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Original Article

Designing and Constructing an Optical System to measure Continuous and Cuffless Blood Pressure Using Two Pulse Signals

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Abstract

Introduction
Blood pressure (BP) is one of the important vital signs that need to be monitored for personal healthcare. Arterial blood pressure is estimated from pulse transit time (PTT). This study uses two pulse sensors to get PTT. The aim of this study was to construct an optical system and to monitor blood pressure continuously and without cuff in people with different ages.
Materials and Methods
To measure blood pressure changes, two infrared optical transmitters were used at the distances of 5 mm to the receivers. Output of the optical receivers was inserted in analog circuits. PTT was defined as the time between the two peaks of pulse signals by the software. Signals were measured continuously through a serial network communication. An external personal computer monitored measured waveforms in real time. BP was related to PTT and the relationship coefficients were calculated at different physical activities. After determining the linear correlation coefficients for each individual, blood pressure was measured by the cuff and the PTT method and the results were compared.
Results
PTT computed between the two peaks of wave pulses was strongly correlated with systolic blood pressure (R=0.88±0.034) and the diastolic blood pressure (R=0.82±0.058). Systolic blood pressure (SBP) was measured more accurately than the diastolic blood pressure (DBP). The results of SBP showed that the maximum difference and the error percentages between the cuff method and the present method were 7.98±2.88 and 6.33±2.51%, respectively. Moreover, the maximum difference and the percentage errors between the cuff method and the present method of DBP were 10.13±3.82 and 10.97±3.89%, respectively.
Conclusion
Monitoring blood pressure with the designed system can be recommended as a useful method to indicate cardiovascular diseases and used for personal healthcare purposes.

Keywords: Blood Pressure Monitoring; Optical System; Pearson Correlation; Pulse Wave.

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1. Introduction

Blood pressure (BP) is a significant parameter to examine physical attributes and it is useful to indicate cardiovascular diseases, so the measurement of blood pressure has gained increasing attention. Therefore, BP is an important indicator for health monitoring [1]. Conventional methods of BP monitoring are divided into direct and indirect ways. In direct way, the pressure sensor must be implanted in artery and can continuously monitor BP, but the operation is complicated and difficultly acceptable for patients. The indirect way is the mercury sphygmomanometer, the current gold standard for BP measurement [2]. It is widely used in clinical practice and it is simple, fast, painless, and easily acceptable by patients, but the continuous monitoring cannot be achieved. The continuous, cuffless, and non-invasive blood pressure estimation is required for the daily health monitoring and those who are in intensive care [3].

Many studies have been focusing on the ways of blood pressure estimation based on other physiological parameters and a large amount of research activities were have been made for non-invasive continuous BP monitoring [4,5]. Tonometric, vascular unloading and Finapres method were sufficiently developed in recent years. Some mature products based on Finapres method are already available in the market [6]. However, they all need cuff - which press the local area of body, which leads to comfortlessness. The cuff must be deflated after a certain period of time or the placement of cuff has to be changed, so it is not really continuous BP monitoring. Therefore, researchers are looking for ways to continuously measure blood pressure without cuff. One method is pulse sensor with impedance plethysmograph (IPG) for detection of blood volume, but it is used less in treatment centers due to the high complexity of this method in the calculation of blood pressure and not simply to make the measurement systems and IPG sensors [7,8]. Another method is based on pulse sensor and using small finger cuff. This method can determinate just the diastolic pressure. Moreover, its cuff mechanism is similar to other methods using the cuff. Another method is NIR CCD camera. With this method, the change of vessel diameter is obtained by NIR CCD camera in each cardiac cycle. The relationship between the change of vessel diameter and the change of BP is evaluated. This method is just in the first phase, image analysis, the result is not yet reported, whether accurate BP can be obtained using this method [9]. Another method is pulse transition time (PTT). PTT is obtained by continues recording of ECG and pulse wave. In recent years, many studies show that it is a safe, non-invasive, and accurate method for continuous BP measurement. The PTT method shows excellent results in many studies [6 - 13] but using ECG signal makes some problems. Based on the PTT method, a mathematical model is proposed using two different pulse wave velocities (PWVs) from ear and toe. However, this method needs to record ECG as reference for calculating PWVs. Therefore, continues recording of ECG needs some electrodes and additional components which increases the system complexity.

