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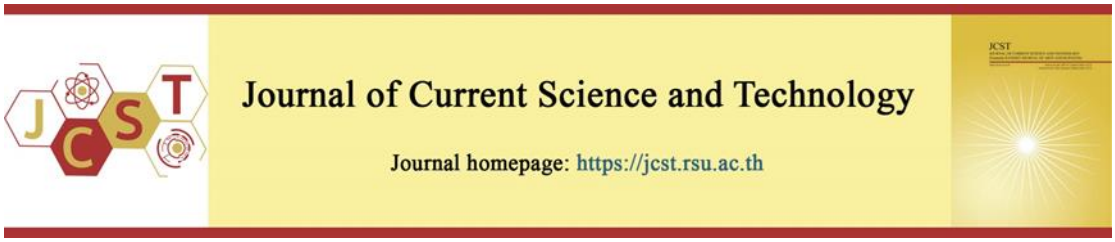

Design and construction of a non-invasive blood glucose and heart rate meter by photoplethysmography

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Abstract

This article describes the design and construction of a non-invasive blood glucose and heart rate meter that can non-invasively measure blood glucose level and heart rate from the fingertip. This device operates on the principle of light absorption, known as the Beer-Lambert Law, tracking changes in near-infrared light absorbance of blood glucose with blood volume changes in a photoplethysmogram (PPG) using opto-electronics. The design incorporates near-infrared 950 nm wavelength and red 630 nm wavelength LED light sources and a photodiode light receiver. An Arduino NANO 3.0 Mini USB microcontroller was used for signal processing, enabling the meter to compute blood glucose levels in the range of 70 to 130 mg/dL and measure heart rate across the range of 60 to 100 bpm. To validate the effectiveness of this device, it was used by a sample group of diabetic patients at the Endocrine Unit, Faculty of Medicine, Vajira Hospital. The results of device evaluation compared with standard clinical measurements were as follows: 1) The non-invasive blood glucose meter accurately measured blood sugar levels in the range of 75 to 150 mg/dL (R^2 = 0.99); 2) Across the ranges of 75 to 130 mg/dL and 131 to 289 mg/dL the device had average percentage error of 3.18% and 22.14%, respectively and the overall average percentage error was 10.76%; 3) Heart rate measurements from 60 to 100 bpm showed a mean percentage error of 2.94%, and these were not statistically different from a vital sign monitor (p= 0.222), and 4) Although readings from the meter appeared to be systematically lower than results of standard blood tests, this was not a statistically significant difference (p= 0.135). Overall, these findings indicate that this non-invasive blood glucose meter may be suitable for non-critical patient monitoring applications where patient comfort and convenience are important considerations.

Keywords**:** *blood glucose level; blood glucose meter; diabetes monitoring; heart rate meter; non-invasive; point of care.*

1. Introduction

Blood glucose monitoring is critical for managing diabetes mellitus. Patients must measure their blood sugar several times a day and if necessary inject insulin to ensure levels do not exceed 120 mg/dL (Mathew & Tadi, 2021). Non-invasive blood glucose meters are thought to help people with diabetes improve their quality of life by minimizing the discomfort associated with invasive technologies.

Heart rate is a measure of the speed of cyclical compressions and relaxations of the heart

muscles over time, typically described in units of beats per minute (bpm). The heart rate can vary according to various health factors, and is most closely associated with the exertion of physical activity during exercise. Heart rate can be measured from many points on the body where arteries are located under the skin (Reimers, Knapp, & Reimers, 2018), although there is a degree of subjectivity in traditional methods where the nurse has to count and time the pulse (Pickering, 2013).

Photoplethysmography (PPG) is primarily used for monitoring blood flow and associated volumetric changes (Fatah, Ali, & Taha, 2018). This is an optical technique that allows measurements to be taken from the surface of the skin. This way, PPG is an optical measurement technique that can be used for monitoring the cardiovascular system non-invasively (Castaneda, Esparza, Ghamari, Soltanpur, & Nazeran, 2018; Tamura, Maeda, Sekine, & Yoshida, 2014). Systems generally consist of light sources that generate wavelengths known to interact with certain constituent components inside the bloodstream. These light sources are paired with suitable photodetectors for measuring the transmitted and reflected light signals. In medicine, PPG systems are used to monitor heart rate, respiratory rate, blood pressure, and oxygen saturation (Fatah et al., 2018; Tamura, 2019).

The PPG sensor measures light intensity changes, producing a waveform signal that consists of alternating current (AC) and direct current (DC) components (Allen, 2007). The AC component of the signal reflects blood volume changes that occur during the cardiac cycle; the DC component of the signal is considered to be extraneous. The signal from the PPG is generally proportional to the amount of blood flowing through the arteries (Allen, 2007). For example, a high volume of blood passing through the vessels under the light source causes greater light absorption, therefore attenuating the AC signal; when the volume of blood is lower there is less light absorption, and the frequency of the resulting AC signal can be used to calculate the heart rate.

