JST: Smart Systems and Devices
Volume 32, Issue 3, September 2022, 034-043

Proposing a Method to Measure NIBP Parameters Using PPG Signal and Analyzing the Morphology of Oscillometric

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Abstract

The demand for monitoring non-invasive blood pressure (NIBP) parameters in health facilities for medical examination and treatment, specifically self-monitoring at home is significantly increasing. The measurement methods are based on many different techniques. However, the accuracy and stability of the measurement results from these techniques are still controversial. In this study, we proposed a novel method to measure the two most important parameters in NIBP measurement by combining two techniques: observing the Photoplethysmogram (PPG) signal to determine the Systolic Blood Pressure (SBP) and analyzing the changes of the morphology of oscillometric pulses to determine the Mean Arterial Pressure (MAP). The results were attained from 30 volunteers by using the proposed model and two commercial NIBP devices from iChoice and Omron for comparison. The measuring results of the proposed model have shown a good correlation and high stability of SBP, DBP (Diastolic Blood Pressure) and MAP measurements compared to the current techniques, expressed by the correlation of determination R^2, the mean difference of proposed model to each commercial device, $NIBP_P$ - $NIBP_{iC}$, $NIBP_P$ - $NIBP_O$, and the mean (SD) between measurement results of volunteers.

Keywords: NIBP, SBP, MAP, DBP, ossilometry, PPG, morphology.

1. Introduction

Non-invasive blood pressure NIBP measurement is a classical technique that is widely used in biomedical science. The blood pressure (BP) is defined as the pressure applied by circulating blood on the walls of the blood vessels. However, in clinical use, the term "blood pressure" usually refers to the arterial pressure measured at the brachial artery, the major artery in the upper arm [1]. The BP value fluctuates over each heartbeat, the minimum value is called Diastolic Blood Pressure (DBP) and the maximum value is called Systolic Blood Pressure (SBP). The average BP over a cardiac cycle is called Mean Arterial Pressure (MAP). These three parameters are normally measured in NIBP measurement. However, clinically, the BP is usually reported in the form of a fraction with only two parameters (SBP/DBP) and is measured in units of millimeters of mercury (mmHg), for example, 120/80 mmHg. The MAP is often estimated by doctors and nurse based on a formula of the SBP and DBP [2].

In recent years, numerous reports and studies show that the average age of patients with chronic diseases is reduced, and hypertension is a precursor to many chronic diseases, such as stroke, cardiovascular disease or chronic kidney disease. Globally, an estimated 26% of the world's population (972 million people) has hypertension, and the prevalence is predicted to increase to 29% by 2025 [3]. Specifically, hypertension affects almost 29% of adults in the United State [4], 20% of adults in Canada [5], 29% adults in the United Kingdom and 32% of adults in Australia. In Vietnam, according to the National survey on the risk factors of non-communicable diseases (STEPS) Viet Nam 2015, the prevalence of hypertension was 18.9% of total population aged 18-69 years old, and in comparison with STEPS 2010 there was significant and large increase in the prevalence from 15.3% in 2010 to 20.3% in 2015 among population aged 25-64 [6]. Then, BP is one of the most importantly measured physiological parameters.

Daily blood pressure monitoring is an important part of cardiovascular risks prediction, evaluating treatment effectiveness and outpatient treatment. In the meanwhile, attending the clinic or health care centers to measure regularly the blood pressure parameters is impractical for most people. Consequently, the demand for automated NIBP measurement devices for home BP monitoring is increasing. These devices measure and determine SBP, DBP and MAP values based on several techniques namely automated auscultatory, Doppler ultrasound sphygmomanometry and oscillometry. Among these techniques, oscillometry is the most popular one as it can be relatively easily implemented in automated NIBP measurement devices and easily performed by patients at home. However, the accuracy of home BP devices is controversial. In current standard for automated BP

ISSN: 2734-9373
https://doi.org/10.51316/jst.160.ssad.2022.32.3.5
Received: July 8, 2022; accepted: August 23, 2022

monitor (such as ANSI/AAMI protocol or BHS protocol), the mean error and the standard deviation (SD) of error should be smaller than 5 and 8 mmHg respectively [7]. Nevertheless, according to a study led by Dr. Jennifer S. Ringrose, home BP devices were not accurate within 5 mmHg about 70 per cent of the time, and the devices were off the mark by 10 mmHg about 30 per cent of the time. Although, in clinical, these results of differences are acceptable, but the precise detection of small increases in BP is also important. A recent 1-million-patient meta-analysis suggests that a 3-4 mmHg increase in SBP would translate into 20% higher stroke mortality and a 12% higher mortality from ischemic heart disease [8]. Therefore, even small errors in the estimation of BP could have large consequences on health. In addition, the accuracy and reliability of the current BP devices for different patient populations such as patients with obesity, arterial stiffness, and atrial fibrilation are questionable [9]. Therefore, the research and development of measurement techniques to increase the accuracy of the determination of blood pressure parameters is essential.

2. The Proposed Measurement Method

2.1. Determining the MAP Based on the Morphology of Oscillometric Pulses

Oscillometry, which is the most widely used technique for automatic NIBP measurement, is based on the analysis of the cardiac induced air-pressure oscillations in the pressure-cuff. This technique is performed similarly to auscultatory method but uses a pressure sensor to record the pressure oscillations within the cuff wrapped around the subject's bicep or wrist, instead of listening to Korotkoff sounds with a stethoscope. The cuff pressure is recorded during cuff deflation after inflating the cuff to a pressure at a level above the SBP. The recorded pressure waveform forms a signal known as the cuff deflation curve shown in Fig. 1a. This curve is composed of two main components: the slow-varying component due to the applied cuff pressure and the pulsations that are caused by the arterial pressure. These pulsations are extracted then form a signal known as the oscillometric waveform (OMW) shown in Fig. 1b. The oscillation amplitudes carry most of the BP information; therefore, many of the oscillometric algorithms are based on analyzing the oscillometric waveform envelope (OMWE) shown in Fig. 1c [10]. The amplitude of the oscillometric pulses increases to a maximum, and then, decreases with further deflation.

