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Development of Continuous Blood Pressure Measurement System Using Photoplethysmograph and Pulse Transit Time

Hong Long Pua and Kok Beng Gan*

***Abstract* – Blood pressure is one of the vital signs that provides important information about cardiovascular health. The current blood pressure detection method uses an oscillometric method. Unfortunately, this method required inflation and followed by deflation of the cuff. In addition, this method gives only instantaneous blood pressure and continuous blood pressure measurement is not available. This method is not applicable for patients who required long term blood pressure monitoring. To solve this problem, an algorithm based on pulse transit time (PTT) using two channel photoplethysmograph (PPG) signals can be used to obtain continuous blood pressure. PPG is a non-invasive method to detect blood volume changed affected by various physiological factors using optical sensors. PPG signal analysis can provide sufficient information about human health health, particularly cardiovascular problems. Previous literature study shows that the PTT has a linear relationship with blood pressure and may be as an index to monitor cardiovascular disease. However, determining the structure of model, order and implementation in real-time to offer continuous measurement of the PTT remains a challenging task in this area. In this project, dynamic model based on PPG pulse transit time is used to measure blood pressure continuously from two different human sites. A low power microcontroller combined with PPG sensor with Bluetooth connectivity was used in this study. MATLAB software is used to calculate PTT from PPG signals obtained from two PPG sensors. Linear regression technique and Fung's algorithm were applied to obtain the line of best fit for measuring systolic and diastolic blood pressure. The experiment results showed that the pulse transit time-based algorithm for systolic and diastolic blood pressure calculation can achieve accuracy of 86.34% and 88.20%, respectively. This technique is a simple, user friendly and operator-independent system that suitable for long term blood pressure monitoring and wearable devices.**

Keywords— Pulse Transit Time, Photoplethysmograph, Blood Pressure, Non-invasive

I. INTRODUCTION

Hypertension is the main risk factor for stroke, coronary artery disease and chronic kidney disease. The blood pressure (BP) varies throughout the day. Therefore, BP measurement is important for the control of hypertension and the evaluation of cardiovascular disease risk [1]. There are two techniques for the measurement of BP such as non-invasive and invasive methods. A peripheral artery with catheter insertion considers as invasive method that allows continuous monitoring of BP. However, it can cause inconvenient and the risk of infection [2]. Non-invasive techniques have been adopted by doctors and patients for example oscillometric and auscultatory methods by using cuff. It may not be efficient and appropriate due to numbness, inconvenient and time needed to diagnose hypertension with individual data. Another non-invasive method is the using of ECG and PPG. Yen et

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al. [3] proposed a measurement platform for the continuous estimation of BP based on dual photoplethysmography (PPG) sensors and a back propagation neural network (BPNN). A conventional sphygmomanometer with the results of a portable ECG monitor combined with photoplethysmography (PPG) for recording pulse waves in patients with arterial hypertension was used to to evaluate the correlation between the results of routine BP measurements [4]. The correlation between sphygmomanometer results and the cuffless method was 0.89 (p = 0.001) for systolic and 0.87 (p = 0.002) for diastolic BP [4]. There are some limitations because some of the PPG sensors have different built-in filters correspond to ECG filter with the generation phase delay between both sensors. This gives a poor reading with the duration of PTT alteration [5].

However, the growing demand for PPG-based wearable devices provides an interesting direction for the continuous BP measurement. Most of the PPG-based BP estimation is divided mainly into two direction of research based on waveform morphology theory and waveform propagation theory [6]. PTT detects the major determinant of cardiovascular disease according to the arterial stiffness index. The function of the elastic arterial wall is to buffer the heart blood pulsatile ejection and offer constant flow in the capillary beds. BP is directly proportional to Pulse Wave Velocity (PWV) at which the arterial pressure wave travels [7]. The time interval between two different pulse waves propagating with the same cardiac cycle from arterial sites are known as PTT. PTT determine the Pulse Wave Velocity provided the measuring distance between two sites [8] is the same. PTT influenced by heart rate, the arterial walls stiffness and the changes of blood pressure [9].