It has been argued that measuring blood constituents with PPG should not be performed while the heart is beating rapidly because the PPG waveform frequency with be heavily influenced by heart rate, causing measurement uncertainty (Elgendi, 2012). Therefore it is recommended to measure constituents within the blood while patients have a normal resting heart rate within the range of 60 to 100 bpm.

Our previously research on the design and construction of non-invasive blood glucose meters demonstrated the feasibility of using a reflective sensor with 950 nm wavelength light to measure blood sugar levels from the fingertip (Anupongongarch, Kaewgun, & O'Reilly, 2020; Anupongongarch, Kaewgun, O'Reilly, & Khaomek, 2019). Voltage output from this sensor changes based on the principle that glucose molecules in the blood influence absorbance of 950 nm light. However, this prior work also identified inconsistent force applied to the sensor as a source of measurement inaccuracy to be improved in future designs.

The aim of this research was to develop a non-invasive blood glucose meter that fixes problems associated with unstable fingertip pressure on the sensor by using finger probe sensor from Nellcor™ (DS-100A), and implements simultaneous heart rate measurement. The resulting device operates using PPG, with light transmitted through the fingertip. Red and near infrared light sources with respective wavelengths of 630 and 950 nm transmit light that gets reflected by the tissue. Voltages produced by two photodetectors paired with the light sources are compared to derive measurements; the 630 nm light provides a background reference, while the 950 nm light is used to infer blood glucose concentrations (Anupongongarch et al., 2020).

Measurements from the device were calibrated using concurrent standardized blood glucose measurements performed at the Endocrine Unit, Faculty of Medicine, Vajira Hospital, Navamindradhiraj University. Device output was plotted against these blood sample measurements to obtain the relationship between digital output and blood glucose concentration. The resulting equations were used to complete the noninvasive blood glucose and heart rate meter, designed to display blood glucose level in mg/dL and heart rate in bpm.

2. Objective

The objective of this research was to design and construct a non-invasive blood glucose and heart rate meter based on PPG with improved stability of fingertip pressure on the sensor using a constant pressure finger probe. Further development of this non-invasive blood monitoring

technology will lead to more convenient disease management for patients with chronic diabetes.

3. Materials and methods

In line with previous work on the design and construction of a non-invasive blood glucose meter (Anupongongarch et al., 2019), this operation of this device was based on the Beer-Lambert Law of light absorbance. Development of this device was conducted broadly in two sections: the first part consisted of designing a non-invasive blood glucose and heart rate meter, and the second part consisted of testing the electronic circuits, obtaining an equation to convert the output digital value into blood glucose (mg/dL), functional testing, and efficiency testing.

3.1 Prototype design

The prototype device includes four parts: signal detection circuit, signal conditioning circuit, signal processing circuit, and display.

3.1.1 Signal detection circuit

A fingertip reflective light sensor (TSKS5400S; Vishay Semiconductors) was used for signal acquisition. This sensor self-contains light emission and reception elements. The emitter incorporates two light-emitting diode (LED) sources: near-infrared 950 nm, absorbed by blood glucose, and red 630 nm, which is not absorbed by blood glucose so provided a reference (Anupongongarch et al., 2019). The sensor included photodiodes for measuring reflected light. The signal detection part of the prototype device consisted of a sensor circuit and a switch control circuit.

a) Sensor circuit

The technical specifications for operating the reflective light sensor were as follows: supply voltage V_{DD} of 5 V direct current; forward bias voltage drop over the infrared LED $V_{F(IR)}$ of 1.25 V; forward bias current through the infrared LED $I_{F(IR)}$ of 50 mA; forward bias voltage drop over the red LED $V_{F(RED)}$ of 1.8 V; and forward current through the red LED $I_{F(RED)}$ equal to 20 mA.

In the sensor circuit, connection to a 5 V_{DC} power supply was provided via the microcontroller board. Two current-limiting resistors were required to protect the reflective light sensor components from damage due to excess current. These were connected in series with infrared and red LEDs, labelled R1 and R2, respectively, in equations 1 and 2 and also in Figure 1.

$$R1=\frac{(V_{DD}-V_{F(IR)})}{I_{F(IR)}} \quad (1)$$

$$R2=\frac{(V_{DD}-V_{F(RED)})}{I_{F(RED)}} \quad (2)$$

Therefore, R1 = 75 Ω and R2 = 160 Ω were used in the sensor circuit.

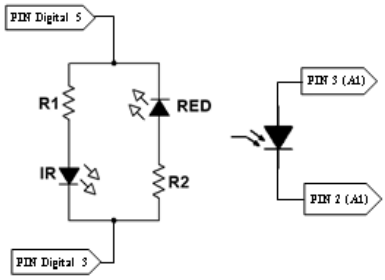

Figure 1 Sensor Circuit

b) Switch control circuit

A switch was used to control the device. This allows the user to perform measurements when the sensor is securely fitted to the fingertip, ensuring good signal quality. The switch was connected to a 10 kΩ pull-down resistor (R10), forming an active high configuration. Therefore this circuit simply works by supplying electricity to the light source when the switch is pressed. The switch control circuit is shown in Figure 2.

