different categories and every category can be classed into several different techniques as shown in Figure 3 [3]. Every technique has its advantages and disadvantages [4].

Figure 2: Invasive blood glucose monitoring

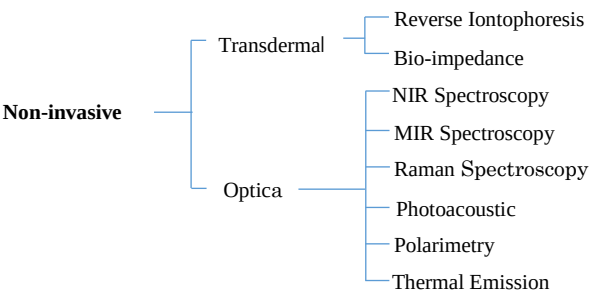


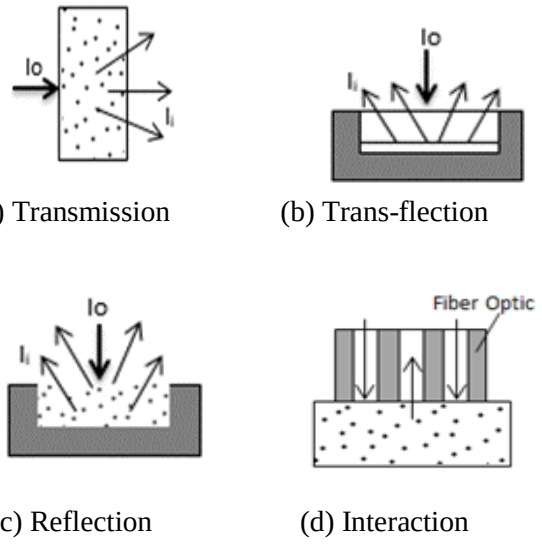
Figure 3: Non-invasive technique [3].

A. NIR Spectroscopy

NIR spectroscopy is one of the optical spectroscopic techniques, which is the interaction between matter and electronic radiation. Spectroscopic techniques are used to determine the concentration or the presence of the sample by measuring how it reacts with light [5]. This spectrum contains molecular information about the sample. Each material will show a specific spectrum, depending on its chemical structure, physical state, and temperature. The amount of information contained in the spectrum can vary tremendously from one region to another.

NIR spectroscopy is a method that uses the NIR region of the electromagnetic spectrum between 700 nm to 2500 nm. NIR light is safe for human cells as it does not induce auto-fluorescence in cells with no strong cellular biological emitters and has more structure in both overtone and combination [5][6].

One of the important factors affecting NIR measurement is depending on how the sample is presented or set to NIR instrument [4]. Figure 4 describes how measurement of the sample in the form of liquids inside of the cuvette can be done by using a NIR sensor.



(a) Transmission (b) Trans-flection

(c) Reflection (d) Interaction

Figure 4: NIR sample presentations of [4].

NIR is said to be a better choice due to its cheaper cost, better sensitivity and selectivity, less complexity in instrumentation and result in a better signal-to-noise ratio (SNR) [7]. Apart from that, different NIR wavelengths have a different absorption characteristic as shown in Table 1.

Table 1
Characteristic for different wavelength [8].

Wavelength	Characteristic
700nm-1300nm	▪ Higher orders of glucose overtone regions ▪ Little glucose absorption ▪ Low light absorption of water
1500nm-2500nm	▪ Highest glucose absorption ▪ Does not get affected by excessive water attenuation ▪ Relative minimum in water absorption spectrum

B. Photodiode

The photodiode is a detector device that converts light into current when the light is present. The photodiode comes with several different types based on a range of wavelength and different active area [9]. Table 2 shows the list of common photodiode detector types that can be used to detect NIR. The detector selection is depending on the range of the NIR wavelength used. The price will be higher for a larger range of wavelength and larger active area.

Table 2
NIR photodiode detectors and their ranges [4].

Types	Working Temperature (K)	Wavelength Range (nm)
Ge	77	600 to 1800
Si	300	400 to 1100
InGaAs	300	900 to 1700
PbS	196	1100 to 3500
InAs detector	77	1500 to 3500
Extended InGaAs	300	1100 to 2800
Ge	300	600 to 1900
InSb	77	2000 to 4000
PbS	300	1000 to 3000

Optical absorption techniques can be described by the Beer-Lambert Law. The absorption of light is directly proportional to the concentration and thickness of a sample as shown in Figure 5 and Equation (1) [10].