Fung's algorithm shows the relationship between BP and BTT based on the energy conservation principle which is the connection of work done by the energy of wave (gravitational potential and kinetic energy) and pulse wave [5,10]. It relate to pressure and force while PTT is specified by Fung et al. along the artery from the heart to the fingertip. To obtain the PTT value, the PPG-PPG technique is used to measure the volumetric blood flow under the skin of an infrared light-emitting diode (IR LED) and to detect the amount of light change by reflecting or transmitting by using a photodetector. When collecting the transmitted signals, PPG acquires the information associated with the pulsation [11]. PPG not only to measure blood pressure, but also monitor hypovolemia, breathing and others health conditions.

The PPG signal classified into two components such as static signals (DC) and dynamic signals (AC) components. DC component is hardly changeable that come from body tissue static elements like epidermis, bone, dermis, and hypodermis. Dynamic signals (AC) came from pulsating of the blood vessels. The main principle of PPG operation is based on the blood volume change associated with the heart pulsation. There are two different types of probe to obtain PPG signals such as transmission and reflectance probe. For transmission probes, the transmitted signal has greater intensity than the reflected signal in a small area. Transmission type of PPG signal is obtained from the locations of ear lobes, toes and fingers. Reflectance probes used to detect reflected light of the tissue where the emitter and detector are at the same level. The amount of reflected light is smaller compare to the transmitted type and produce weaker PPG signals. Fingertip is the general area for PPG measurement. The researchers use reflection probes for operative care of patient at the forehead as a hair band [12], the esophagus [13] and ring casing at the finger [14].

According to the Fung's algorithm as shown in Figure 1, two reflected PPG signals were acquired from toe and carotid. These PPG signals used to calculate PTT using a set of data containing 60s of PPG signals. PTT can be obtained by identifying the time interval of PPG signals in collected between the carotid artery and the toe. For BP estimation, PTT is defined as PTTd and PTTs that related to systolic BP (SBP) and diastolic BP (DBP) as shown in (1) and (2), respectively. The value of A and B can be obtained from individual calibration. Various techniques and system has been developed to enhance the PPG acquisition system using support vector machine algorithm [15] with compression technique [16] to reduce data to be transferred for high resolution PPG signals.

In this paper, a continuous non-invasive blood pressure (NIBP) monitoring device was developed based using PPG and PTT. This system consists of hardware and software development. The PPG signal resolution and performance of this system were evaluated using limited subjects. The estimated BP using this system were compared to the current BP measurement method. The developed system is the patient monitoring device that can be used to monitor BP in long term and short term.

$$SBP = \frac{A}{PTTs^2} + B \quad (1)$$

$$DBP = \frac{A}{PTTd^2} + B \quad (2)$$

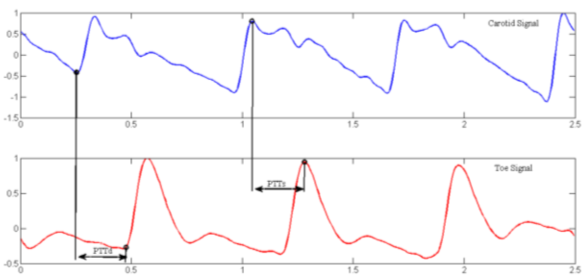


FIGURE 1. PTTs and PPTd calculation between carotid artery and toe position.

II. METHODOLOGY

The Development process of continuous blood pressure measurement system and algorithm based on pulse transit time (PTT) consists of hardware and software development. Firstly, it incorporates hardware development with PPG sensors. Second, the development of the graphical user interface (GUI) using MATLAB software to ease the users during data acquisition session. Each patient's record will be saved into computer for future reference. Finally, GUI will be used to estimate the systolic and diastolic blood pressure with Fung's algorithm. System overview and sensor positions for PPG signals acquisition is shown in Figure 2.