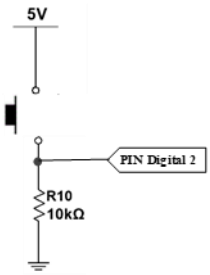

Figure 2 Switch Control Circuit

3.1.2 Signal conditioning circuit

The raw, low-amplitude signal received from the sensor is typically contaminated with noise. Therefore, signal conditioning must be applied to prepare the signal for digital conversion and further processing. The analogue signal conditioning circuits included a current to voltage converter, high pass filter, non-inverting amplifier, and low pass filter. A block diagram of this signal conditioning circuit is shown in Figure 3.

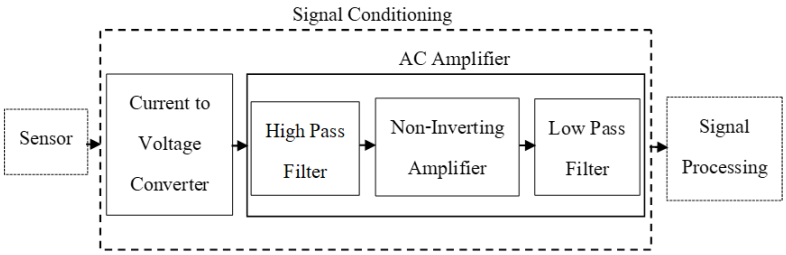

Figure 3 Signal conditioning circuit block diagram

The signal conditioning section consisted of a current-to-voltage converter, passive high-pass filter, and two-stage non-inverting amplifier circuit. Input to the current-to-voltage converter was obtained from a photodiode (EPM-4001), which converts light energy into electric current. This current is thus transformed into to a proportional voltage. Using zero-biasing to produce only positive output, a voltage signal (V_{out}) of 80 mV was derived from an input current (I_D) of 16 nA. Therefore, resistance R_3 in the circuit (Figure 4) was calculated from Ohm's law to be 5 MΩ.

The AC-coupled non-inverting amplifier circuit included two stages, named B1 and B2 in Figure 4. These each include LM358 operational amplifiers. Both have passive high-pass filters connected to their inputs. The cut-off frequency (f_c) was designed to be 0.5 Hz, and capacitors C_1 and C_3 were selected to be 1 µF. Resistors R_4 and R_7 of the high-pass filters were calculated according to equation 3.

$$R=\frac{1}{2\pi f_c C} \qquad (3)$$

Thus, the value of resistance calculated was 318.3 kΩ and $R_4 = R_7 = 318.3$ kΩ.

For amplifier B1, when the input voltage (V_{in}) was equal to 80 mV, the output voltage (V_{out}) was 920 mV; therefore the signal gain (Av) was 11.5. The current (I) in the B1 circuit can be calculated by equation 4.

$$I=100\times I_{B(max)} \qquad (4)$$

Where $I_{B(max)}$ is 500 nA therefore I is 50 µA.

The resistance in B1 can be calculated by using Ohm's law in equation 5.

$$R_i=\frac{V_{in}}{I} \qquad (5)$$

Let $R_i = R_6$ therefore R_6 is 1.6 kΩ. The feedback resistance $R_f = R_5 = 16.8$ kΩ in the circuit can be determined from the signal gain in equation 6.

$$A_V=1+\frac{R_f}{R_i} \qquad (6)$$

The low-pass filter in B1 had $f_c = 2.5$ Hz, thus $C_2 = 3.8$ µF can be calculated using equation 7 as follows.

$$C_2=\frac{1}{2\pi f_c R} \qquad (7)$$

In the second amplifier circuit (B2), $V_{in} = 920$ mV, $V_{out} = 3.60$ V, thus Av = 3.9. Using equations 4, 5, 6, 7, it is found that current I = 50 µA, R9 = 18.4 kΩ, $R_8 = 53.4$ kΩ, and $C_4 = 1.2$ µF. The signal conditioning circuit is shown in Figure 4.

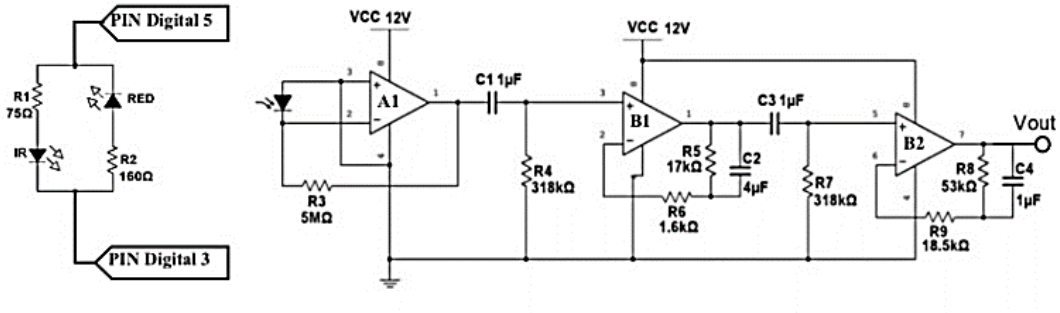

Figure 4 Analogue circuit diagram

3.1.3 Signal processing circuit

In the signal processing circuit, an Arduino microcontroller NANO 3.0 Mini USB was used. This has a 10-bit analog to digital converter (ADC) with an input range of 5 V. The signal obtained from the ADC was used to create a calibration curve from which to derive a correlation equation between blood glucose in mg/dL and digital output. Thereby the system captures undulating signals from the blood volume changing at the fingertips. The software algorithm is illustrated in Figure 5. The values of blood glucose level and heart rate are shown on an LED screen.