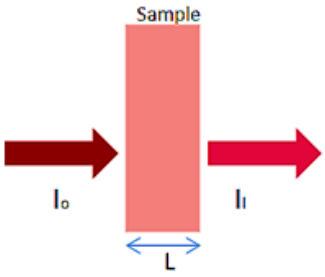


Figure 5: Light absorption

$$A = log\ (Io/Ii) = \varepsilon lc \quad (1)$$

Where: A = Absorbance
Io = Intensity of incident light
Ii = Intensity of Transmitted light
ε = Constant molar absorptivity
l = length of light through
c = Concentration

In glucose solution, light absorption will only occur in two substances; glucose and water. However, in human tissue, it is made by a complex substance. There are several parameters that should be considered when applying spectroscopy techniques in human tissue, such as effective pathway length, pigment and absorptivity. Figure 6 shows the spectrum for different samples [11].

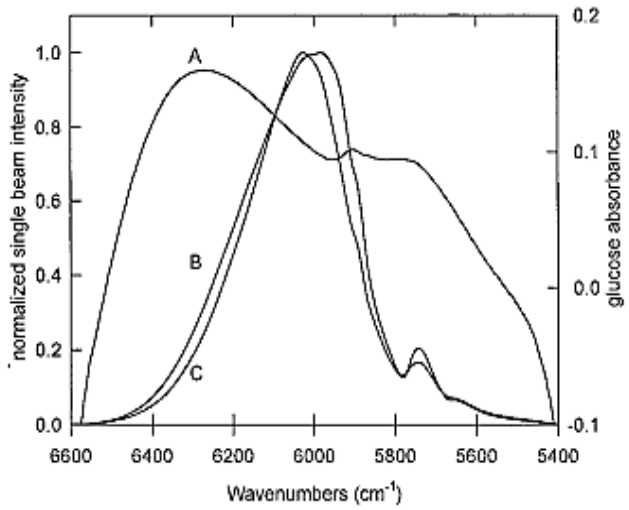


Figure 6: First-overtone absorbance spectrum of a 1 mol/L aqueous glucose solution (spectrum A), a single beam spectrum collected through the in vitro model of human tissue (spectrum B), and a corresponding non-invasive single-beam spectrum collected through human webbing tissue (spectrum C) [11].

II. Design and Experimental

A. Components Selection.

NIR LEDs from Thorlab are used as a light source with wavelengths; 1050 nm, 1200 nm, 1300 nm, 1450 nm and 1550 nm as in Figure 7 (a). These LEDs have a narrow spectral width with peak intensity is around ±10 nm. Figure 7 (b) shows an FGA01 photodiode from Thorlab that had been used as a light detector. This is Indium Gallium Arsenide (InGaAs) type of photodiode. The FGA01 wavelength is ranged between 800 nm to 1700 nm with a peak detection wavelength of 1550 nm. This photodiode had an active area diameter about Ø0.12 mm and designed with ball lens (package TO-46). LM358N IC is chosen as an amplifier to amplify the photodiode voltage output.

(a) LEDs (b) FDA01photodiode packaging

Figure 7: Type of the components used as a NIR pair.

B. Circuit Design.

The circuit was powered by 5V. This circuit can be divided into two parts; 1) Transmitter circuit and 2) Detector circuit. The transmitter circuit used a resistor to limit the current that can flow through LED. The detector circuit used few combinations. The RC filter (R2 and C1) is connected to the photodiode to filter DC power supply. R3 is the load resistor (RL) and it will affect the voltage output. By increasing the value of RL, will increase the value of the output voltage. A non-inverting amplifier is added with a gain of Vo/Vi =1.195 as anticipation from the smallest value of output voltage. The entire circuit connection is shown in Figure 8.

