Continuous Monitoring of Blood Pressure Based on Heart Pulse Analysis

Valerie Tan¹, Audrey Huong¹, Xavier Ngu¹
¹ Faculty of Electrical and Electronic Engineering
University Tun Hussein Onn Malaysia

E-mail: audrey@uthm.edu.my

Abstract. This paper aims to demonstrate the use of a finger-cuff system in the approximation of one's systolic and diastolic value based on the acquired heart pulse data. The prediction of the required systolic and diastolic value of blood pressure is via the use of two-element Windkessel Model. The results are compared for three groups of individuals of different clinically measured blood pressure range. A comparison with the result given from clinically available arm-cuff blood pressure monitor revealed a relatively low mean difference of $1.6 \pm 3$ mmHg predicted for the systolic values, while a considerably larger difference of $25.3 \pm 6.3$ mmHg is found for the estimated diastolic values. This work concluded that the proposed strategy that used heart pulse in its analysis may be used as an alternative means for continuous measurement of one’s blood pressure, but a system with high sampling resolution may be required to improve the accuracy of the predicted value.

1. Introduction

Continuous measurement of blood pressure is vital especially for aged population, pregnant women and individuals who either have just undergone surgery or with critical medical conditions. It is crucial to continuously monitor the blood pressure of these groups so that prompt action can be taken following the detected sudden change in their blood pressure as the latter may result in death. The conventional sphygmomanometer technique, which required the use of a blood pressure cuff and a stethoscope, is inconvenient for continuous measurement of blood pressure. The arm-cuff blood pressure monitor is a more convenient alternative as it provides continuous measurement of the value and it does not require the use of a stethoscope. Nonetheless both of these approaches may potentially cause harm especially to those who suffered from hypertension and hypotension. The exertion of pressure on the arm of these populations via the use of a cuff narrows the size of local blood vessels; this increases the chances of one getting stroke due to a possible insufficiency in the supply of oxygen to the brain. Therefore, cuffless Photoplethysmography (PPG) [1] and the use of a finger-cuff [2] were previously introduced to overcome these problems. Both of these techniques are wearable technologies that do not require the occlusion of artery in their measurement. While the implementation of the latter technique is limited to fingertip, the former may include a wide range of wearable devices such as wrist-watch, ring and clothing [3, 4].

PPG is a non-invasive optical technology that measures relative blood volume changes in vessels close to the skin surface. Many works have been done in the past to predict one’s blood pressure using the PPG data and via the use of Windkessel model [5, 6], wherein it was reported that the accuracy of value predicted using this model increases with the order of the element used. Meanwhile other study
[7] emphasized the importance of PPG signals measurement from the wrist. According to this study, only blood pressure predicted from the wrist radial artery can be validated via the sphygmomanometer. Many of these inventions allow portable and non-invasive measurement of blood pressure. It is the objective of this work to explore the feasibility of using heart pulse collected from the developed circuit for continuous and real-time prediction of one’s blood pressure value via the measurement from fingertip.

2. Materials and Methods

2.1. Finger-cuff blood pressure system

The finger-cuff system developed in this study worked in transmission mode for real-time measurement of heart pulses from one’s fingertip. The schematic diagram of the constructed circuit is shown in figure 1, while figure 2 showed the overall operation diagram of the system. This work used infrared (IR) ray in the wavelength of 940 nm for the illumination of the selected skin site. The detection of the PPG signals was via the use of market available finger pulse sensor (HRM-2511E), which wrapped and held in position around the selected finger during the experiment, to minimize the possibility of motion artifacts. The measured analog PPG signals were converted to digital pulses via a 10-bit analog to digital (A/D) converter (MCP3008). These pulses were processed in real-time for the prediction of the required systole and diastolic blood pressure; these values were then sent to a computer via Raspberry Pi 3 for online monitoring of one’s blood pressure value.