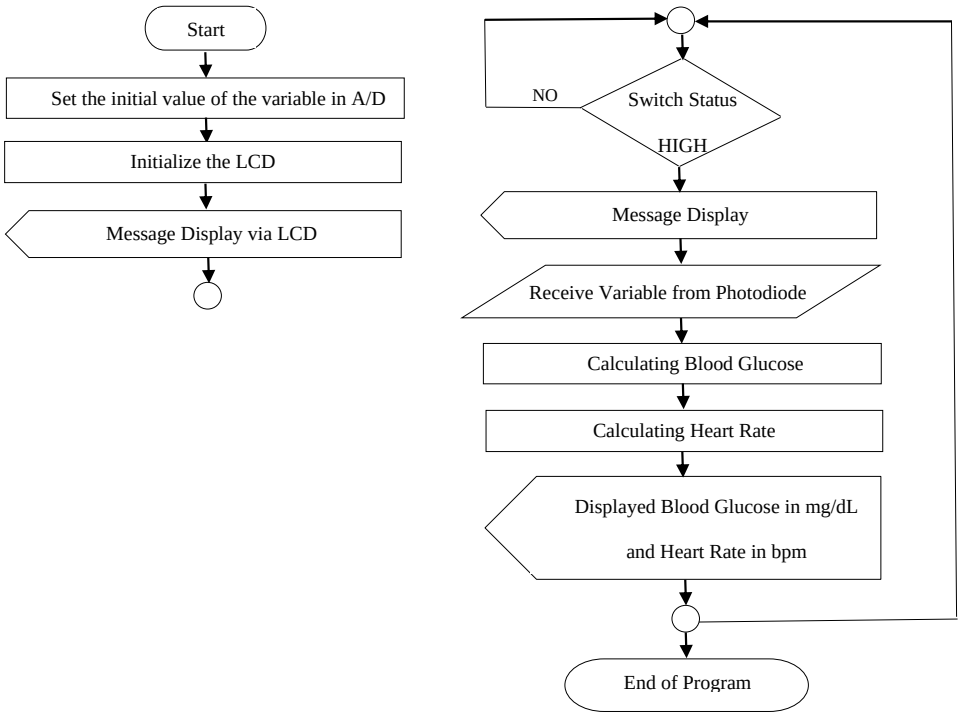

Figure 5 Algorithm of program

Blood glucose level measurements take 1 min. During this time the program measures the maximum voltage of the signal from blood volume changes at the fingertip 3 times, each taking 20 s. Thereafter the program computes the average and converts it into blood glucose level in mg/dL.

For heart rate measurements, the program records the time between three consecutive cycles

of semi-periodic blood volume changes detected at the fingertip. From experiment, it was found that on average 42.7 digital output values, equaling 0.64 seconds, could capture one complete waveform. Therefore 120 digital output values were stored to measure heart rate, capturing approximately three wavelengths of the PPG signal. Using 120 digital output values to measure heart rate was amenable to signal processing. Peak to peak time measured from 120 length segments was repeated three times to obtain measurements of heart rate, which was then converted into the scale of bpm. Figure 6 shows the signal from measurements of undulating waves.

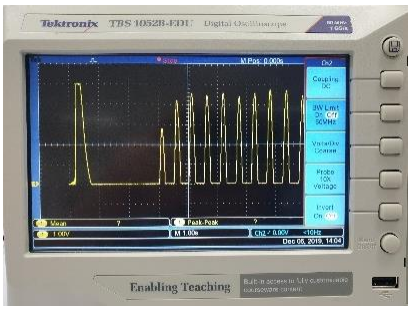

Figure 6 The voltage of undulating waves

3.1.4 Display

A 16x4 LCD was used to display the blood glucose level in milligrams per decilitre (mg/dL) and heart rate in beats per minute (bpm).

3.2 Testing

The prototype non-invasive blood glucose and heart rate meter was tested to evaluate its accuracy. These tests included: 1) Sensor IC testing, 2) The correlation equation between voltage (V) with blood glucose (mg/dL), 3) Functional test, and 4) Accuracy test.

3.2.1 Sensor IC testing

This simply consisted of confirming the signal output from the sensor circuit. The index fingertip was placed into the probe and an oscilloscope was used to measure the output voltage signal. This was recorded as a picture of the oscilloscope display.