This study describes a system for continuous monitoring of BP which is based on the PTT method as many other studies, but uses two pulse sensors to get PTT and not ECG. The aim of this study was to construct optical system to monitor blood pressure continuously using no cuff in people with different ages.

2. Materials and Methods

2.1. Estimating blood pressure

The following equation describes how pulse wave velocity (PWV) relates to arterial dispensability [14].

$$PWV = \sqrt{\frac{V\Delta P}{\rho \Delta V}} = \sqrt{\frac{e^{bP}+1}{\rho b}} = \frac{1}{\sqrt{\rho b}} \frac{\sqrt{2}}{(1-\frac{bP}{4})} \cong \frac{1}{cP - c/4}$$

(1)

Where Δp and ΔV are the changes of blood pressure and volume and ρ is the blood density. PWV relation by PTT is shown in Equation 2.

$$PWV = L / PTT \quad (2)$$

Where L is the distance the pulse travels (roughly equals to the arm length).

By substituting Equation 1 to Equation 2 and re-arranging the equation with Taylor expansions, we obtain the relationship between PWV or PTT and blood pressure (P).

$$PTT = L(cP - c/4) \longrightarrow P = A + B(PTT) \quad (3)$$

This derived equation suggests that BP is linearly related to PTT and the coefficients A and B could be achieved by curve fitting based on the PTT and BP at different physical situation. In this paper, PTT was defined as the time between the two peaks of pulse signals.

2.2. Experiments

For continuous measurement of blood pressure, the constant coefficients are needed in addition to the continuous extraction of PTT. A and B coefficients were calculated for diastolic and systolic blood pressure in different physical activities. Physical activity included going up and down the stairs to increase the arterial blood pressure. The workload was kept until the submaximal heart rate was achieved thereafter 3-7 minutes was considered for individuals to restore to normal condition. PTT, systolic, and diastolic blood pressures were measured for each individual in the normal conditions and in different physical activities to calculate the coefficients. All BP measurements were done using digital brachial blood pressure monometer (Citizen, BK202) on the left upper arm. After initial measurements, the relation between measured PTT and blood pressure was obtained for all the subjects. A and B coefficients were obtained based on PTT for estimating blood pressure. Moreover, for evaluating the relationship between measured blood pressure and PTT in different physical activities, the correlation coefficients were calculated using Pearson method. For the calibration, each subject was requested to perform twenty trials of measurements in order to obtain the constant coefficients with high accuracy. After the initial calibration, the regression line was drawn for each subject. This line formed a function between the blood pressure and the PTT. When the PTT was input to the function, the corresponding blood pressure value could be calculated. Different regression lines were used to represent systolic and diastolic pressures. These values were then uploaded to the software for viewing at a computer. In order to validate the obtained results, they were compared with the results obtained by cuff method. Therefore, after determining the linear correlation coefficients for each individual, blood pressure was measured by cuff method in 20 minutes with 4 minutes intervals. The continuous measurement of blood pressure was also proposed. This study was carried out for different people and effect of age on blood pressure according to the PTT was calculated. Fifteen subjects participated ranging from 16 to 52 and 10 were males and 5 were females. For all of the subjects, the mean arterial blood pressure was 128±11 mmHg, mean heart rate 78±9 BPM, and the average height 1.66±0.06 m. Data collection was done in room at temperature of 26 ±1° C.