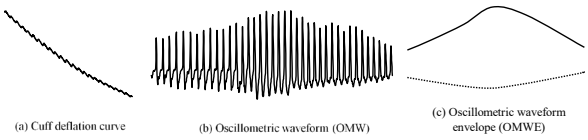

Fig. 1. Waveform of the signals extracted from pressure of cuff during deflation

In the conventional oscillometric method, the MAP is approximated as the cuff pressure at which the OMWE attains a maximum. Then, the SBP and DBP are determined as the cuff pressure at which the oscillation amplitude is equal to empirically determined fraction (0.4-0.75) of the maximal amplitude. However, this shape of OMWE is not always clearly shown. In some cases of patients with cardiovascular disease or high age, the OMWE has trapezoid shape [11]. The amplitude of the oscillometric pulses increases gradually, then remains almost constant over the period of time before decreases. In these cases, the estimation of MAP is difficult because it is hard to find the maximum magnitude of oscillometric pulse.

To solve this problem, we use a method of estimating MAP through the morphology changing. During the cuff deflation, we observe the left slope of the oscillometric pulses and found that the slope value of these slopes also increases to a maximum value, then decreases, which shown in Fig. 2. The characteristic quantity for this slope of each oscillometric pulse is calculated based on (1) as follows:

$$D = \frac{y_B - y_A}{x_B - x_A} \tag{1}$$

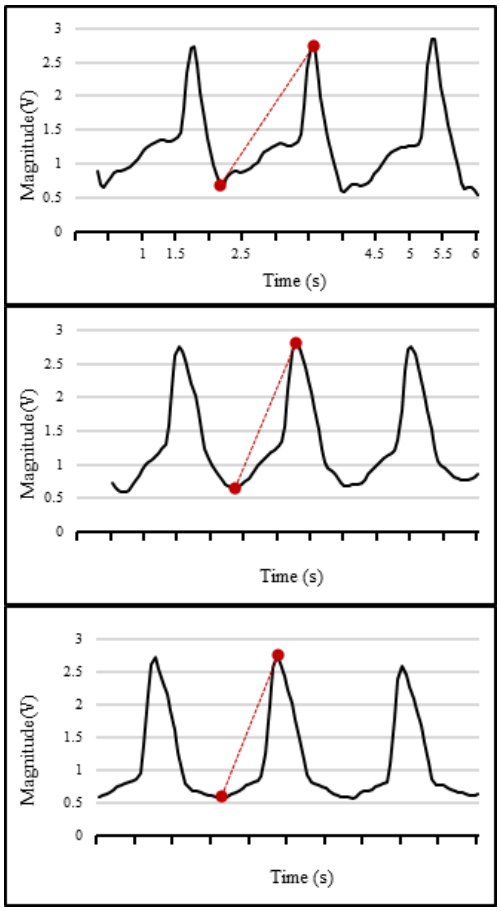

Fig. 2. The morphological change in oscillometric pulses during cuff deflation

During a cuff deflation, the D values is similar in shape to the OMWE, which is shown in Fig. 3, and the MAP is determined based on the time when the D value reaches its maximum. This is a detectable indication, and it can be simply processed on electronic circuits.

2.2. Determining the SBP Based on Observing the PPG Signal

In the oscillometric method, during inflation, arterial lumen area decreases until it becomes flat and occluded. Therefore, the pressure pulses in the arteries disappear. The cuff is then deflated gradually. When the cuff pressure decreases below the SBP, arterial lumen area starts increasing until it becomes completely open at very low cuff pressures and the pressure pulses reappear. This effect can be used for the SBP measurement using PPG signal for the detection of the pressure pulses (for example we use PPG signal at left index finger). When the cuff pressure increases to above the SBP, PPG pulses disappear, and when the cuff pressure decreases below SBP these pulses reappear. Hence, the SBP can be determined from the value of the cuff pressure for which PPG pulses reappear during cuff deflation. These techniques enable the measurement of SBP with no need for empirical formula.

For the method of determining the SBP based on the first pulse in PPG signal, a major cause of error is the time interval (τ second) for blood to flow from the cuff position (bicep) to the PPG sensor's position (fingertip). When the cuff is deflated using continuous or linear deflation technique, this τ time causes the moment at which the first PPG pulse is detected no longer matches with the moment at which cuff pressure equals to the SBP. As a result, the determined SBP would be lower than the actual SBP. To minimize the error caused by this phenomenon, our solution is using step deflation method during determining SBP process. In this method, the cuff pressure is deflated in a sequence of distinct pressure steps. Additionally, the duration of each step (t second) must be greater than the cardiac cycle of subject ($pulse\_time$) to make sure that the peak of oscillometric pulse is not missing. To sum up, the duration of each step must satisfies the equation $t \geq \tau + pulse\_time$, then the cuff pressure at which the first pulse is detected in PPG signal at the fingertip is unchanged to the pressure at which the arterial lumen reopens. As a result, the determining SBP value is more accurate. Fig. 4 illustrates the method of determining the SBP based on the PPG signal. If t is too great, it will make the total measurement time longer. To determine the optimal t value, we studied the theory of the usual velocities of blood in the arteries of the arm, forearm and hand. By the time the blood pressure reaches the SBP value, the velocity of blood also nearly reaches its maximum value.

