Application of Reflectance Mode Photoplethysmography for Non-Invasive Monitoring of Blood Glucose Level with Moving Average Filter

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ABSTRACT
With the continuous increase in number of people suffering from diabetes, the demand of a device that can noninvasively monitor blood glucose level has been greater. The goal of the study is to develop a device that can monitor the blood glucose level that would not cause any discomfort to the patients by utilizing reflectance mode photoplethysmography equipped with a filtering technique, Moving Average filter. Initially, the device prompts the user to choose from two categories depending on his condition: diabetic or non-diabetic, and then would choose between the two modes: fasting or post meal mode. The parameters utilized in the study are the force in Newton (N) which corresponds to the applied pressure on the finger, the peak-to-peak voltage (V) of the photopletyhsmography signal, and lastly, the blood glucose level measured in milligram per deciliter (mg/dL). The force is acquired using a force sensitive resistor that is incorporated in the ring. The suggested device employs a photoplethysmography sensor which can diagnose variations on microvascular bed of tissue. The variations in the distribution of blood volume have a significant relation with the measurement of blood glucose level. The technique used to estimate the photoplethysmography in terms of peak-to-peak voltage is the Moving Average filter, and the result is then compared to that of the OneTouch glucometer and Fasting Plasma Glucose. From the results acquired, two equations are derived which output the blood glucose level for diabetic and non-diabetic patients in mg/dL. The equations are described to be both linear, a positive correlation for non-diabetic patients with a percentage of 70.3004% and a negative correlation for the diabetic with a percentage of 91.9226%.

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CCS CONCEPTS
Applied computing → Life and medical sciences

Keywords
Photoplethysmography; Blood glucose level; Peak-to-peak voltage; Non-invasively; Glucometer

1. INTRODUCTION
With the advancement of wireless technology, the tasks of keeping track of patients' medical records and vital statistics is made simple, making it very helpful for the medical practitioners on their jobs. [1]. Diabetes is considered as one of the life-threatening diseases today and the number of patients suffering from this disease is increasing incessantly. There are 415 million people from around the world who are suffering from the complications of Diabetes, about 153 million patients from it are from the Western region. As of 2015, there are about 3.5 million cases of the disease in the Philippines [2]. Diabetes is a chronic, escalating disease wherein the glucose is not utilized properly by the body cells, thus it stays in the blood. [3]. Complications from diabetes may be avoided or distinguished by monitoring the blood glucose level of a patient, however the standard method causes discomfort on the patients since it involves invasive measures like pricking the finger [4]. It is the conventional method used since it is accurate, convenient, and easy to process. [5]. With the technology constantly evolving, it is now possible to monitor blood glucose level noninvasively [6]. These technological advancements gave way to wearable health monitoring devices which is made possible with biosensors [7]. Photoplethysmography is an optical technique which can measure the blood glucose level of a patient by detecting blood volume

changes [8]. It is easy to use, reliable, and low cost, which makes it helpful in monitoring the heart rate [9], [10]. Photoplethysmography (PPG) is mainly divided into two categories namely reflectance and transmission mode. Photoplethysmography consists of two components, the photodetector and light source. The reflectance mode is utilized in the device in which the components are positioned side-by-side. The function of the photodetector is to absorb the reflected or back-scattered light by the tissues, bone, and blood vessels [11], [12]. The factors affecting the AC variation of the photoplethysmography signal are the amount of tissue thickness, blood perfusion bone, and light intensity [13].

Designing and developing a wearable finger strap that can noninvasively monitor the blood glucose level using photoplethysmography reading is the target of this study. In line with this, (1) experiments must be carried out to determine the correlation between the blood glucose level (in mg/dl) and the peak-to-peak voltages of the photoplethysmography signal which is affected by motion and the contact force applied on the proximal phalanges; (2) a filtering method must be incorporated to the photoplethysmography signal in order to produce a smoothened signal, and (3) the results from the study's prototype must be compared with glucometer and with a clinical lab tests.