After obtaining signals from the PPG sensor located on the skin, the analog input in the form of electrical current (I) signals was fed into transimpedance amplifier with a gain of 1 MOhm to convert the current into voltage (V) for further processing. The PPG signal is then filtered by a second-order Butterworth filter to attenuate high frequency noise. The infrared current was adjusted to avoid saturation or clipping of signals by shifting down or up the whole signal within the range given by observed PPG signals. The developed analog front end design was fabricated and the components were assembled on a donut board. Analog PPG signals after the analog front end were then fed into an analog to digital converter (ADC). To evaluate the effect for ADC resolution in signal analysis stage, a 10-bit (Arduino UNO Board) and 24-bit (NI USB-9161 with NI-9229) ADC were used as shown in Figure 2. All digitalized PPG signals were transferred to the computer using a USB interface for BP estimation.

The MATLAB software has been used to implement BP estimation algorithm due to its capability to execute computationally intensive task rapidly with high level language. The digitized signals with sampling frequency of 125 Hz (10-bit) and 2000 Hz (24-bit) were displayed with in MATLAB and stored in computer. The acquired PPG signals will be processed offline to estimate beat-to-beat systolic and diastolic BP based on pulse wave transit time concept. After acquired the PPG signals, PTTs and PTTd calculations were obtained by measuring the time interval between the dual mode peak and trough detection of PPG signals recording from Carotid artery and toe. The difference between maximum points detection of two different PPG signals considers as systolic blood pressure (SBP) while minimum points detection of two different PPG signals is called as diastolic blood pressure (DBP).

Graphical user interface (GUI) was developed using MATLAB and implemented Fung's algorithm to produce a single executive application. The purpose of creating GUI is to establish the connection between PTT and BP with the simple method, user-friendly and operator independent PPG system that is suitable for the long term BP monitor. Final, the system has been tested with a limited subjects for its functionality and initial hardware verification. In this pilot test, nine samples of PPG signals from healthy volunteers aged around 22-24 were collected. The linear regression method was used as a calibration process to minimize the sum of squares errors to achieve proximal values for the SBP and DBP, respectively. The estimated blood pressure results using the PTT-based method were compared to the cuff-based BP method (Kodea machine).

III. Results And Disccusion

The reflectance-based PPG acquisition system was successfully developed and interfaced with MATLAB for data processing and display. All PPG signals acquired from subjects were in the supine position. The acquired PPG signals from carotid and toes with 10-bit and 24-bit resolutions are shown in Figure 3 and Figure 4, respectively. The left graph in Figure 2 and Figure 3 show the raw PPG signals acquired from the carotid part blue color signal) and the toe part (red color signal). By implementing the developed algorithm, the right graph in Figure 2 and 3 show the filtered PPG signals and its detected final peaks and trough. The data acquired from these subjects provide mean PTTs and PTTd information for BP estimations.

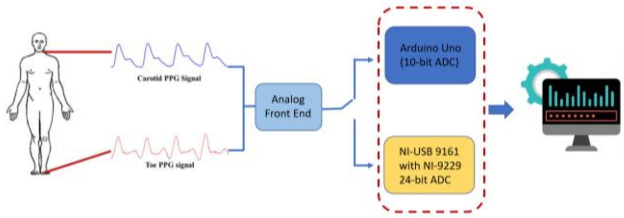


FIGURE 2. System overview and sensor positions for PPG signals acquisition.

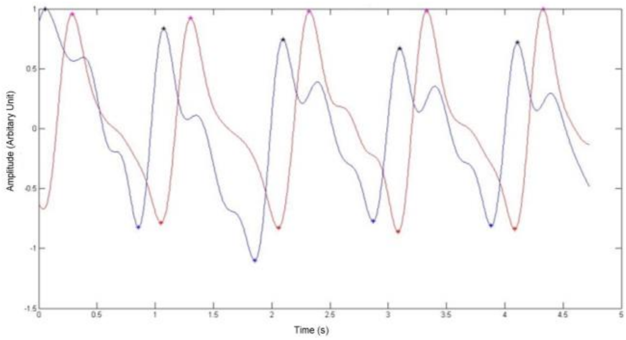


FIGURE 3. PPG signals after preprocessing with peak and trough detection for 10-bit resolution.