2.3. Optical system for blood pressure monitoring

In designing this system, two infrared optical sensors (two optical transmitters) and two optical receivers were employed. The optical transmitters were located at a distance of 5 mm from the optical receiver. The distance between two transducers was defined 55 mm. For primarily preprocessing on the signal, the output of the optical receiver was inserted in an instrumentation amplifier (AD620). Since PPG signal has DC frequency components to 30 Hz frequency, to eliminate low frequency distortions caused by skin absorption, bone, and other non-pulsatory tissues, a passive high pass filter with 0.5 Hz cut off frequency, and to eliminate high frequency noises greater than 30 Hz, a passive low pass filter as well as two active low pass filters of 2nd degree with 20 Hz cut off frequency were employed. Moreover, to have a signal with an appropriate range, an amplifier was utilized with variable gain. While recording, the recorded signal might have positive voltage level as well as negative voltage level and since a microcontroller is not possible with negative voltage level, in the last level of the circuit a level shifter was used to shift voltage level into an appropriate range 0-5 V positive voltage level [15]. The output of the designed analog circuit was inserted into an analog-to-digital converter of ATMEGA 32 microcontroller so that the analog signal could be transferred digitally to the computer [16]. Sampling frequency was 50 Hz. Software interface (Microsoft Visual C#.NET) was used to display, save, process, and software analyzing of the signal in the computer. Using a gate, PPG serial data was arrayed in a 512-byte buffer. Code 13 was used in transferring the data as the end of the data. After adding the serial port to the software, receiving line from the port was activated. When the data were transferring to the computer, they were arrayed until code 13 was received. When receiving data from serial gate was activated, software ran the related subprogram. In this subprogram, the buffer read and saved in codes 0 and 1 in a 750-byte array. Reason to use a 750-byte array was that it should be displayed as a signal on the monitor with 750 pixels wide screen and that a counterpart width with the saved digit was displayed for each pixel. Moreover, in order to display, it recovered each and every 100 ms of the screen and the signal was displayed.

Figure 1 shows blood pressure measurement by the cuff method and the designed system and Figure 2 is the block diagram of the main participants of the designed amplifier. Figure 3 shows a view of the software designed. The software can calculate the PTT according the differences of pulse peak arrival time between two optical pulse sensors.

Figure 1. Blood pressure measurement by cuff method and the present method.

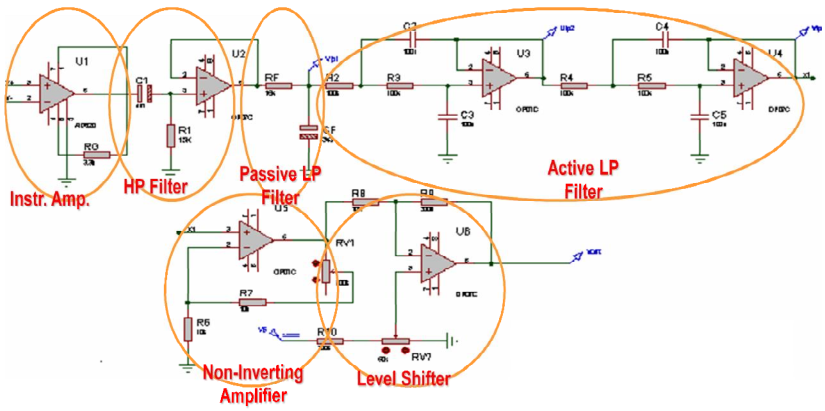

Figure 2. The block diagram of the main participants of the designed amplifier in one channel.

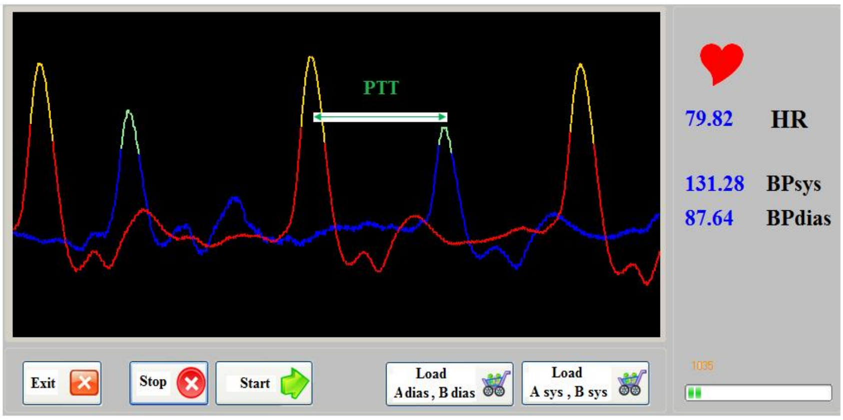

Figure 3. The software for real time monitoring blood pressure.