2. RESEARCH METHODOLOGY

2.1 Research Development

The conceptual framework, as shown in Figure 1, is the basis of the researchers on making the device. The input parameters of the device include the force applied on the proximal phalanges and the captured photoplethysmography signal from the patient. A peak-to-peak voltage will be obtained from the signal and will be reconstructed to a blood glucose level reading in mg/dL by using the equation which is the result of the calibration of the study. The obtained glucose level will be the output to be displayed on the screen. The flowchart as shown in Figure 2 describes further emphasis on designing the prototype device. The prototype is cased and attached to the patient as shown on Figure 3.

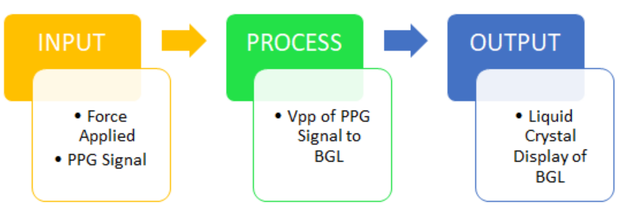

Figure 1. Conceptual framework of the non-invasive PPG-based blood glucose level monitoring device

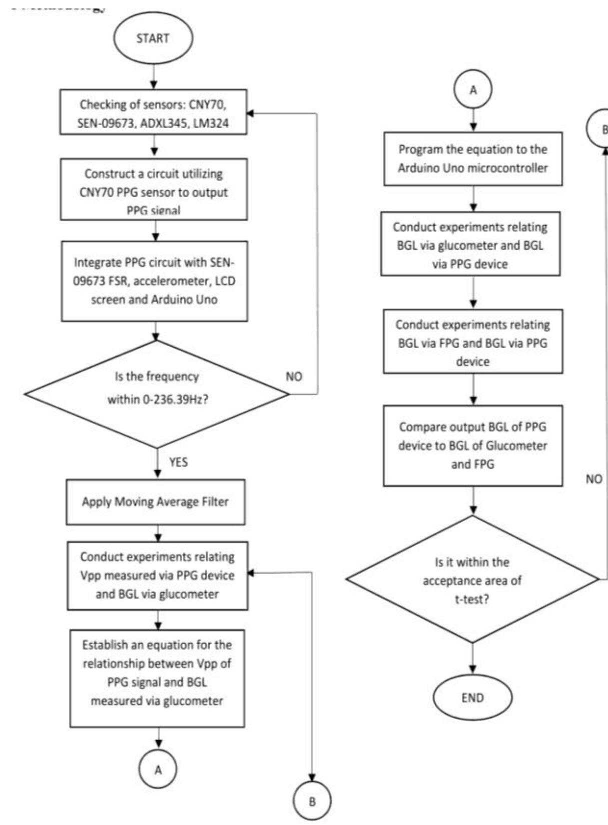

Figure 2. Development flowchart

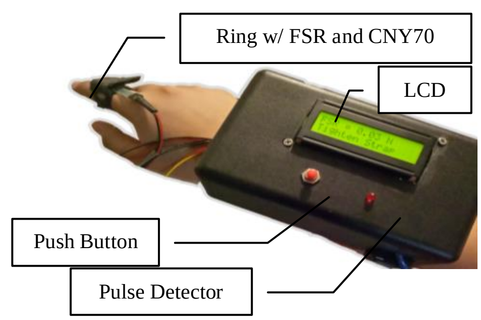

Figure 3. Prototype Design

2.2 Acquisition of PPG Signal

The photoplethysmography signal is acquired with the use of CNY70 sensor and is connected to an interface circuit, as shown on Figure 4, designed specifically for capturing the photoplethysmography signal of the patient. An Arduino Uno microcontroller is used to interpret the data obtained and it is also connected to the circuit. Nevertheless, inaccurate measurements are still produced from the photoplethysmography technique because of the several factors affecting the results which include the location of measurement, motion, and contact force applied on the probe. The importance of the location of measurement on the design is that this factor affects the quality of the signal and the strength against the motion artifacts. Another factor that affects the signal is motion in which a filtering technique is used in order to eliminate its artifacts. The last factor is the contact force. To obtain the best photoplethysmography signal, it must be within the range of 0.2 N to 0.4 N [1]. A force sensitive resistor is connected to the circuit in order to determine and measure the ideal amount of force.