3.2.2 The correlation equation

A correlation equation was found relating the blood glucose level and the digital value from the ADC. Three hundred diabetic patients attending the diabetes clinic at Endocrine Unit, Faculty of Medicine, Vajira Hospital, Nawamindradhiraj University volunteered to participate in an experiment to confirm the operation of this device. This sample included patients who have hypoglycemia in the range of 70-99 mg/dL, hypoglycemia in the range of 100-125 mg/dL, and others in the range of >126 mg/dL, spanning the full range of blood glucose levels and also encompassing the range for healthy individuals. A medical team accessed the subjects' and collected blood test results at the same time as recording the device output. The testing method is as follows:

On the date of data collection, subjects were instructed not to eat or drink at least 8-12 hours prior to blood test. Data collection was then performed as follows.

1. Subjects had a blood test at the diagnostic room, the Pathology Unit, Vajira Hospital, recording their blood glucose value.
2. Due to the high sensitivity of the blood sugar meter, arrange the volunteer to sit in an upright position. Put your arms flat on the table. Put the tip of the index finger into the probe, record digital output values measured from subjects from noninvasive blood glucose meters.
3. The correlation coefficient was found relating blood glucose data of all subjects with digital output values from the prototype device.
4. This correlation equation was programmed into the microcontroller to convert the digital value to blood glucose level in millimeters per deciliter.

3.2.3 Functional testing

1. Test the accuracy and precision of blood glucose from the device that has been designed and constructed. The 15 subjects were tested in a blood test at the autopsy. Pathology unit, Vajira Hospital and measure the blood sugar by non-invasive blood glucose meters. Record the data of blood glucose. Using the data obtained to calculate the standard deviation and percentage error.
2. Test the accuracy and precision of heart rate test. This was compared with heart rate measurements with a vital signal monitor from 15 subjects, and heart rate data obtained from non-invasive blood glucose meter and monitors were used to calculate the values of standard deviation and percentage error.

3.2.4 Performance testing

1. Measurements from the non-invasive blood glucose meter were compared with blood glucose values from blood test results performed by a diagnostic laboratory. A paired t-test was used to evaluate whether these measurements were not statistically different (null hypothesis). Alpha was considered to be 0.05.
2. Clarke error grid analysis, as a efficiency testing (Clarke, Cox, Gonder-Frederick, Carter, & Pohl, 1987). Clarke error grid analysis is a graph showing the accuracy of a glucose meter to detect errors in blood glucose for clinical decision-making where the y-axis represents the glucose level measured by the non-invasive blood glucose meter, and the x-axis represents the blood glucose level by standard method. The graph is divided into 5 zones: zone A means the glucose level measured with a standard error of less than 20%, or the glucose level measured by both methods is less than 70 mg/dl, does not make a difference in decision making of the clinic, zone B means Glucose levels more than or equal to 20 percent higher or lower than the standard value. It may lead to treatment adjustments but has no or little effect on health outcomes, zone C means that glucose levels that are monitored tend to lead doctors to adjust treatment despite sugar levels being within the acceptable range. (overcorrection), zone D means the level of sugar that can be detected in an acceptable threshold, but in reality, the glycemic value is either too high or too low (failure to correct), and zone E refers to levels detectable glucose tend to alter treatments that contradict the reality, which can be dangerous for the patient.
3. Find the coefficient of determination (R^2) between measurements from the non-invasive blood glucose meter with blood glucose values from blood test results performed by a diagnostic laboratory.

The data analysis in this research was as follows:

1. The data correlation between the glycemic index and the digital output value. Show the correlation coefficient (Pearson Product-Moment Correlation).
2. Descriptive statistical analysis of clinical data from the sample. The mean ($\bar{X}$) in equation (8) and the standard deviation (σ) in equation (9) were used to find the accuracy of measurement. If the standard deviation is low value, it means that the values is closed to the mean.

$$\bar{X}=\frac{1}{N}\sum_{i=1}^{N} X_i \qquad (8)$$

$$\sigma=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i-\bar{X})^2} \qquad (9)$$

where N is the number of subjects and X_i are measured values.

The percentage error was then calculated as in equation (10):

$$\%\text{error}=\left|\frac{E-S}{S}\right|\times 100\% \qquad (10)$$

where S is the standard value and E is the experiment value.

4. Analyze blood glucose values obtained from the prototype noninvasive blood glucose meters. These were compared with the standard blood drawing method using SPSS 21.0 program to test the null hypothesis with the threshold for significant difference considered to be 0.05, Clarke error grid analysis was performed graphically, in Microsoft Excel program (Mondal, & Mondal, 2020). The correlation equation was found between the non-invasive blood glucose meter with blood glucose values from blood test results performed by a diagnostic laboratory.

4. Results

The complete prototype is shown in Figure 7.

Figure 7 Non-invasive blood glucose and heart rate meter

4.1 Sensor circuit testing

A sample result from testing the output of the sensor circuit with a digital oscilloscope (model TDS1001B; Tektronix, OR, USA) is plotted in Figure 8. This signal exhibits six low-amplitude peaks, representing red light absorption, followed by six higher-amplitude peaks, representing infrared light absorption. The voltage difference between these two sets of peaks is approximately 760 mV, which is suitable for digitization and further signal processing using a microcontroller.