![Heart pulse detection circuit diagram](image1)

**Figure 1.** Heart pulse detection circuit diagram

![Operation diagram of the constructed finger-cuff PPG system](image2)

**Figure 2.** The operation diagram of the constructed finger-cuff PPG system
2.2. Two-element Windkessel model

The Windkessel model was previously used in the past to describe the in-vivo arterial system with respect to the blood flow and blood pressure. The use of this model in the prediction of one’s blood pressure was extensively demonstrated in the work by Choudhury et al. [5]. This study employed a two-element Windkessel model shown in equation (1) due to the simplicity of the model. This model has an analogy of an electrical circuit, wherein a resistor was placed in parallel with a capacitor. It was reported that the resistance, \( R \), represents total peripheral resistance while capacitance, \( C \), represents the arterial compliance. Both of these values were taken to be 1 [8].

\[
\frac{P(t)}{R} + C \frac{dP(t)}{dt} = I(t) \tag{1}
\]

where \( I \) and \( P \) represent blood flow and blood pressure, respectively. Solving for equation (1) yields an expression of blood pressure during systolic and diastolic cycle. This is viable with the assumption that \( I \) is a sinusoidal wave during systole with peak blood flow represented by \( I_o \), and is zero during diastole. The expression of \( I_o \) from ventricles to artery is given by [5]:

\[
I_o = \frac{C_o T_c}{60 \int_0^{T_s} \sin\left(\frac{\pi t}{T_s}\right) dt} \tag{2}
\]

where \( C_o \) and \( T_c \) represent cardiac output and cardiac time, respectively. The cardiac output is defined as the product of stroke volume and average heart rate in a minute. The stroke volume in the unit of millilitre was assumed to have the same value as the body weight of the investigated individual in kilogram. In this study \( T_c \) was taken as the total duration of the high of the pulse as shown in figure 3.

![Figure 3. Measurement of cardiac time from a pulse](image)

It was also assumed that the systolic time, \( T_s \), is one-third of the total cardiac time, while the diastolic time, \( T_d \), is two-third of the total cardiac time as followed:

\[
T_s = \frac{1}{3} T_c \tag{3}
\]

\[
T_d = \frac{2}{3} T_c \tag{4}
\]

From equation (3) and (4), the systolic blood pressure value is expressed as:

\[
P_s = P_{ts} \exp\left(\frac{-T_s}{RC}\right) + \frac{I_o T_s C \pi R^2}{T_s^2 + C^2 \pi R^2} \left(1 + \exp\left(\frac{-T_s}{RC}\right)\right) \tag{5}
\]

while the diastolic blood pressure is given by:

\[
P_d = P(t | t = T_d) = P_{td} \exp\left(\frac{-T_d}{RC}\right). \tag{6}
\]
where $P_n$ and $P_d$ is the value of $P_s$ and $P_d$ calculated from its preceding pulse. In this work the initial value of $P_n$ is set as 80 mmHg; the $P_s$ value calculated from equation (5) is then used as the initial value of $P_d$ in the calculation of $P_d$ from equation (6).

2.3 Experimental subject and method

This study recruited three groups of individuals (aged between 20 and 30 years) from University Tun Hussein Onn Malaysia (UTHM) for a comparison of their blood pressure value measured from the conventional cuff technique and the developed approach. The device used for the cuff technique, which was used as the gold standard in this study, is OMRON arm-cuff blood pressure monitor (model no. HEM 907). These volunteers were grouped according to their blood pressure value measured from the arm-cuff technique. There were ten subjects from each group of blood pressure value range shown in Table 1. All self-declared healthy with no known underlying illness, and the recruited females were not pregnant during the study. These recruits gave their consent prior to the study.

During the experiment, the subjects were told to relax in a chair and breathe normally for five minutes before blood pressure measurement was collected from either their right or left arm using the arm-cuff blood pressure monitor. This is repeated for measurement using the finger-cuff system on their index finger.

Table 1. Blood pressure value range defined in this study

| Blood Pressure range | Systolic Value (mmHg) | Diastolic value (mmHg) |
|----------------------|-----------------------|------------------------|
| Low                  | < 115                 | < 75                   |
| Normal               | < 140 and > 115       | < 90 and > 75          |
| High                 | > 140                 | > 90                   |

3. Results

The systolic and diastolic blood pressure value measured for the recruited subjects of different blood pressure range tabulated in table 1 using arm-cuff blood pressure monitor and the developed system is shown in table 2. From table 1 the mean and standard deviation of systole pressure value measured using cuff blood pressure monitor and the developed system, respectively, for groups of individuals with high, normal and low blood pressure is calculated as 151.4 ± 4.51 mmHg, 128.5 ± 7.82 mmHg, 104.9 ± 6.72 mmHg and 151.3 ± 5.59 mmHg, 128.6 ± 5.93 mmHg, 106.7 ± 6.36 mmHg. Meanwhile the mean and standard deviation of the diastole pressure value measured using cuff blood pressure monitor and the developed system for these groups is given by 90.9 ± 6.41 mmHg, 81.9 ± 3.54 mmHg, 67.7 ± 3.83 mmHg and 123.9 ± 3.84 mmHg, 105.1 ± 4.77 mmHg, 87.3 ± 5.2 mmHg, respectively. The average of the mean and standard deviation of absolute difference in the systolic and diastolic value given from these systems is calculated as 1.6 ± 3 mmHg and 25.3 ± 6.3 mmHg, respectively.