3. Results

In this study, the appropriate and acceptable linear correlation was determined for constant coefficients A and B. Figure 4(A) shows the relationship between PTT and systolic pressure and Figure 4(B) demonstrates the relation between PTT and diastolic pressure for one case. Table 1 shows the relation between PTT and systolic blood pressure (SBP) with correlation coefficient and error calculation. Table 1 shows that the maximum difference between cuff method and PTT was 13 mmHg and the highest percentage error was 9.2%. Mean correlation coefficients in subjects were equal to 0.88±0.034. Table 2 shows the relationship between PTT and diastolic blood pressure (DBP) with correlation coefficient and error calculation. Table 2 shows that maximum difference and error percent between cuff method and PTT were 14 mmHg and 15.7%, respectively. Mean correlation coefficients in subjects were also 0.82±0.058.

The lowest range of correlation coefficients was 0.82 for systolic pressure and 0.72 for diastolic pressure. For systolic blood pressure, mean values of A constant was calculated 286.33±7.51 and B constant -9.37±0.53. Mean values of A and B constants for diastolic were equal to 256.16±18.16 and -9.87±1.46, respectively.

Table 1. The linear regressions between SBP and PTT with error calculation.

Subject	SBP=A+B*PTT		Correlation	Test Results	
	A (mmHg)	B (mmHg/ms)	Coefficient (R)	$\lvert BP_{cuff} - BP_{estimate} \rvert$	Error (%)
1	282.1	-9.5	0.88	$\lvert 131 - 124 \rvert$ =7	5.3
2	279.8	-10.2	0.84	$\lvert 126 - 135 \rvert$ =9	7.1
3	293.2	-9.36	0.91	$\lvert 143 - 134 \rvert$ =9	6.2
4	283.4	-9.27	0.89	$\lvert 124 - 132 \rvert$ = 8	6.4
5	277.5	-9.31	0.93	$\lvert 128 - 132 \rvert$ = 4	3.1
6	279.3	-9.22	0.91	$\lvert 121 - 118 \rvert$ =3	2.4
7	298.4	-9.71	0.91	$\lvert 131 - 123 \rvert$ =8	6.1
8	301.2	-8.31	0.82	$\lvert 141 - 128 \rvert$ = 13	9.2
9	293.6	-9.41	0.89	$\lvert 127 - 120 \rvert$ = 7	5.5
10	288.6	-10.12	0.93	$\lvert 129 - 124 \rvert$ =5	3.9
11	278.4	-8.48	0.84	$\lvert 121 - 110 \rvert$ =11	9.1
12	283.9	-9.44	0.91	$\lvert 129 - 133 \rvert$ =4	3.1
13	288.2	-9.31	0.89	$\lvert 142 - 132 \rvert$ =10	7.1
14	279.6	-9.81	0.92	$\lvert 133 - 128 \rvert$ = 5	3.7
15	284.8	-9.16	0.86	$\lvert 141 - 135 \rvert$ =6	4.2
mean	286.33±7.51	-9.37±0.53	0.88±0.034	7.98±2.88	6.33±2.51