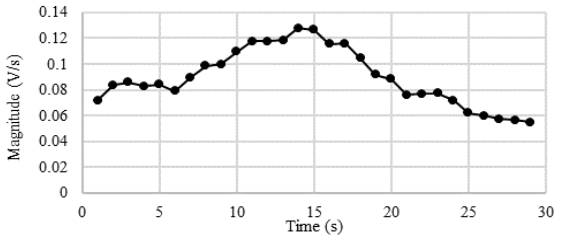

Fig. 3. The example of the D values during a cuff deflation

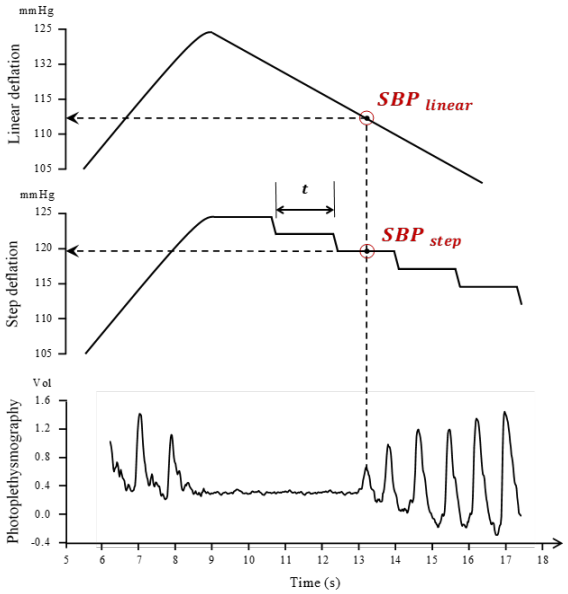

Fig. 4. The method of determining the SBP based on the PPG signal

In the brachial arteries, this velocity is about 80-120 cm/s; in the artery in the hand, this value is about 40-70 cm/s [11]. With an estimated length of the forearm is about 40 cm and the hand is about 20 cm, the value of τ can be determined to range from 0.4 s to 1s. The average time of a heart cycle, pulse_time, can be calculated based on the PPG signal at the time before the measurement. Therefore, we propose that the t value should be selected as (2):

$$t = (1 \div 1.5) + pulse\_time(s) \quad (2)$$

Thus, according to the proposed measurement methods, we can determine exactly 2 parameters of NIBP: MAP and SBP. The DBP will be calculated based on the formula of the SBP and DBP [2] as follows:

$$MAP = DBP + \frac{1}{3} \times (SBP - DBP) \quad (3)$$

3. Estimation of the Proposed Method

3.1. Designed Measurement Model Using Proposed Method

The block diagram of the model measuring NIBP parameters based on the proposed methods is illustrated in Fig. 5. The cuff pressure is recorded

by a pressure sensor (MPS20N0040D), which is manufactured using MEMS technology and commonly used in patient monitoring and diagnostic equipment, especially blood pressure monitors. The differential pressure range is from 0-300 mmHg and max pressure capacity is three times of the measuring range. The PPG sensor is a reflective optical sensor with transistor output (TCRT5000, Vishay) placed in a finger clip. It has a compact construction where the emitting-light source and the detector are arranged in the same direction to sense the presence of an object by using the reflective IR beam from the object. The operating wavelength is 950 mm. The detector consists of a phototransistor.

The two signals received from two sensors have small amplitude and could be affected by many noise sources. Therefore, these two signals are led into a circuit block including filter circuits and amplifier circuits. The filter circuit is designed as a second order active bandpass filter, with bandwidth from 0.5 Hz to 20 Hz. It is aimed to remove any unwanted noises and AC components. Additionally, these two signals are amplified to match the resolution of the ADC module. To perform ADC, signal processing and calculation, we use a Tiva C Development Kit - TM4C123GH6PM (Texas Instruments). Signals are sampled with the sampling rate $f_s = 100\ sps$ and resolution of the ADC module is 12 bits. KIT is also programmed to control pump motor, valve and display the measured results on the LCD screen. The cuff is pumped and released automatically. The pump motor used is KPM27U (Koge Micro Tech) and the valve used is linear valve KSV15C (Koge Electronics). The proposed measurement model based on the proposed methods is designed and manufactured as shown in Fig. 6.

3.2. Estimation of NIBP Measurement Model

3.2.1. The assessment scenario

The proposed measurement model is compared to two commercial NIBP devices from iChoice, model BP1, Omron, model HEM-7130, through three NIBP parameters: SBP, MAP, and DBP. The NIBP parameters were measured on 30 volunteers at the laboratory, fifteen males and fifteen females, aged 22-56 years without known cardiovascular disease. The volunteer should be comfortably seated on a chair, the back and arm supported with their hands comfortably laid on the table. All clothing that covers the location of the cuff should be removed before performing the BP measurement. The cuff is placed around the volunteer's upper arm, such that the middle of the cuff is at the level of the heart. The ratio between the circumference of the biceps and the length of the cuff is between 0.4 - 0.8 times.