4. Discussion

From table 2, it can be clearly seen that the results for systolic value measured from the developed system for all groups of volunteers are similar to that from the arm-cuff blood pressure monitor with the average mean error of 1.6 ± 3 mmHg. Nonetheless, a comparatively larger mean difference was observed for diastolic measurement using these two techniques given by 25.3 ± 6.3 mmHg. This is likely due to the poor measurement of the cardiac time shown in figure 3 where the $T_d$ and $T_s$ value used in equation (5) and (6) were deduced. The heart pulses used in this study were obtained following
the conversion of analog PPG signals to digital pulses via a 10-bit converter, this converter provides a fast sampling rate at the price of a low resolution, and this poor sampling may misrepresent the shape of the PPG. Moreover, the foot of PPG pulse wave signals, which contains the latter part of the diastole, is likely masked by noise and may go undetected. This yields an underestimation of the $T_d$ value calculated from equation (4), the erroneous in this value propagates through equation (6) resulting in an overestimation of the diastolic blood pressure. This error is then manifested itself in the following diastole blood pressure values through the equation (6). This leads to a relatively consistent difference in the diastolic blood pressure value predicted using the arm-cuff blood pressure monitor and the developed system with the mean standard deviation given by 6.3 mmHg.

This work demonstrated that the information deduced from a heart pulse may potentially be used to approximate one’s systole and diastole blood pressure value. This approach allows a real time processing of the signals as it placed a lower demand on the system required for processing and sampling of the signals. However, an A/D conversion system with high sampling resolution may be needed to allow a more accurate measurement of the cardiac time, and to more accurately predict the required systole and diastole blood pressure.

**Table 2.** The measured diastolic and systolic value from gold standard (arm-cuff blood pressure monitor) and the developed finger-cuff system
Conclusion

This study showed that the developed finger-cuff system is able to provide an online prediction of one’s systolic and diastolic value based on the analysis of the heart pulse. The results showed high consistency in the systolic value given from the market available arm-cuff blood pressure monitor and the developed system for all the recruited groups. Nonetheless a relatively large difference is observed in the measured diastolic value due to a lack in the A/D conversion efficiency. This work concluded that the systolic and diastolic blood pressure value may be approximated from heart pulse signals through an accurate measurement of cardiac time and with the use of a two-element Windkessel model.

Acknowledgement

The authors would like to thank all volunteers who participated in this study. The authors are also grateful to Nooreis Shadilla Jarkasi from Department of Electronic Engineering, UTHM, for her help during data collection. This work was financially supported in part by the Ministry of Education Malaysia under FRGS grant no. 1581.

References

[1] Y Zheng, C C Y Poon, B P Yan and J Y W Lau 2016 Journal of Medical System 40 1
[2] K Matsumura, T Yamakoshi, P Rolfe and K Yamakoshi 2016 IEEE Transactions on Biomedical Engineering 64 1131
[3] C C Y Poo, Q Liu, H Gao, W H Lin and Y T Zhang 2011 Journal of Computing Science and Engineering 5 246
[4] Y T Zhang, C C Y Poon, C H Chan, M W W Tsang and K F Wu 2006 3rd IEEE/EMBS International Summer school on medical devices and Biosensors
[5] A D Choudhury, R Banerjee, A Sinha and S Kundu 2014 Conf Proc IEEE Eng Med Biol Soc p 4567
[6] E Maksuti, N Westerhof, B E Westerhof, M Broome, N Stergiopulos 2016 Plos one
[7] S H Song, J S Cho, H S Oh, J S Lee and I Y Kim 2009 IEEE Explore: Computer in Cardiology 741
[8] M Hlaváč, “Windkessel 2004 Proc 2004 Student Electrical Engineering, Information and Communication Technologies 1