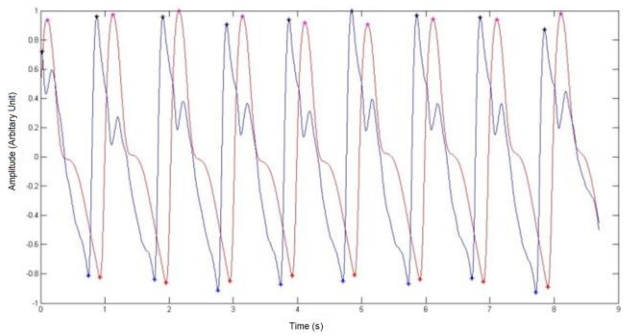


FIGURE 4. PPG signals after preprocessing with peak and trough detection for 24-bit resolution.

Graphical user interface (GUI) was developed using MATLAB and implemented Fung's algorithm to produce a single executive application. The purpose of creating GUI is to establish the connection between PTT and BP with the simple method, user-friendly and operator independent PPG system that is suitable for the long term BP monitor. Final, the system has been tested with a limited subjects for its functionality and initial hardware verification. In this pilot test, nine samples of PPG signals from healthy volunteers aged around 22-24 were collected. The linear regression method was used as a calibration process to minimize the sum of squares errors to achieve proximal values for the SBP and DBP, respectively. The estimated blood pressure results using the PTT-based method were compared to the cuff-based BP method (Kodea machine).

The Equation (3) and (4) were obtained from the experiment data to estimate the SBP and DBP. These two equations were used to estimate BP for PPG signals acquired using 10-bit resolutions ADC.

$$SBP(y) = \frac{0.134}{PTT^2} + 105.8 \quad (3)$$

$$DBP(y) = \frac{0.218}{PTT^2} + 58.43 \quad (4)$$

The Equation (5) and (6) were obtained from the experiment data to estimate the SBP and DBP. These two equations were used to estimate BP for PPG signals acquired using 24-bit resolutions ADC.

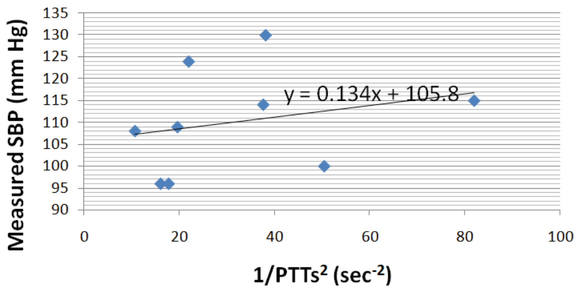
$$SBP(y) = \frac{0.321}{PTT^2} + 100.5 \quad (5)$$

$$DBP(y) = \frac{0.175}{PTT^2} + 59.46 \quad (6)$$

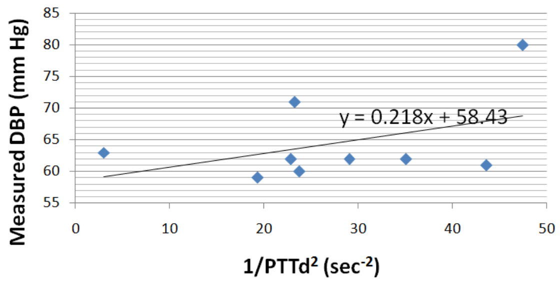
The acquired PPG signals were processed to obtain PTTs and PTTd parameters for both resolution of 10-bit and 24-bit. These parameters were used to calculate the systolic blood pressure (SBP) and diastolic blood pressure (DBP). The unknown variables of A and B were identified from linear regression. The A and B coefficients were obtained from the linear regression shown in Figure 5 and Figure 6, respectively. Linear regression results showed that the BP is inversely proportional to square PTT.

To assess the effect of the ADC resolution, PPG signals with 10-bits and 24-bits were processed by the algorithm to find both systolic and diastolic BP. The unknown coefficients were derived using linear regression between BP, PTTs and PTTd according to the sampling frequency used. The Figure 7 and Figure 8 showed the comparison between estimated SBP and DBP with 10-bits and 24-bits PPG signals with the BP measured by cuff method. The results showed that the PTT based BP estimation can be used to identify BP by placing the PPG sensors on carotid and toe. Both systolic and diastolic BP algorithms were evaluated using PPG signals obtained from nine healthy subjects.