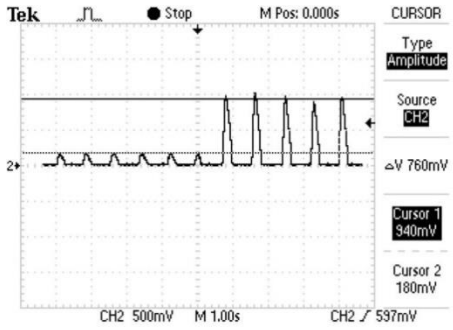

Figure 8 The output signal of the sensor IC

4.2 Calibration equation testing

Data were collected between the noninvasive blood glucose values in milligrams per deciliter (mg/dL) and the output digital values. The sample group was assigned 300 people. Data analysis revealed that the blood glucose level was negatively correlated with digital output, with a correlation coefficient, $r = -0.81$ ($p < 0.001$).

The blood glucose and digital output data of all subjects were used to finds the graph in Figure 9 and correlation equation between blood glucose values and digital output values found that:

$$y=-7\times10^{-6}x^3+7.7\times10^{-3}x^2-2.743x+419.35$$

$$R^2=0.971$$

Where y represents the blood glucose level in mg/dL,

x represents the digital output,

R^2 represents the coefficient of determination.

When the graph equation was calibrated between the blood glucose level in milligrams per deciliter (mg/dL) and the digital output value that used to write programs on the microcontroller to convert digital output values to blood glucose values in milligrams per deciliter (mg/dL) and display them on the display screen.

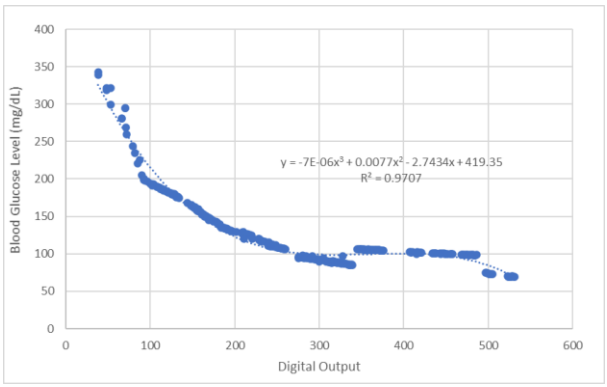

Figure 9 The graph between blood glucose level and digital output

4.3 The results of functional testing

Functional testing results from 15 subjects are shown in Table 1. Blood glucose levels measured using the device is compared with blood test results from the diagnostic laboratory, Pathology unit, Vajira Hospital.

Table 1 Blood glucose level from device compared with the standard blood glucose measurements.

Subject	Blood glucose level from the standard measurement (mg/dL)	Blood glucose level from the non-invasive blood glucose and heart rate meter		Average blood glucose level from the non-invasive blood glucose and heart rate meter	Standard Deviation	Percentage Error
		1	2			
1	75	77	77	77	0.00	2.67
2	86	84.06	84.06	84.06	0.00	2.26
3	95	100.01	85.05	92.53	10.58	2.60
4	98	97.48	97.48	97.48	0.00	0.53
5	100	97.82	97.82	97.82	0.00	2.18
6	105	99.38	97.36	98.37	1.43	6.31
7	115	114.03	108.41	111.22	3.97	3.29
8	125	118.57	118.57	118.57	0.00	5.14
9	130	123.38	127.2	125.29	2.70	3.62
10	137	120.78	115.76	118.27	3.55	13.67
11	150	140.28	135.53	137.91	3.36	8.06
12	207	180.8	175.75	178.28	3.57	13.88
13	211	111.22	111.22	111.22	0.00	47.29
14	221	271.17	271.17	271.17	0.00	22.70
15	289	200.1	220.38	210.24	14.34	27.25
Average		-	-		**2.90**	**10.76**

According to the data in Table 1, the non-invasive blood glucose meter measures blood sugar level in the range from 75 to 289 mg/dL with a mean standard deviation of 2.90. When the value of blood glucose from a non-invasive blood glucose meter compared with the blood test results at the diagnostic laboratory found that blood sugar levels ranged from 75-130 mg/dL, the mean blood glucose level was 100.26 mg/dL and the percentage error was 3.18%, in the range from 131-289 mg/dL, found that the mean blood sugar level was 171.18 mg/dL. The percentage error was 22.14% and the blood sugar level ranged from 75-289 mg/dL, the mean blood glucose level was 128.63 mg/dL with the average percentage error of 10.76%. From Table 1, it may be noted that subjects 3 and 15 had relatively high standard deviations compared with the other subjects. Following discussions with medical personal, it was suggested that this may be due to patient movement, talking, or incorrect posture during the test.

The results of testing the accuracy of the non-invasive heart rate meter from 15 subjects compared with a vital sign monitor are shown in Table 2.

Table 2 The results of the heart rate value from non-invasive blood glucose and heart rate meter compared to the heart rate value from the vital sign monitor.