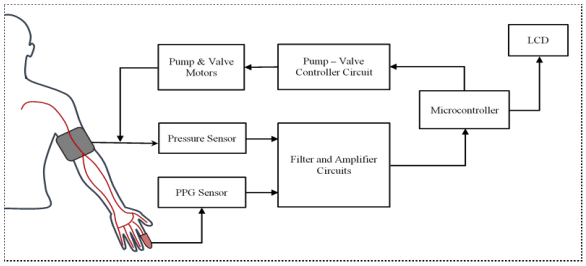

Fig. 5. The block diagram of the model measuring NIBP parameters

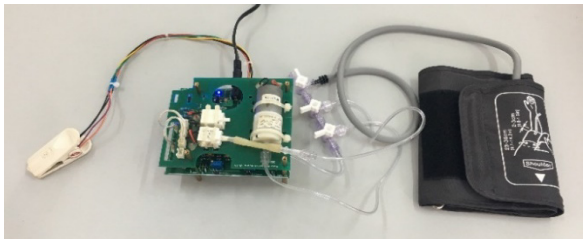

Fig. 6. Picture of measurement model based on the proposed method

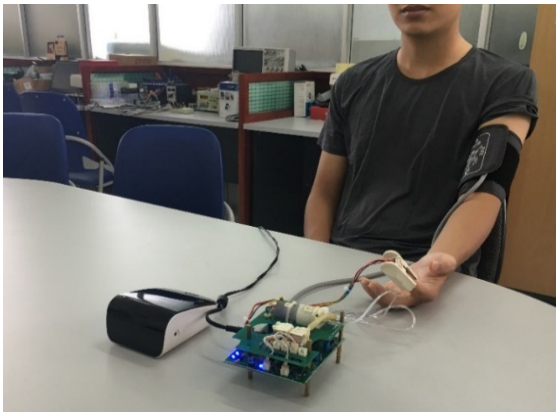

Fig. 7. The assessment scenario of designed model and Omron monitor

The volunteers were asked not to move during the measurement [12]. In addition, the volunteers wore a finger clip PPG sensor at the index finger of the left hand, which is fixed on the table, at a position 10 cm below the cuff. This is to ensure that blood can easily flows from the cuff position to the fingertips during the measurement. Each volunteer was measured five times on each device (the designed model, Omron device and iChoice device). The assessment scenario is illustrated as in Fig. 7.

3.2.2. Results

a) Evaluating the SBP measurement results: The results of measured SBP on 30 volunteers with the proposed model and two iChoice and Omron devices are summarized in Table 1. The correlation and the agreement Bland-Altman between SBP values measured by proposed model, iChoice device and Omron device are shown in Fig. 8.

Table 1. Summary table of the SBP measurement results

No	SBP_P mmHg (Proposed model)		SBP_{iC} mmHg (iChoice device)		SBP Difference of Proposed model and iChoice device	SBP_O mmHg (Omron device)		SBP Difference of Proposed model and Omron device
	Average SBP_P	Max Difference	Average SBP_{iC}	Max Difference		Average SBP_O	Max Difference	
1	112.4	3	113.4	6	1	112.4	4	0
2	111	2	106.8	8	4.2	107.2	5	3.8
3	116.8	2	116.4	5	0.4	119.8	9	3
4	114.2	4	115.8	6	1.6	116.8	6	2.6
5	113.8	3	112.8	6	1	114.8	5	1
6	117	3	114	5	3	115.4	6	1.6
7	111.2	3	107.6	7	3.6	113	5	1.8
8	118.8	4	116.6	5	2.2	114.6	6	4.2
9	112.2	2	114.6	6	2.4	110	5	2.2
10	113.2	3	114.2	7	1	112	6	1.2
11	111.8	2	107.8	6	4	114.6	7	2.8
12	115.6	3	115.2	6	0.4	117.4	4	1.8
13	118.4	2	122.8	6	4.4	116.8	6	1.6
14	121.4	1	117.4	9	4	124	4	2.6
15	116.6	3	115.6	6	1	117.8	5	1.2
16	117.2	3	123.6	5	6.4	122.4	6	5.2
17	105.6	4	112.8	6	7.2	115.8	6	10.2
18	115.8	2	114.2	6	1.6	112.2	6	3.6
19	114.6	3	113.4	5	1.2	114.2	5	0.4
20	115.6	3	114.4	7	1.2	119.2	6	3.6
21	110.8	4	114.6	7	3.8	116	6	5.2
22	131.8	4	127.6	7	4.2	126.2	6	5.6
23	127.2	3	125.6	7	1.6	129.8	5	2.6
24	122.4	4	118.2	7	4.2	115.6	7	6.8
25	131.4	6	127.6	9	3.8	124.2	7	7.2
26	127.2	3	124.8	6	2.4	132.2	7	5
27	133.8	4	134.4	7	0.6	135.6	7	1.8
28	121.6	2	125.2	7	3.6	126.4	5	4.8
29	115.4	3	117.4	7	2	118.8	5	3.4
30	107.2	3	113.4	8	6.2	114.8	7	7.6
Mean		3.03 ± 0.95		6.50 ± 1.06	2.81 ± 1.81		5.80 ± 1.08	3.48 ± 2.31

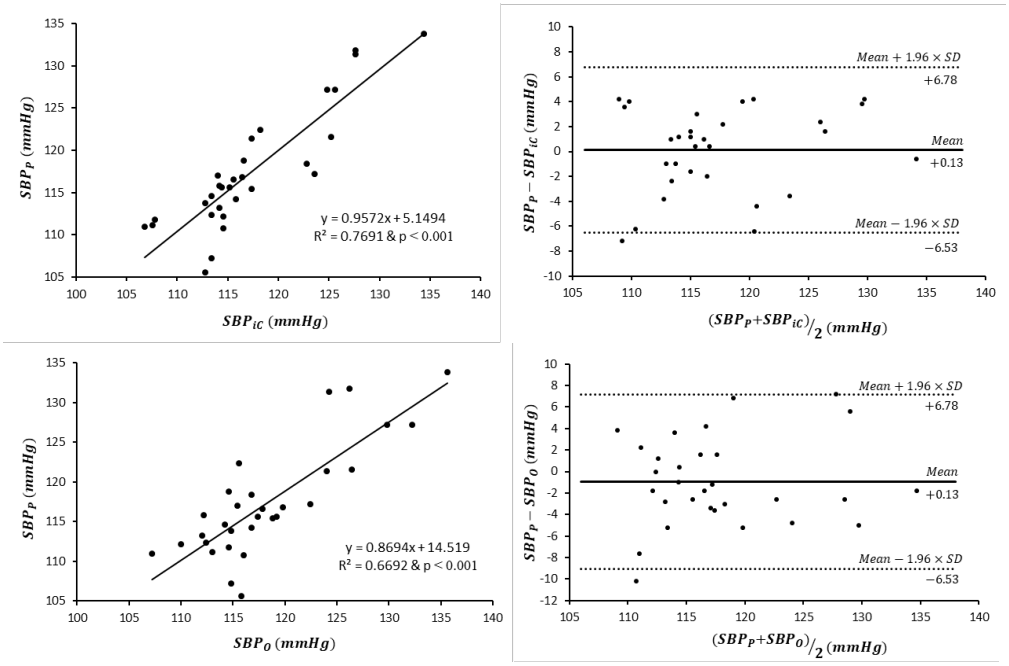

Fig. 8. The scatter plot with R-squared and agreement Bland-Altman between SBP measurement results of 2 devices