By using Fung's algorithm, the estimated SBP and DBP using 24-bits resolution PPG signals have accuracy up 86.34% and 88.20%, respectively compared 10-bits resolution PPG for BP estimation. Based on this finding, PPG signals with higher resolution can results in better accuracy of BP estimation. However, some changes are needed to make the PPG sensor more sensitive in the detection of PPG signal.

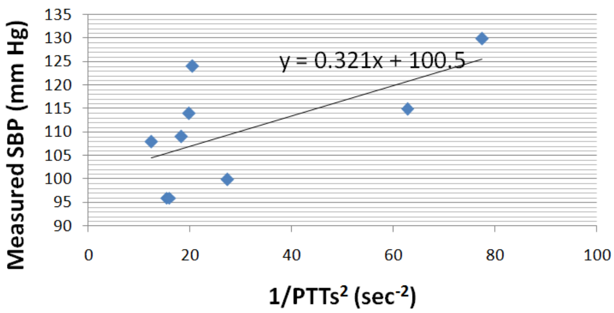


a. Systolic blood pressure (SBP).

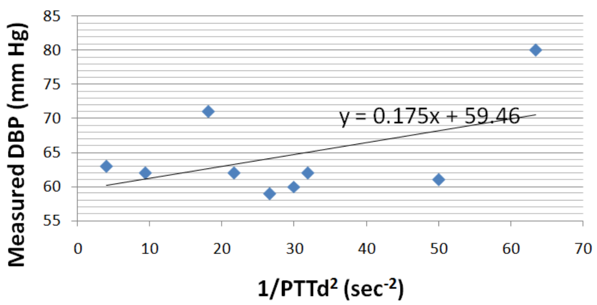


b. Diastolic blood pressure (DBP).

FIGURE 5. Linear regression for measured SBP (a) and DBP (b) versus 1/PTTs2, respectively for PPG with 10-bit resolutions.

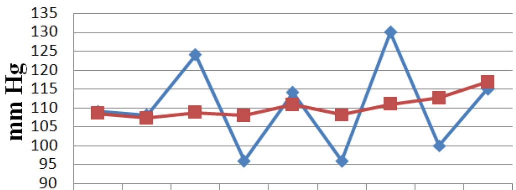


a. Systolic blood pressure (SBP).



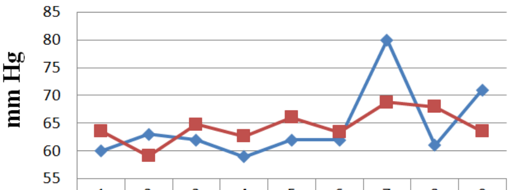
b. Diastolic blood pressure (DBP).

FIGURE 6. Linear regression for measured SBP (a) and DBP (b) versus 1/PTTs2, respectively for PPG with 24-bit resolutions.



	1	2	3	4	5	6	7	8	9
Real SBP	109	108	124	96	114	96	130	100	115
Estimated SBP	108.4	107.2	108.7	107.9	110.8	108.1	110.9	112.5	116.7

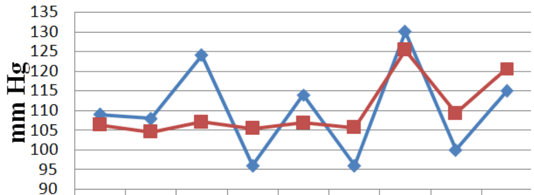
a. SBP estimation vs real SBP.



	1	2	3	4	5	6	7	8	9
Real DBP	60	63	62	59	62	62	80	61	71
Estimated DBP	63.61	59.10	64.77	62.65	66.08	63.42	68.78	67.94	63.51

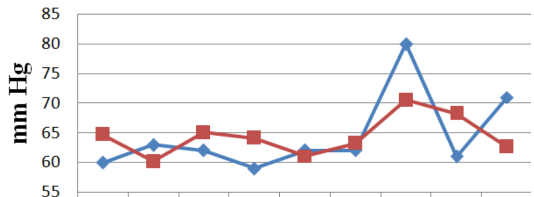
b. DBP estimation vs real SBP.