Subject	Heart rate value from the vital sign monitor (bpm)			Average Heart rate value from the vital sign monitor (bpm)	Standard Deviation	Heart rate value from the non-invasive blood glucose and heart rate meter (bpm)			Average Heart rate from the non-invasive blood glucose and heart rate meter (bpm)	Standard Deviation	Percentage error
	1	2	3			1	2	3			
1	63	64	64	63.67	0.58	64	65	67	65.33	1.53	2.62
2	64	65	64	64.33	0.58	68	65	66	66.33	1.53	3.10
3	76	79	80	78.33	2.08	96	70	77	81.00	13.45	3.40
4	80	81	79	80.00	1.00	72	78	80	76.67	4.16	4.16
5	83	82	84	83.00	1.00	82	84	83	83.00	1.00	0.00
6	83	86	85	84.67	1.53	78	79	81	79.33	1.53	6.30
7	83	84	86	84.33	1.53	89	87	88	88.00	1.00	4.35
8	85	84	87	85.33	1.53	89	88	87	88.00	1.00	3.13
9	88	90	91	89.67	1.53	90	89	90	89.67	0.58	0.00
10	90	92	91	91.00	1.00	97	90	95	94.00	3.61	3.30
11	92	91	90	91.00	1.00	84	90	91	88.33	3.79	2.93
12	92	91	93	92.00	1.00	92	93	90	91.67	1.53	0.36
13	93	96	97	95.33	2.08	99	97	98	98.00	1.00	2.80
14	94	93	92	93.00	1.00	99	96	97	97.33	1.53	4.66
15	101	102	100	101.00	1.00	106	102	104	104.00	2.00	2.97
Average				**85.11**	**1.23**				**86.04**	**2.61**	**2.94**

From the data in Table 2 it was found that the mean heart rate measurement with the vital monitor was 85.11 bpm with a mean standard deviation of 1.23. The heart rate of the non-invasive blood glucose and heart rate meter was a mean 86.04 bpm, a mean standard deviation of 2.61, and a mean percentage error compared to the vital signs monitor of 2.94%

4.4 The results of performance testing

1. Measurements from the non-invasive blood glucose meter were compared with blood glucose values from standard blood test results using a paired t-test. The results of this analysis were $t(14) = 1.587$, $p = 0.135$, suggesting that there were no statistically significant differences between the two groups of measurements (i.e. $p > 0.05$).
2. Measurements from the non-invasive heart rate meter were compared with readings from a vital sign monitor using a paired t-test. The results of this analysis were $t(14) = 1.277$, $p = 0.222$, suggesting that there were no statistically significant differences between the two groups of measurements (i.e. $p > 0.05$).
3. Blood glucose measurements taken from 15 subjects using the non-invasive blood glucose meter were compared with standard blood tests in Clarke error grid analysis. The graph between blood glucose values from the non-invasive blood glucose meter are plotted on the y-axis, while results from standard blood tests are plotted on the x-axis, as shown in Figure 10. From the figure it can be seen that 73.7% of the blood glucose values tested were in zone A, while the other 26.7% were in zone B. Therefore, the accuracy range of the non-invasive blood glucose meter is 75-150 mg/dl.

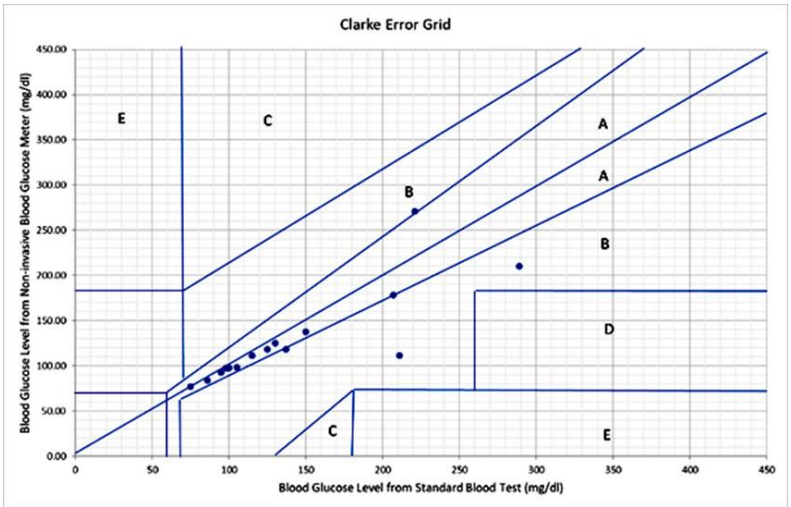

Figure 10 Clarke error grid use for estimating errors in blood glucose values as measured by non-invasive blood glucose meter

4. Data were collected between the non-invasive blood glucose values and blood glucose values from blood test results performed by a diagnostic laboratory in milligrams per deciliter (mg/dL). The sample group was assigned 15 people. Data analysis revealed that the blood glucose level was positively correlated with blood glucose values from standard blood test with a coefficient of determination (R^2), R^2 = 0.68 in range of 75-289 mg/dL and R^2 = 0.99 in range of 75-150 mg/dL, therefore the accuracy range of the non-invasive blood glucose meter is in range 75-150 mg/dl.