Table 2. Summary table of the DBP measurement results

No	DBP_P mmHg (Proposed model)		DBP_{iC} mmHg (iChoice device)		DBP Difference of Proposed model and iChoice device	DBP_O mmHg (Omron device)		DBP Difference of Proposed model and Omron device
	Average DBP_P	Max Difference	Average DBP_{iC}	Max Difference		Average DBP_O	Max Difference	
1	71.4	3	73.8	7	2.4	72.6	4	1.2
2	73.2	3	72.6	7	0.6	73	5	0.2
3	75.4	3	77.8	6	2.4	75.4	9	0
4	74.4	3	74	8	0.4	72.2	6	2.2
5	75	2	73.8	7	1.2	73	5	2
6	79.8	3	76.4	7	3.4	76.2	6	3.6
7	65.8	2	67.2	7	1.4	71.2	5	5.4
8	81.6	3	81.6	7	0	82.2	6	0.6
9	73.2	2	73.2	9	0	73.8	5	0.6
10	69.2	3	65.4	7	3.8	65.2	6	4
11	70.6	3	63	4	7.6	65.2	7	5.4
12	71.2	3	66	4	5.2	65.2	4	6
13	74.8	2	76.6	6	1.8	76	6	1.2
14	79.2	3	76.4	7	2.8	77.8	4	1.4
15	75.2	3	73.6	6	1.6	75.2	5	0
16	80.6	3	83.8	4	3.2	85	6	4.4
17	69	4	76.2	6	7.2	76.4	6	7.4
18	73.8	3	74.8	6	1	75.8	6	2
19	78.4	4	73.6	6	4.8	74.2	5	4.2
20	75.8	2	65.8	5	10	65.6	6	10.2
21	70.6	3	64.4	5	6.2	65.8	6	4.8
22	84	4	83.8	5	0.2	84.4	6	0.4
23	83.8	3	85.4	4	1.6	83.6	5	0.2
24	82.2	2	82.4	3	0.2	84.4	7	2.2
25	85.2	2	87.2	6	2	86.6	7	1.4
26	82.2	2	84.8	5	2.6	86	7	3.8
27	86.8	3	86.2	4	0.6	86.4	7	0.4
28	80.6	3	83.6	3	3	85.6	5	5
29	77.6	3	81.4	5	3.8	83.8	5	6.2
30	66.8	3	75.8	3	9	76.8	7	10
Mean		2.83 ± 0.59		5.63 ± 1.54	3.00 ± 2.71		5.17 ± 0.99	3.21 ± 2.85

Evaluation: The results show a strong correlation and a good fit between the SBP measurement results of proposed model with two commercial devices, shown on the parameters R2 = 0.7691 and $p < 0.001$ (with iChoice device), and R2 = 0.6692 and $p < 0.001$ (with Omron device). The differences between average SBP values measured by three devices, (SBPP - SBPiC) and (SBPP - SBPO), were calculated for each volunteer. The mean and SD of the differences between SBP measured by proposed model and iChoice device were 2.81 ± 1.81 mmHg (lower than 5% of SBP values), and by proposed model and Omron device were 3.48 ± 2.31 mmHg (lower than 5% of SBP values). The max difference between measurements on same volunteer was calculated for each device. The mean and SD of the max differences of proposed model, iChoice device and Omron device were 3.03 ± 0.95 mmHg, 6.50 ± 1.06 mmHg, and 5.80 ± 1.08 mmHg, respectively. Thus, it can be seen that the SBP measurement results by the proposed model have higher stability than that by two iChoice and Omron devices.

b) Evaluating the DBP measurement results: The results of measured DBP on 30 volunteers with the proposed model and two iChoice and Omron devices are summarized in Table 2. The correlation and the agreement Bland-Altman between DBP values measured by proposed model, iChoice device and Omron device are shown in Fig. 9.