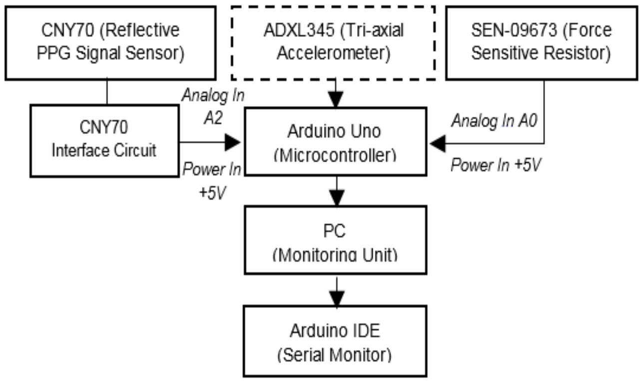

Figure 4. Setup of Photoplethysmography-based Blood Glucose Level Monitoring Device

2.3 Moving Average Filter Algorithm for Estimation of Peak-to-Peak Voltage

Moving average filter is an algorithm that captures a number of samples then averaging these samples to one single output point as depicted by Eq. 1 [14], [15]. With the use of this algorithm, the output of the system will be the average peak-to-peak voltage of the acquired waveform of the photoplethysmography signal. As shown on Figure 5, the peak-to-peak voltage is the estimated difference between the maximum peak voltage and the minimum peak voltage. Upon measuring the peak-to-peak voltage of the photoplethysmography signal, the pulsatile component of the signal is also determined.

$$\bar{V} = \frac{V_1 + V_2 + V_3 + \cdots + V_n}{n} = \frac{1}{n}\sum_{i=0}^{n} V_i \quad (1)$$

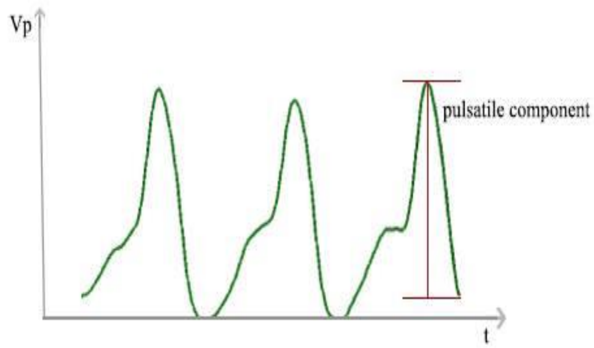

Figure 5. Photoplethysmography signal

2.4 Correlation between Peak-to-Peak Voltage of PPG Signal and Blood Glucose Level

In order to determine the correlation between the blood peak-to-peak voltage of the photoplethysmography signal and blood glucose level measured in milligram per deciliter (mg/dL), experiments are done which are categorized into two namely non-diabetic and diabetic conditions [16]. See Figure 6 for the flow diagram on how the prototype works.