Table 2. The linear regressions between DBP and PTT with error calculation

Subject	DBP=A+B*PTT		Correlation Coefficient (R)	Test Results	
	A (mmHg)	B (mmHg/ms)		$\lvert BP_{cuff} - BP_{estimate} \rvert$	Error (%)
1	263.5	-10.81	0.79	$\lvert 98-84 \rvert =14$	14.2
2	251.3	-10.22	0.83	$\lvert 92-105 \rvert = 13$	14.1
3	241.4	-9.28	0.88	$\lvert 88-83 \rvert = 5$	5.6
4	255.6	-9.73	0.91	$\lvert 89-97 \rvert = 8$	8.9
5	246.8	-9.28	0.78	$\lvert 91-102 \rvert =11$	12.1
6	271.1	-10.48	0.81	$\lvert 97-88 \rvert = 9$	9.2
7	291.4	-12.72	0.72	$\lvert 74-63 \rvert = 11$	14.86
8	277.8	-10.61	0.86	$\lvert 70-59 \rvert = 11$	15.7
9	271.6	-10.94	0.92	$\lvert 77-71 \rvert = 6$	7.7
10	266.5	-11.77	0.78	$\lvert 90-76 \rvert =14$	15.5
11	239.5	-7.21	0.86	$\lvert 88-94 \rvert =6$	6.8
12	241.6	-8.81	0.81	$\lvert 89-99 \rvert = 10$	11.2
13	267.7	-10.05	0.75	$\lvert 89-98 \rvert = 9$	10.1
14	224.8	-7.95	0.88	$\lvert 92-101 \rvert = 9$	9.7
15	231.8	-8.29	0.86	$\lvert 91-96 \rvert =5$	5.4
mean	256.16±18.16	-9.87±1.46	0.82±0.058	10.13±3.82	10.97±3.89

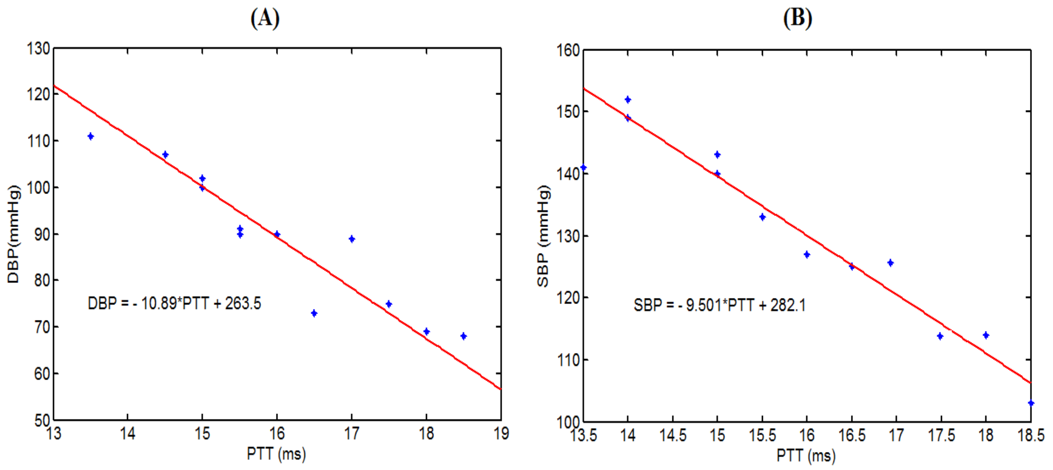

Figure 4. (A) Shows the relation between PTT and systolic pressure, (B) the relation between PTT and diastolic pressure for one case.

It was observed that blood pressure increased while PTT decreased. Constants of A and B changed in the subjects with different ages. Figure 5 shows variations of pulse transition time according to age. According to Figure 5, age and PTT changes were linear. In people older than 50 years old, changes did not follow this linear relationship because maximum error was made in these subjects. The relationship between PTT and age differences was estimated in a linear relationship with a correlation coefficient of 0.81. Significant difference was observed between the hand angel changes. By changing angel of hand from -90 to +90, the blood pressure was decreased as PTT increased.