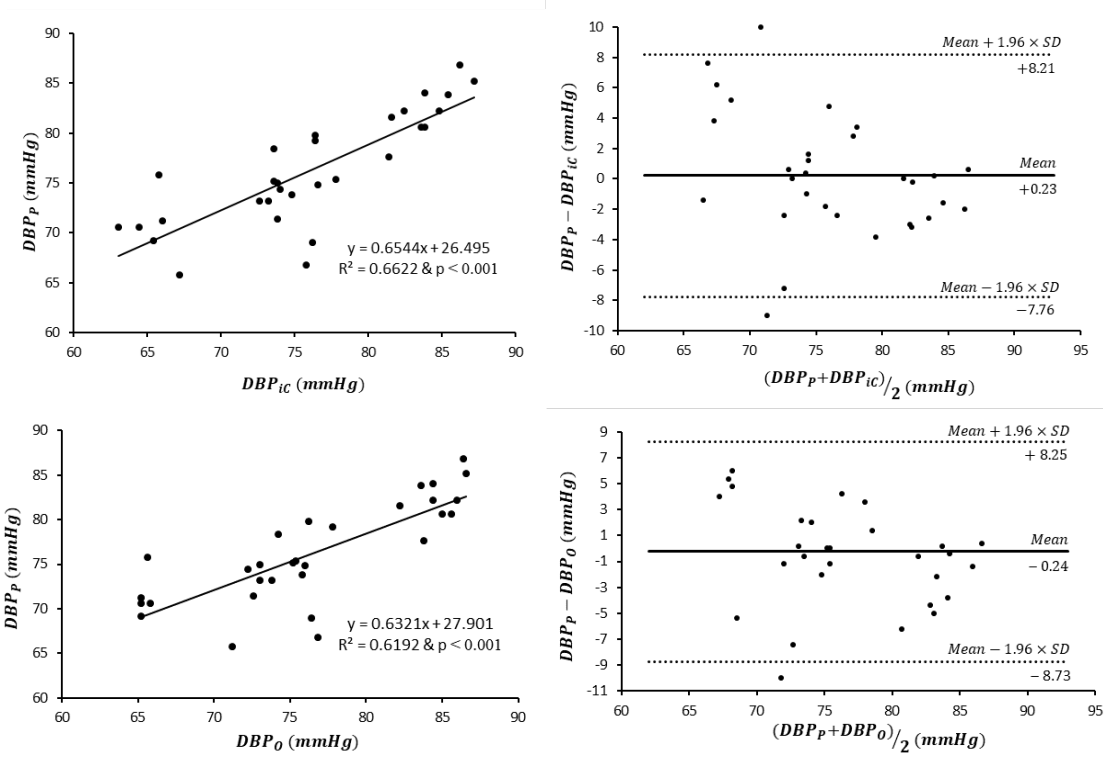

Fig. 9. The scatter plot with R-squared and agreement Bland-Altman between DBP measurement results of 2 devices

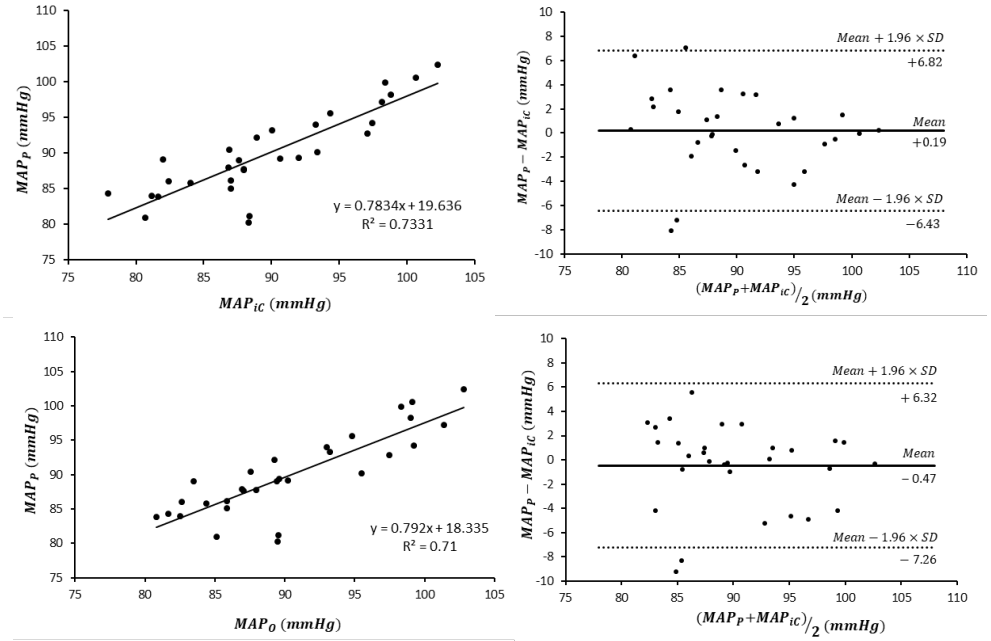

Fig. 10. The scatter plot with R-squared and agreement Bland-Altman between MAP measurement results of 2 devices

Evaluation: The results show a good correlation and a good fit between the DBP measurement results of proposed model with two commercial devices, shown on the parameters $R^2 = 0.6622$ and $p < 0.001$ (with iChoice device), and $R^2 = 0.6192$ and $p < 0.001$ (with Omron device). The differences between average DBP values measured by three devices, (DBP_P - DBP_{iC}) and (DBP_P - DBP_O), were calculated for each volunteer. The mean and SD of the differences between DBP measured by proposed model and iChoice device were 3.00 ± 2.71 mm Hg (lower than 10% of DBP values), and by proposed model and Omron device were 3.21 ± 2.85 mmHg (lower than 10% of DBP values). The max difference between measurements on same volunteer was calculated for each device. The mean and SD of the max differences

of proposed model, iChoice device and Omron device were 2.83 ± 0.59 mmHg, 5.63 ± 1.54 mmHg, and 5.17 ± 0.99 mmHg, respectively. Thus, it can be seen that the DBP measurement results by the proposed model have higher stability than that by two iChoice and Omron devices.

c) Evaluate the MAP measurement results: The results of measured MAP on 30 volunteers with the proposed model and two iChoice and Omron devices are summarized in Table 3. The correlation and the agreement Bland-Altman between MAP values measured by proposed model, iChoice device and Omron device are shown in Fig. 10.

Evaluation: The results show a good correlation and a good fit between the MAP measurement results of proposed model with two commercial devices, shown on the parameters $R^2 = 0.7331$ and $p < 0.001$ (with iChoice device), and $R^2 = 0.7100$ and $p < 0.001$ (with Omron device). The differences between average MAP values measured by three devices (MAP_P - MAP_{iC}) and (MAP_P - MAP_O), were calculated for each volunteer. The mean and SD of the differences between MAP measured by proposed model and iChoice device were 2.51 ± 2.22 mmHg (lower than 6% of MAP values), and by proposed model and Omron device were 2.49 ± 2.41 mmHg (lower than of MAP values). The max difference between measurements on same volunteer was calculated for each device. The mean and SD of the max differences of proposed model, iChoice device and Omron device were 2.03 ± 0.61 mmHg, 4.47 ± 1.45 mmHg, and 3.98 ± 1.25 mmHg, respectively. Thus, it can be seen that the MAP measurement results by the proposed model have higher stability than that by two iChoice and Omron devices.