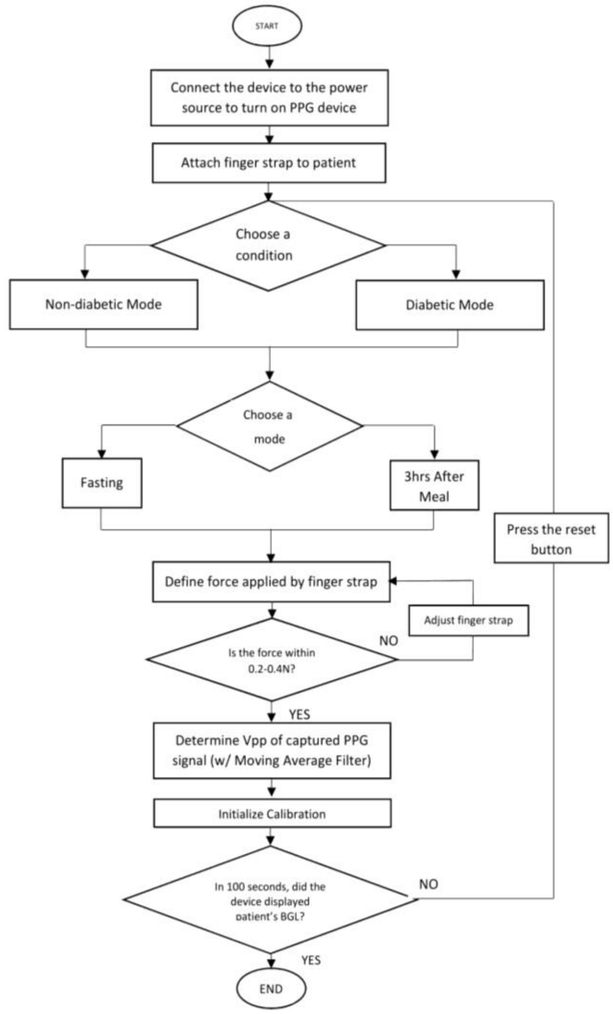

Figure 6. Methodology on how the prototype works

2.4.1 For Non-Diabetic Patients:

Based on the graph in Figure 7, it is determined that the the peak-to-peak voltage of the non-diabetic patients are directly proportional with the blood glucose level thus producing a linear and positive correlation of 70.3004%.

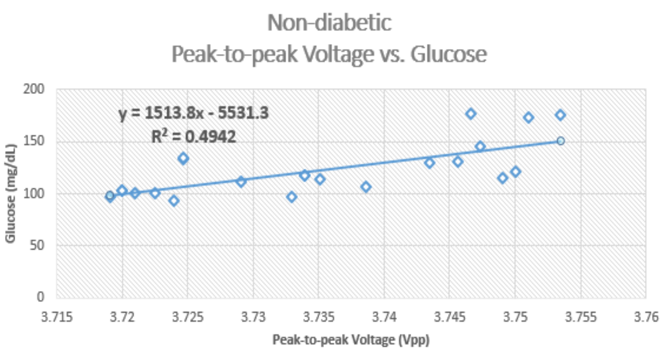

Figure 7. Correlation between non-diabetic's blood glucose level and photoplethysmography peak-to-peak voltage

2.4.2 For Diabetic Patients:

As illustrated on the graph in Figure 8, the data acquired produced a linear and negative correlation of 91.9226%

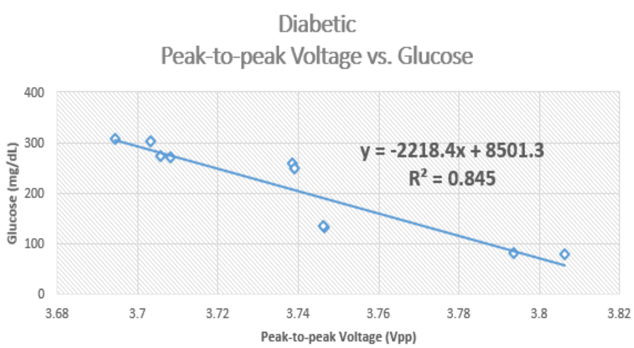

Figure 8. Correlation between diabetic's blood glucose level and photoplethysmography peak-to-peak voltage

3. RESULTS AND DISCUSSION

3.1 Equations

From the acquired data, two equations for non-diabetic and diabetic patients are established which results to a blood glucose level measured in mg/dL. For the non-diabetic patients, the equation acquired is as stated by Eq. 2.

$$y = 1513.8\phi - 5531.3 \tag{2}$$

For diabetic patients, the equation is shown by Eq. 3.

$$y = -2218.4\phi - 8501..3 \tag{3}$$

3.2 Data Gathered

The blood glucose level established from the photoplethysmography signal is compared to the conventional method which is finger pricking as shown on Table 1 and the clinical laboratory test, specifically, Fasting Plasma Glucose (FPG) as shown on Table 2.