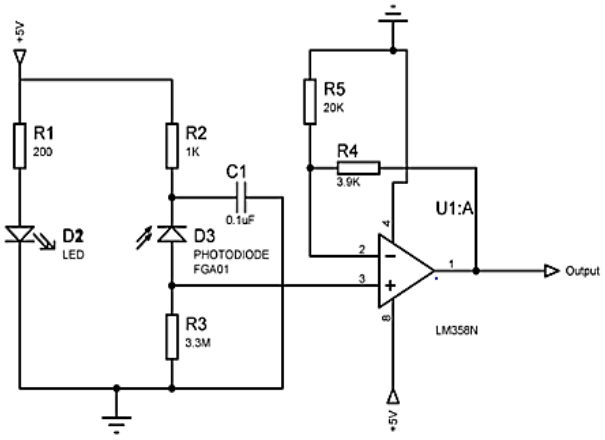
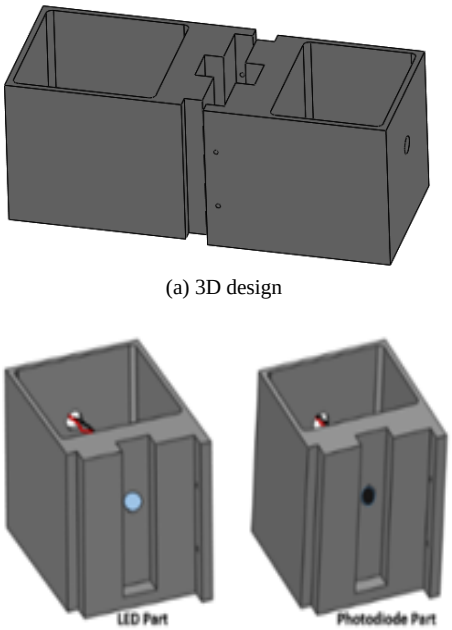


Figure 8: LED and photodiode circuit

C. The Design of Placeholder

LED and photodiode are mounted in parallel position by facing each other and a corvette container that contains a sample of glucose concentration is placed in between. This design is drawn by using CAD software and printed by using a 3D printer. This placeholder is designed to make sure that LED and photodiode are in a fix position when the experiment is running and it also to reduce the noise that can be caused by ambient light. The design is shown in Figure 9.



(a) 3D design

(b) LED and photodiode place

Figure 9: Placeholder design view.

This experiment uses transmission technique. This technique is the easiest way for spectrum data collection. The light source pass through the sample and the transmitted light from the sample is collected by the detector.

D. Glucose Sample Preparation

Glucose powder (dextrose, C6H12O6) from SYSTERM® and 1 dL of distilled water are used to dissolve the glucose powder (50 mg, 100 mg, 150 mg, 200 mg, 250 mg, and 300 mg). The glucose solutions of different concentration range between 50 mg/dL to 300 mg/dL are prepared for this experiment. Equation (2) and (3) is used to prepare the glucose solutions.

$$1\ dL = 100\ ml \quad (2)$$

$$Concentration, \rho i = \frac{(Glucose\ powder\ (mg))}{(Distilled\ water\ (dL))} \quad (3)$$

The glucose solution is stored in a tinted amber reagent bottle to avoid from being affected by light as shown in Figure 10 (a) and cuvette container in Figure 10 (b) is used to place a sample when the experiment is running. The cuvette of quartz glass type is used to hold the samples when the spectroscopic experiment is running. The quartz glass type is most suitable to be used for UV and NIR ranges of the experiment [4].

(a) Reagent bottle

(b) Cuvette

Figure 10: Container used to store the sample solution

E. Experiment Setup

Figure 11 shows how this experiment was being set up. The circuit is tested on the breadboard and a multimeter is used to measure the output voltage from the circuit and an Analog Discovery is used as a digital oscilloscope to view the signal of DC output voltage from the photodiode circuit.