Table 3. Summary table of the MAP measurement results

No	MAP_P mmHg (Proposed model)		MAP_{iC} mmHg (iChoice device)		MAP Difference of Proposed model and iChoice device	MAP_O mmHg (Omron device)		MAP Difference of Proposed model and Omron device
	Average MAP_P	Max Difference	Average MAP_{iC}	Max Difference		Average MAP_O	Max Difference	
1	85.1	2.0	87.0	6.0	1.9	85.9	5.3	0.8
2	85.8	2.7	84.0	7.3	1.8	84.4	1.7	1.4
3	89.2	2.7	90.7	5.0	1.5	90.2	5.7	1.0
4	87.7	2.0	87.9	5.0	0.3	87.1	3.3	0.6
5	87.9	2.0	86.8	5.3	1.1	86.9	5.3	1.0
6	92.2	2.0	88.9	6.3	3.3	89.3	4.0	2.9
7	80.9	1.3	80.7	4.3	0.3	85.1	2.3	4.2
8	94.0	2.3	93.3	4.7	0.7	93.0	1.7	1.0
9	86.2	1.3	87.0	7.3	0.8	85.9	4.7	0.3
10	83.9	1.3	81.7	5.0	2.2	80.8	3.3	3.1
11	84.3	2.3	77.9	4.3	6.4	81.7	3.0	2.7
12	86.0	3.0	82.4	4.7	3.6	82.6	3.0	3.4
13	89.3	1.0	92.0	6.0	2.7	89.6	4.0	0.3
14	93.3	1.7	90.1	4.3	3.2	93.2	4.7	0.1
15	89.0	2.3	87.6	4.3	1.4	89.4	5.0	0.4
16	92.8	2.3	97.1	4.3	4.3	97.5	4.7	4.7
17	81.2	1.3	88.4	4.7	7.2	89.5	5.0	8.3
18	87.8	2.3	87.9	4.7	0.1	87.9	4.7	0.1
19	90.5	3.3	86.9	4.7	3.6	87.5	5.0	2.9
20	89.1	1.3	82.0	3.0	7.1	83.5	5.3	5.6
21	84.0	2.0	81.1	1.3	2.9	82.5	2.0	1.5
22	99.9	2.7	98.4	2.3	1.5	98.3	4.0	1.6
23	98.3	2.3	98.8	5.0	0.5	99.0	1.7	0.7
24	95.6	1.3	94.3	1.3	1.3	94.8	4.3	0.8
25	100.6	2.7	100.7	3.3	0.1	99.1	3.7	1.5
26	97.2	2.0	98.1	4.0	0.9	101.4	3.0	4.2
27	102.5	1.0	102.3	2.0	0.2	102.8	5.0	0.3
28	94.3	2.3	97.5	4.3	3.2	99.2	5.7	4.9
29	90.2	1.3	93.4	4.7	3.2	95.5	5.0	5.3
30	80.3	2.7	88.3	4.3	8.1	89.5	3.3	9.2
Mean		2.03 ± 0.61		4.47 ± 1.45	2.51 ± 2.22		3.98 ± 1.25	2.49 ± 2.41

4. Discussion

For SBP measurement, to iChoice device, $R^2 = 0.7691$, SBP_P - $SBP_{iC} = 2.80 \pm 1.81$ mmHg (lower than 5% of *SBP* values), to Omron device, $R^2 = 0.6692$, SBP_P - $SBP_{iC} = 3.48 \pm 2.31$ mmHg (lower than 5% of *SBP* values);
mean $(SD)_P$ difference = 3.03 ± 0.95 mmHg,
mean $(SD)_{iC}$ difference = 6.5 ± 1.06 mmHg,
mean $(SD)_O$ difference = 5.80 ± 1.08 mmHg.

For Diastolic Blood Pressure *(DBP)* measurement, to iChoice device,

$R^2 = 0.6622$, DBP_P - $DBP_{iC} = 3.00 \pm 2.71$ mmHg (lower than 4% of DBP values), to Omron device, $R^2 = 0.6192$, DBP_P - $DBP_O = 3.21 \pm 2.85$ mmHg (lower than 4% of *DBP* values);
mean $(SD)_P$ difference = 2.83 ± 0.59 mmHg,
mean $(SD)_{iC}$ difference = 5.63 ± 1.54 mmHg,
mean $(SD)_O$ difference = 5.17 ± 0.99 mmHg.

For *MAP* measurement, to iChoice device, $R^2 = 0.7331$, MAP_P - $MAP_{iC} = 2.51 \pm 2.22$ mmHg (lower than 4% of *MAP* values), to Omron device, $R^2 = 0.7100$, MAP_P - $MAP_O = 2.49 \pm 2.41$ mmHg (lower than 4% of *MAP* values);
mean $(SD)_P$ difference = 2.03 ± 0.61 mmHg,
mean $(SD)_{iC}$ difference = 4.47 ± 1.45 mmHg,
mean $(SD)_O$ difference = 3.98 ± 1.25 mmHg.

Measurement results of SBP, MAP, and DBP parameters achieved from the proposed model show a high similarity with commercial non-invasive blood pressure monitor of both iChoice device and Omron device on the same volunteers. In addition, the author also assessed the mean error between measurements of volunteers to evaluate the reproducibility of the proposed model. The results show that the mean error of the repeated measurements is low ensuring the accuracy and stability of the device. In order to have a more adequate evaluation, in further study, the authors would assess the results of the proposed model compared with the invasive method blood pressure method (considered to be the gold standard) at health facilities when it is approved by the Ethics committee.