Table 1. Blood glucose level via PPG device and Glucometer

Subject	Condition	Mode	BGL PPG (mg/dL)	BGL GLUCO (mg/dL)	%Error
A	ND	**After**	113.3	114	0.61%
B	ND	After	88	92	4.35%
C	ND	After	109	108	0.93%
D	ND	After	153.3	163	5.95%
E	ND	After	112	124	8.63%
F	D	Fasting	82	79	3.80%
G	D	Fasting	82.7	80	3.38%

Table 2. Blood glucose level via PPG device and fasting plasma glucose

Subject	Condition	Mode	BGL PPG (mg/dL)	BGL FPG (mg/dL)	%Error
A	ND	Fasting	93.69	93.69	0%
B	D	Fasting	275	273.87	0.41%
C	ND	Fasting	121	120.72	0.23%
D	ND	Fasting	92	95.5	3.66%
E	ND	Fasting	104.67	109.91	4.77%

3.3 Accuracy Test

The statistical analysis used in the study is the two-tail t-test.

- Null Hypothesis: The photoplethysmography device gives accurate blood glucose level.
- Alternate Hypothesis: The photoplethysmography device does not give accurate blood glucose level.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}}} \tag{4}$$

$$d.o.f. = \frac{\left(\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}\right)^2}{\frac{{s_1}^4}{(n_1-1){n_1}^2} + \frac{{s_2}^2}{(n_2-1){n_2}^2}} \tag{5}$$

To test the accuracy of the device, the t value and degrees of freedom of the data are computed as shown by Eq. 4 and 5. The computed t value is 0.007219015446 and 4 as degrees of freedom. Comparing this value to the t-distribution table which is 2.776, the value from t-distribution table is greater than the computed t value.

Based on the two-tail t-test statistical analysis, hypothesis is accepted. It is conclusive that the photoplethysmography device gives accurate blood glucose level interpretations.

4. CONCLUSION

A wearable finger strap is designed and developed that can non-invasively measure the blood glucose level which is made possible with the use of photoplethysmography. A series of experiments is done with a device that incorporates a CNY70 photoplethysmography sensor and SEN-09673 force sensitive resistor equipped with Moving Average Filter to monitor the patient's peak-to-peak voltage. The obtained peak-to-peak voltage is then compared with the glucometer results wherein the sampling process is categorized into two namely non-diabetic and diabetic. For the non-diabetic patients, the relationship between the peak-to-peak voltage and blood glucose level is directly proportional. On the other hand, for the diabetic category, the relationship is inversely proportional. From these results, two equations are established yielding a blood glucose measured in mg/dL. The equation obtained for the non-diabetic patients is $y = 1513.8x - 5531.3$ with a linear and positive correlation of 70.3004% while the equation obtained for diabetic patients is $y = -2218.4x + 8501.3$ with a linear and negative correlation of 91.9226%. The readings obtained from the device are compared with OneTouch glucometer results and Fasting Plasma Glucose test results indicating a direct relationship for both comparisons. Based on the results obtained, it is verified that the photoplethysmography device can be an alternative to the standard method of monitoring the blood glucose level.

5. REFERENCES

[1] T. Tamaura, Y. Maeeda, M. Seekine and M. Yoshiada, "Wearable Photoplethysmographic Sensors—Past and Present," *Electronics 2014,* vol. 3, pp. 282-302, 2014.