FIGURE 7. Real SBP and DBP compare with estimated SBP and DBP with 10-bit resolution



	1	2	3	4	5	6	7	8	9
Real SBP	109	108	124	96	114	96	130	100	115
Estimated SBP	106.3	104.4	107.0	105.4	106.8	105.6	125.3	109.3	120.6

a. SBP estimation vs real SBP.



	1	2	3	4	5	6	7	8	9
Real DBP	60	63	62	59	62	62	80	61	71
Estimated DBP	64.69	60.16	65.04	64.12	61.11	63.24	70.55	68.21	62.62

b. DBP estimation vs real SBP.

FIGURE 8. Results for Real SBP and DBP compare with estimated SBP and DBP with 24-bit resolution

IV. CONCLUSION

The continuous and non-invasive blood pressure algorithm based on pulse transit time using PPG was developed to calculate systolic and diastolic blood pressure with 86.34% and 88.20% accuracy, respectively. The effect of ADC resolution need be taken into consideration suring design phase to enable better BP estimation accuracy. The average time to perform blood pressure measurement using this system is less than 1 minutes and able to store patient's record in database for future analysis.

The noninvasive and continuous BP monitoring using PTT does not required complex control systems and expensive sensors. However, proper calibration is required at regular basis, which can cause inconvenience to the users. Some improvement is required to reduce measurement errors and calibration-free system to improve user experience in this system. Besides that, the collection of data with a larger sample size and proper pressure exerted to the measurement position would increase the accuracy of this system. It is important for clinical applications to continuously monitor the blood pressure and health status of the patient in critical ward and home

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AUTHOR CONTRIBUTIONS

Hong Long Pua: Conceptualization, Data Curation, Methodology, Validation, Writing – Original Draft Preparation;

Kok Beng Gan: Project Administration, Supervision, Writing – Review & Editing

CONFLICT OF INTERESTS

No conflict of interests were disclosed.

ETHICS STATEMENTS

Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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REFERENCES

[1] P. -K. Chan, C. -C. Chen, and C. -L. Yang, "Systolic and diastolic blood pressure estimation from pulse transit time using dual split-ring resonators with notch structure," in *Proc. 2019 IEEE MTT-S Int. Microw. Symp. (IMS)*, Boston, MA, USA, Jun. 2–7, 2019, pp. 361–364. DOI: https://doi.org/10.1109/MWSYM.2019.8701050

[2] L. Xu, X. Guo, F. Yang, S. Yin, X. Zhang, and M. Q. -H. Meng, “Implementation of cuff-less continuous blood pressure measurement system based on Android,” in *Proc. 2012 IEEE Int. Conf. Inf. Autom.*, Shenzhen, China, Jun. 26–29, 2012, pp. 1040–1045.
DOI: https://doi.org/10.1109/ICInfA.2012.6246866

[3] C. -T. Yen, S. -N. Chang, and C. -Y. Cai, “Development of a continuous blood pressure measurement and cardiovascular multi-indicator platform for Asian populations by using a back propagation neural network and dual photoplethysmography sensor signal acquisition technology,” *J. Nanomater.*, vol. 2021, pp. 1–15, 2021.
DOI: https://doi.org/10.1155/2021/6613817

[4] Z. Sagirova, N. Kuznetsova, N. Gogiberidze, D. Gognieva, A. Suvorov, P. Chomakhidze, S. Omboni, H. Saner and P. Kopylov, “Cuffless blood pressure measurement using a smartphone-case-based ECG monitor with photoplethysmography in hypertensive patients,” *Sensors (Basel)*, vol. 21, no. 10, p. 3525, 2021.
DOI: https://doi.org/10.3390/s21103525