The most notable advantage of the proposed method is that the SBP is determined completely based on the natural mechanism of the blood vessels instead of using the empirical criteria. Our proposed method requires the PPG signal from a finger as an indicator signal to determine the SBP. The combination of a PPG signal and a step deflation eliminates pulse delays due to the blood propagation time from the arm to the finger. However, the method of step deflation will limit the accuracy of the measurement results to the level of step deflation, the level of step deflation should not be too small as it will prolong the measurement time causing inconvenience for users. The algorithm for detecting pulse peaks should be tested and improved in order to work efficiently with more pathological types of measurement objects.

5. Conclusion

In this study, we have proposed a method for measuring NIBP parameters by using a combination of measurement of SBP based on PPG signal and measurement of MAP based on analyzing the changes of the morphology of oscillometric pulse, then calculating the DBP value. We designed a measurement model using the proposed method and compared parameters measured by this model to two commercial blood pressure monitors from iChoice and Omron. The evaluation results show that the SBP, DBP and MAP values measured by the proposed model have higher stability than two commercial devices. Standard deviation and mean difference of measured parameters are both within the current acceptable limits on electronic blood pressure monitors.

The application of observing PPG signal to determine SBP value and analyzing the morphology of oscillometric pulses to determine MAP value has brought significant efficiency in MAP and SBP measurements. Although an additional optical sensor is required to attach to the tip of the finger, this measurement is quite simple and easy to apply to normal blood pressure measurement. The most notable advantage of the proposed method is that the SBP is determined completely based on the natural mechanism of the blood vessels instead of using the empirical criteria. This is also a highly reliable measurement technique, less affected by noise. With proposed method, it is possible to improve the accuracy and stability of automatic self-monitoring of blood pressure at home.

Acknowledgments

This work was supported by the Domestic Master/PhD Scholarship Programme of Vingroup Innovation Foundation.

References

[1] W.W.Nichols, M.F.O'Rourke and C.Vlachopou-Los, McDonald's Blood Flow in Arteries: Theore-tical, Experimental and Clinical Principles, 6th ed.,2011. London, U.K.: Hodder Arnold Publishers. https://doi.org/10.1201/b13568

[2] L. A. Geddes, M. Voelz, C. Combs, D. Reiner, C. F. Babbs, Characterization of the oscillo-metric method for measuring indirect blood pressure. Annals of Biomedical Engineering,1982, Vol. 10, pp. 271-280. https://doi.org/10.1007/BF02367308

[3] Kearney PM, Whelton M, Reynolds K, Muntner P, Whelton PK, He J, Global burden of hypertension: analysis of worldwide data. Lancet. 2005 Jan 15-21. 365 (9455):217-23. https://doi.org/10.1016/S0140-6736(05)17741-1

[4] V. L. Roger, A. S. Go, D. M. Lloyd Jones, E. J. Benjamin, Heart disease and stroke statistics-2012 update: A report from the Ameri-can Heart Association, Circulation, 2012, vol. 125, pp. 2-220. https://doi.org/10.1161/CIR.0b013e31823ac046

[5] A. V. Chobanian, G. L. Bakris, H. R. Black, Seventh report of the joint national committee on prevention, detection, evaluation, and treatment of high blood pressure, Hypertension, 2003, vol. 42, pp. 1206-1252. https://doi.org/10.1161/01.HYP.0000107251.49515.c2

[6] T.G.Pickering, J.E.Hall, L. J. Appel, Recommendations for blood pressure measurement in humans and experimental animals: Part 1: Blood pressure measurement in humans: A statement for professionals from the subcommittee of professional and public education of the American Heart Association council on high blood pressure research. Circulation, 2005, vol. 111, pp. 697-716. https://doi.org/10.1161/01.CIR.0000154900.76284.F6

[7] W. Gerin, A. R. Schwartz, J. E. Schwartz, T. G. Pickering, K. W. Davidson, J. Bress, E. O'Brien, and N. Atkins, Limitations of current validation protocols for home blood pressure monitors for individual patients, Blood Press. Monit., 2002, vol. 6, pp. 313-318. https://doi.org/10.1097/00126097-200212000-00004

[8] Jennifer S. Ringrose, Gina Polley, Donna Mc-Lean, Ann Thompson, Fraulein Morales, and Raj Padwal, An assessment of the accuracy of home blood pressure monitors when used in device owners, 2017, American Journal of Hypertension. https://doi.org/10.1093/ajh/hpx041

[9] S. Lewington, R. Clarke, N. Qizilbash, R. Peto, and R. C. R, Age specific relevance of usual blood pressure to vascular mortality: A meta-analysis of individual data for one million adults in 61 prospective studies, Lancet, 2002, vol. 360, pp. 1903-1913. https://doi.org/10.1016/s0140-6736(02)11911-8

[10] A. M. G. Pierina, D. C. Alavarcea, Josiane, Blood pressure measurement in obese patients: Comparison between upper arm and forearm measurements, Blood Press. Monit., 2004, vol. 9, pp. 101-105. https://doi.org/10.1097/01.mbp.0000132425.25263.ac

[11] A. M. Thompson, K. Eguchi, M. E. Reznik, S. S. Shah, and T. G. Pickering, Validation of an oscillometric home blood pressure monitor in an end-stage renal disease population and the effect of arterial stiffness on its accuracy, Blood Press. Monit.,2007, vol. 12, pp. 227-232. https://doi.org/10.1097/MBP.0b013e328108f544

[12] M. Forouzanfar, H.R. Dajani, V.Z. Groza, M. Bolic, S. Rajan, and I Batkin, Oscillometric blood pressure estimation: past, present, and future. IEEE Reviews in Biomedical Engineering, 2015, vol. 8, pp. 44-63. https://doi.org/10.1109/RBME.2015.2434215.