[2] G. H. Tan, "Diabetes Care in the Philippines," *Annals of Global Health,* vol. 81, no. 6, pp. 863-869, 2015.

[3] Diabetese Inself-Management, "What is a normal blood sugar level," 2016. [Online]. Available: https://www.diabetesselfmanagement.com/blog/what-is-a-normal-blood-sugar-level/. [Accessed 1 November 2016].

[4] Massachusetts Institute of Technology School of Engineering, "Ask an Engineering: How Do Glucometers Work?," 2011. [Online]. Available: https://engineering.mit.edu/engage/ask-an-engineer/how-do-glucometers-work/. [Accessed 1 November 2016].

[5] S. H. Golden and T. Sapir, "Methods for Insulin Delivery and Glucose Monitoring in Diabetes: A Comparative Effectiveness Review," *Journal of Managed Care Pharmacy,* vol. 18, no. 6, pp. 1-17, 2012.

[6] J. Lu, R. Bu, Z. Sun, H. Jin, Y. Wang, Q. Lu, S. Wang, L. Li, Z. Xie and B. Yang, "Comparable Efficacy of Self-monitoring of Quantitative Urine Glucose with Self-Monitoring of Blood Glucose on Glycaemic Control in Non-insulin-treated Type 2 Diabetes," *Diabetes Research and Clinical Practice,* vol. 93, no. 2, pp. 179-186, 2011.

[7] G. Song, C. Zhao and Y. Sun, "A classification-based fault detection method for Continuous glucose monitoring (CGM)," in *IEEE 2016 12th World Congress on Intelligent Control and Automation (WCICA),* Guilin, China, 2016.

[8] C. Manlises, J. D. Cruz, J. Fausto, L. Muralla, D.M.Payas and M. Posada, "Monitoring of Blood Pressure Using Photoplethysmographic (PPG) Sensor with Aromatheraphy Diffusion," in *IEEE International Conference on Control System, Computing and Engineering (ICCSCE),* Penang, Malaysia, 2016.

[9] F. Ubels, J. Muntinnga, T. Linksys, K. Hiogenberg, R. Dulart, W. Reatsma and A. Smait, "Redistribution of blood volume in type I diabetes," *Diabetokas,* vol. 44, no. 4, pp. 429-432, 2001.

[10] B. Paulo, S. Manual and Z. Alexis, "Design and Development of Non invasive Glucose Measurement System," in *2010 1st International Symposium on Physics and Technology of Sensors (ISPTS),* Pune, India, 2012.

[11] C. Pujary, "Investigation of Photodetector Optimization in Reducing Power Consumption by a Noninvasive Pulse Oximeter Sensor," *Advantages and Disadvantages of Reflectance and Transmittance Pulse Oximetry,* pp. 9-10, 2004.

[12] J. Webster, "Photoplethysmography (PPG) system," in *Medical instrumentation, application and design,* 2010.

[13] J. Spigulis, "Optical non-invasive monitoring of skin blood pulsations," *Optical Materials and Applications,* vol. 44, pp. 1850-1857, 2005.

[14] Wikipedia, "Processing (programming language)," 2015. [Online]. Available: Available: https://en.wikipedia.org/wiki/Processing_(programming_language). [Accessed 1 November 2016].

[15] Gaussianwaves.com – Signal Processing Simplified, "Moving Average Filter (MA Filter)," 2010. [Online]. Available: https://www.gaussianwaves.com/2010/11/moving-average-filter-ma-filter-2/. [Accessed 1 November 2016].

[16] A. Paglinawan, W. Chung, Y. Wang, S. Cheng, W. Lee, A. Albason, C. Chuang and S. Lou, "A System Design with Mode-Switching Power Management for Closed-loop Implantable Glucose Biosensor," *Journal of Medical and Biological Engineering,* vol. 31, no. 5, pp. 321-329, 2011.