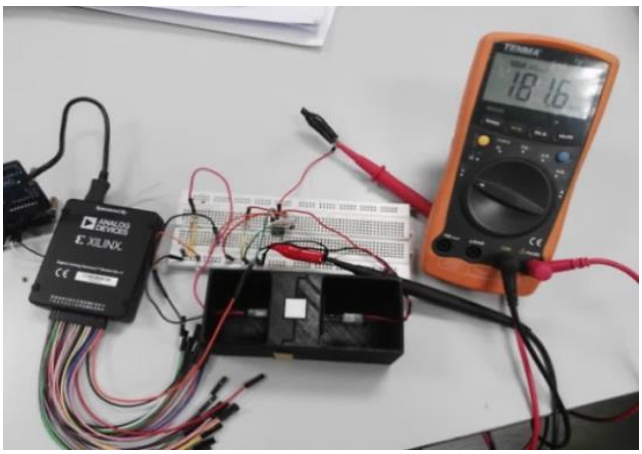


Figure 11: Experiment set up

By using a dropper 10ml of glucose solution is loaded into the cuvette. The experiment is conducted by referring to the flowchart in Figure 12. This experiment is repeated five times by placing the LED with different wavelengths (1050 nm, 1200 nm, 1300 nm, 1450 nm and 1550 nm). Thus the voltage output is recorded.

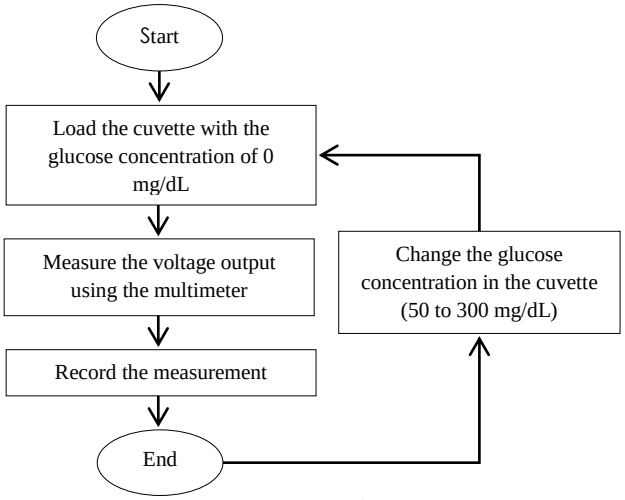


Figure 12: Flow chart of the experiment.

III. RESULTS AND DISCUSSION

The example of the voltage output from the collector circuit is shown in Figure 13. The signal is stable only change in very small value. The consisting of voltage output able be recorded by the multimeter.

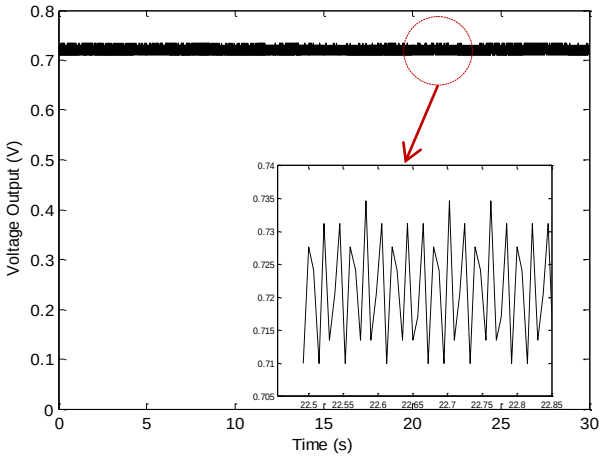


Figure 13: Output voltage signal of the photodiode circuit

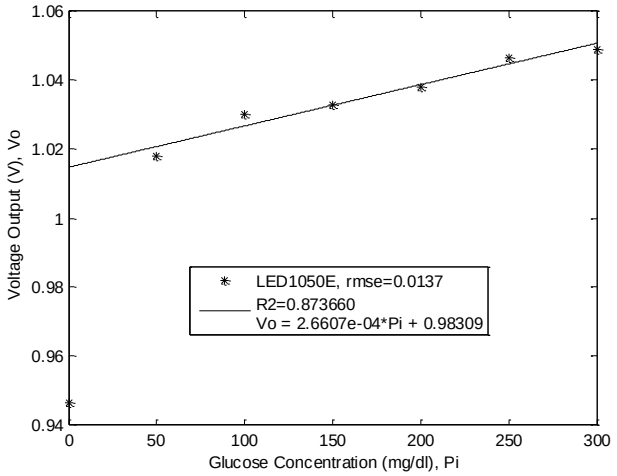
The voltage outputs of a photodiode for every different wavelength are recorded as in Table 3 and the graph of voltage outputs, V_o versus glucose concentrations, ρ_i is plotted as illustrated in Figure 14 (a) - (e).

Table 3
The result of the voltage output from photodiode circuit.