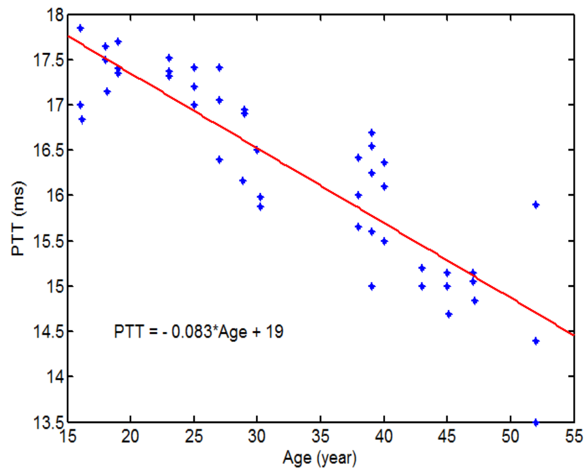

Figure 5. Variations of pulse transition time according to age.

4. Discussion

This study presents a system to measure continuous blood pressure. The results for SBP show that maximum difference and error percent between cuff method and the present method were 13 and 9% and for DBP were 14, 15%, respectively. The relation between PTT and measured SBP and DBP followed a linear function with suitable correlation coefficients but systolic blood pressure could be measured more accurately than diastolic blood pressure. Our results were in good agreements with the previous reports [20, 21]. However, a number of authors obtained a non-linear relationship between PTT and BP [17-19], while a number of authors reported linear relations [20, 21]. Yan Chen et al. acquired pulse waves with two clip type light transducers which are utilized for ear and toe. The results of clinical trials showed that the mean deviation and standard deviation of SBP and DBP measurement by PWV met the test standard in ANSI/AAMI SP10 [22]. Youngsung Kim et al. developed a wrist type device for the continuous non-invasive BP monitoring based on PTT. The device could connect to the PDA phone by wireless connection. Its error rate was higher than the commercial product, but it was a novel attempt which could approach the reliability of traditional BP measurement product [23]. Fiala J et al. implanted the PPG sensor inside the body to estimate BP measuring the PTT. Most of PTT-based systems for BP measurement contain PPG sensors positioned on body surface. It can be influenced by ambient light, movement and temperature. With the use of an implanted sensor, such problems can be minimized or eliminated entirely [24]. Zakaria NA et al. recorded the values of pulse wave transit time (PWTT) and SBP in three experiments. After the experiments, three different mathematical equations for calculation of SBP from PWTT were obtained. The accuracy of derived BP values was low in comparison with the conventional method [25]. Comparing with other studies, this study had a limitation which was the use of the cuff method for the reference BP could not be considered as the standard. Moreover, we used 2 PPG-sensors along an artery to get the PTT so that the position of the hand could change BP and had to be calculated at any time with the information of hand position and the system could correct the value of BP automatically. The initial calibration was required on each subject because of different physiological parameters, such as the blood density and the stiffness of the arterial wall. Those parameters can be treated as constant for each personal subject and by doing several measurements, the linear regression line could be established and the coefficients obtained. Then, the blood pressure could be predicted based on the PTT. However, the prediction accuracy depended on the accuracy of the initial calibration similar to the blood pressure. PPG measurements should be performed with the standard devices to obtain high accuracy results. The number of measurements could be altered during the initial calibration. However, 5-6 times of measurements were formal to be acceptable to obtain a reasonable regression line. Due to the small number of subjects, these results are preliminary and have to be confirmed by studies with representative number of persons or even patients. To achieve the reliability and accuracy in blood pressure estimation sufficient for medical use, additional studies have to be conducted.

5. Conclusion

The aim of this study was to construct optical blood pressure monitoring system. The system was based on the PTT method but different from other systems which use ECG and PPG signals to obtain the PTT. The results showed that maximum error between the cuff method and the present method was 14 mmHg and systolic blood pressure was measured more accurately than diastolic blood pressure. Therefore, the proposed system can monitor blood pressure continuously without using a cuff. Monitoring blood pressure with the designed system can be recommended as a useful method to indicate cardiovascular diseases and for personal healthcare purposes.

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