[5] P. Fung, G. Dumont, C. Ries, C. Mott, and M. Ansermino, “Continuous noninvasive blood pressure measurement by pulse transit time,” in *Conf. Proc. IEEE Eng. Med. Biol. Soc.*, vol. 2006, pp. 738–741, 2004.
DOI: https://doi.org/10.1109/IEMBS.2004.1403264

[6] M. Elgendi, R. Fletcher, Y. Liang, N. Howard, N.H. Lovell, D. Abbott, K. Lim and R. Ward, “The use of photoplethysmography for assessing hypertension,” *NPJ Digit. Med.*, vol. 2, no. 1, p. 60, 2019.
DOI: https://doi.org/10.1038/s41746-019-0136-7

[7] S. Ye, G. Kim, D. Jung, S. Baik, and G. Jeon, “Estimation of systolic and diastolic pressure using the pulse transit time,” *Int. J. Biomed. Biol. Eng.*, vol. 4, no. 7, pp. 303–308, 2010.
URL: https://publications.waset.org/11733.pdf (Accessed: 10 Jun. 2021).

[8] M.W. Claridge, G.R. Bate, J.A. Dineley, P.R. Hoskins, T. Marshall, D.A. Adam, A.W. Bradbury and A.B. Wilmink, “A reproducibility study of a TDI-based method to calculate indices of arterial stiffness,” *Ultrasound Med. Biol.*, vol. 34, no. 2, pp. 215–220, 2008.
DOI: https://doi.org/10.1016/j.ultrasmedbio.2007.08.010

[9] R. J. Vidmar, “Physiology and Biophysics of the Circulation,” Chicago, IL, USA: Year Book Medical Publishers, Inc., 1972.

[10] A. Rasool, M. Rafiq, A. Nasir, and F. M. Kashif, “Continuous and noninvasive blood pressure estimation by two-sensor measurement of pulse transit time,” in *Proc. 2018 14th Int. Conf. Emerg. Technol. (ICET)*, Islamabad, Pakistan, Oct. 3–4, 2018, pp. 1–6.
DOI: https://doi.org/10.1109/ICET.2018.8603612

[11] M. Maguire and T. Ward, “The photoplethysmograph as an instrument for physiological measurement,” in Engineering, NUI Maynooth: Department of Electronic, 2002.
URL: https://www.slideserve.com/alisa/the-photoplethysmograph-as-an-instrument-for-physiological-measurement-powerpoint-ppt-presentation (Accessed: 10 Jun. 2021).

[12] R.P. Dresher and Y. Mendelson, "Reflectance Forehead Pulse Oximetry: Effects of Contact Pressure During Walking," *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, pp. 3529-3532, 2006.
DOI: https://doi.org/10.1109/IEMBS.2006.260136

[13] P. A. Kyriacou, S. Powell, R. M. Langford, and D. P. Jones, “Investigation of oesophageal photoplethysmographic signals and blood oxygen saturation measurements in cardiothoracic surgery patients,” *Physiol. Meas.*, vol. 23, no. 3, pp. 533–545, 2002.
DOI: https://doi.org/10.1088/0967-3334/23/3/305

[14] S. Rhee, B. H. Yang, and H. H. Asada, “Artifact-resistant power-efficient design of finger-ring plethysmographic sensors,” *IEEE Trans. Biomed. Eng.*, vol. 48, no. 7, pp. 795–805, 2001.
DOI: https://doi.org/10.1109/10.930904

[15] S. Shobitha, P. M. Amita, B. N. Krupa, and G. K. Beng, “Cuffless blood pressure prediction from PPG using relevance vector machine,” in *Proc. 2017 Int. Conf. Electr. Electron. Commun. Comput. Optim. Technol. (ICEECCOT)*, Mysuru, India, Dec. 15–16, 2017, pp. 1–4.
DOI: https://doi.org/10.1109/ICEECCOT.2017.8284610

[16] K. S. Chong, K. B. Gan, and E. Zahedi, “Development of a real-time adaptive delta compression algorithm for photoplethysmography system,” *IEEJ Trans. Electr. Electron. Eng.*, vol. 13, no. 3, pp. 366–373, 2018.
DOI: https://doi.org/10.1002/tee.22712