5. Discussion

There was a negative correlation between blood glucose level and digital output from the device, meaning that when the digital output value is small, the blood sugar level is high, and vice versa. This follows the Beer-Lambert principle of light absorption.

The photoplethysmography (PPG) method can be used to measure changes in blood volume at the fingertip in terms of voltage produced by the signal detection circuit. The heart rate is derived from the three 20 second recordings, whereby the period of the PPG waveform is approximated by detecting peaks in the signal and using this to calculate the frequency in beats per minute. Calculated values of blood sugar level and heart rate are then displayed on the device in units of mg/dL and bpm, respectively.

From the fixed problems associated with unstable fingertip pressure on the sensor by using figure probe sensor from Nellcor™ (DS-100A) found that the use of a finger probe reduced the inaccuracy of blood glucose measurements. This makes the display of blood glucose level that more stable because the force exerted on the sensor is a spring force. The spring force acting on the individual finger is constant that causes the measured value to have a lower standard deviation. Tests for the standard deviation of non-invasive blood glucose meter using a finger probe and non-invasive blood glucose meter by using a fingertip pressure on the sensor of previous models showed that the mean standard deviation non-invasive blood glucose meter using a finger probe was 2.90 milligrams per deciliter (mg/dL), while the previous model had a mean standard deviation of 7.91 milligrams per deciliter (mg/dL) (Anupongongarch et al., 2020).

From functional testing with blood glucose levels across the range of 75-289 mg/dL the device was found to be accurate within the range of 70-130 mg/dL; repeat measurements were similar, mean standard deviation was 2.90, and the mean percentage error was 3.18%. Performance decreased when blood glucose levels were in the range from 131-289 mg/dL, with a mean percentage error of 22.14%. From these findings it is fair to say that this device can accurately measure blood glucose levels in the range of 75 -130 mg/dL, but is inaccurate when blood glucose level is higher than 130mg/dL. Therefore, in it its current stage of

development, this device should only be considered for measuring blood glucose levels in range of 75-130 mg/dL.

Heart rate can be derived from the signal acquired during non-invasive blood glucose measuring. This signal is used to monitor changes in blood volume that occur due to the compression of the heart and blood vessels. It is possible to calculate the heart rate by detecting peaks in this signal over time. This means that heart rate and blood glucose measurements are carried out simultaneously with this device. Testing showed that a mean percentage error compared to a vital sign monitor of 2.94%. The values of heart rate obtained in this manner were similar to those measured from a vital sign monitor. This device can measure the heart rate from the photoplethysmography principle which corresponds to previous study a design, development analysis and application in clinical and physiological measurement (Jayadevappa & Holi, 2016).

The performance of this device was tested by comparing values obtained from it with results from blood tests performed at a diagnostic laboratory (Pathology Unit, Vajira Hospital). The non-invasive meter was found to have a systematic error that yielded lower estimates of blood glucose than test results from the diagnostic laboratory. This difference was not statistically significant ($p = 0.135$), but nonetheless should be counted among the practical considerations for this device. Zone A in Clarke error grid analysis and coefficient of determination of $R^2 = 0.99$ across blood glucose concentrations of 75-150 mg/dL demonstrates that the accuracy of this device is in range 75-150 mg/dL.

The design and construction of a non-invasive blood glucose meter by photoplethysmography that can measure blood glucose level from the fingertip. The glucose estimation, distribution of the points on a Clarke error grid placed 73.7% of points in zone A, 26.3% in zone B and coefficient of determination $R^2 = 0.99$ in range of 75-150 mg/dL which corresponds to previous study a non-invasive estimate of blood glucose and blood pressure from a photoplethysmograph by means of machine learning techniques (Monte-Moreno, 2011) and estimation of blood glucose by non-invasive method using photoplethysmography (Habbu, Dale, & Ghongade, 2019).

While conducting these experiments several factors were recognized to have an adverse effect on measurements taken with this non-invasive blood glucose and heart rate meter. It was found that talking, movement, and posture while using the device influenced heart rate measurements. Other factors that affected the accuracy of blood glucose measurements included arm position, nail paint, blue fingernails due to congenital disease, thick nails, and fingers larger than the probe.

Future work will aim to study photoplethysmography of light at a wavelength of 950 nm with various substances in the blood to determine any effects that may cause blood sugar level measurements to become inaccurate, and improve the meter in the range >150 mg/dL.

6. Conclusion

The device described in this article offers an improvement upon previous designs by stabilizing fingertip pressure on the sensor using a constant-pressure finger probe. This has been shown to enhance the reliability of non-invasive blood glucose and heart rate measurements made using the Beer-Lambert principle of light absorption. Nine-hundred and fifty nanometer infrared and 630 nm red LED light sources were paired with a photodiode light receiver to record light absorption with blood volume changes. Light absorption at different wavelengths was used to derive blood glucose measurements. This was validated with data from a sample of 315 diabetic patients treated at the Endocrine Unit, Faculty of Medicine, Vajira Hospital, Navamindradhiraj University. The next stage in the development of this device is to seek a larger validation cohort, minimize the error for cases at the edges of the distribution and collected data with an accuracy in the range of 150 mg/dL and above.

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