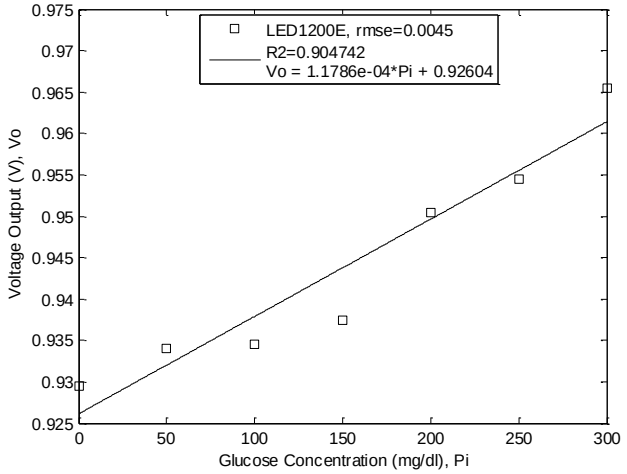
	Voltage Output				
Wavelength(nm)	**1050**	**1200**	**1300**	**1450**	**1550**
Concentration (mg/dl)					
0	0.946	0.929	0.765	0.174	0.144
50	1.018	0.934	0.770	0.175	0.148
100	1.030	0.935	0.801	0.175	0.150
150	1.033	0.938	0.843	0.176	0.151
200	1.038	0.950	0.844	0.175	0151
250	1.047	0.954	0.840	0.176	0.153
300	1.049	0.965	0.863	0.176	0.161

There is a difference in the range of voltage output for each NIR. The collector circuit has been modified to get readable value by the multimeter. Considering that the initial

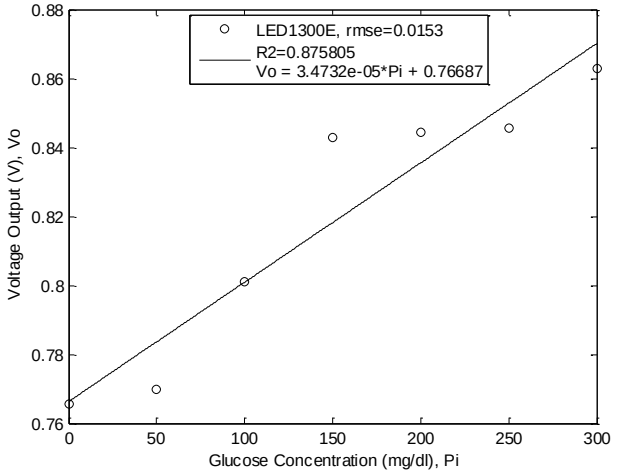
output voltage from the original circuit for each NIR are quite small and hard to read by the multimeter.



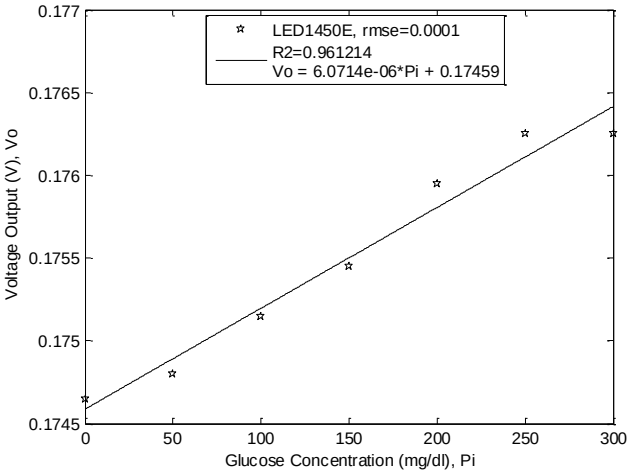
(a) The response of LED wavelength 1050 nm.



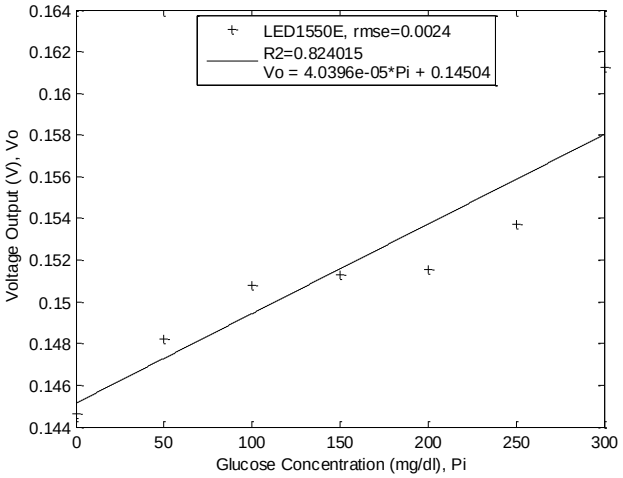
(b) The response of LED wavelength 1200 nm.



(c) The response of LED wavelength 1300 nm.



(d) The response of LED wavelength 1450 nm.



(e) The response of LED wavelength 1550 nm.

Figure 14: Graph of voltage outputs, Vo versus glucose concentrations, ρi by using different transmitter wavelength**.**

Based on the results shown in Figure 14(a)-(e), there are a direct proportional in between the increment of photodiode output voltage toward the increment of glucose concentration used. This means that less light is absorbed by the solution and more light is transmitted to the photodiode when glucose concentration is increased. The R2, RMSE and the linear equation are calculated based on the regression line for each of the graphs as in Table 4.

Table 4
Data summary from the graph in Figure 12(a) – 12(e).

LEDs (nm)	Linear Equation	R^2	RSME
1050	V_o=0.00026607*ρ_i+0.98309	0.87366	0.0137
1200	V_o=0.00011786*ρ_i+0.92604	0.904742	0.0045
1300	V_o=0.00034732*ρ_i+0.76687	0.875805	0.0153
1450	V_o=6.0714e-06*ρ_i+0.17459	0.961214	0.0001
1550	V_o=4.0396e-05*ρ_i+0.14504	0.824015	0.0024

LED with wavelength 1450 nm has the smaller RMSE (0.0001) and higher R2 (0.961214) is compared to other wavelengths which show a good correlation between the output voltage and glucose concentration. Besides that, from the graph of LED 1450 nm response also can see there is more stable voltage increment compared to other LED.

Therefore, glucose concentration can be predicted using NIR LED by knowing the output voltage from the photodiode

The accuracy of the glucose concentration can be predicted by using a linear equation in Table 3. This linear equation was extracted from the linear line in the graph in Figure 13. The accuracy of the glucose concentration is tested by using several different concentrations. The LED with a wavelength of 1450 nm is used for this test since it has a good correlation between the output voltage and glucose concentration. The voltage outputs from the photodiode circuit are recorded for every different glucose concentration.

Table 5 shows the predicted results based on the calculation by using Equation (4) that was extracted from the fitted function plotted in Figure 13(d). Five different concentration samples are tested and the percentage error of the predicted concentration in comparison to the actual concentration is also calculated. The percentage error is calculated by using Equation (5).

$$Vo = 6.0714\text{e}-06 * \rho i + 0.17459 \quad (4)$$

$$\%\ error = \frac{(|A-B|)}{(A)} * 100 \quad (5)$$

Where: A = concentration value of the sample
B = concentration predicted value.

Table 5
Predict reading of the sample.

Concentration sample (mg/dL)	Voltage Output (V)	Concentration Predict (mg/dL)	Error (%)
70	0.1751	84.00	20.00
120	0.1754	133.41	11.17
160	0.1757	182.82	14.26
230	0.1761	248.70	8.13
280	0.1764	298.11	6.46

The range of percentage error is not more than 20%. From the observation based on Table 5, when the value of glucose concentration is higher than the percentage of error become smaller. From that, the sensitivity of this sensor to detect the concentration is higher when the concentration increase.

IV. CONCLUSION

NIR spectroscopy has a potential to be used in the development of non-invasive blood glucose measurement. In the experiment, five wavelengths are tested and the results reflect a significant correlation between voltage outputs of a photodiode toward a variation of glucose concentrations. However, this result is only applicable for glucose concentration test solely and there are some issues and challenges that need to be considered in order to have a high accuracy prediction, especially when applying this non-invasive method to human directly since human tissues have a different thickness and skin tones. Besides that, NIR sensor reading also can be affected by skin temperature. Therefore, as suggestion multi-sensors can be used to overcome certain issues in the development of non-invasive blood glucose.

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