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Estimation of Systolic and Diastolic Pressure using the Pulse Transit Time

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***Abstract*—In this paper, algorithm estimating the blood pressure was proposed using the pulse transit time (PTT) as a more convenient method of measuring the blood pressure. After measuring ECG and pressure pulse, and photoplethysmography, the PTT was calculated from the acquired signals. Thereafter, the system to indirectly measure the systolic pressure and the diastolic pressure was composed using the statistic method. In comparison between the blood pressure indirectly measured by proposed algorithm estimating the blood pressure and real blood pressure measured by conventional sphygmomanometer, the systolic pressure indicates the mean error of ±3.24mmHg and the standard deviation of 2.53mmHg, while the diastolic pressure indicates the satisfactory result, that is, the mean error of ±1.80mmHg and the standard deviation of 1.39mmHg. These results are satisfied with the regulation of ANSI/AAMI for certification of sphygmomanometer that real measurement error value should be within the mean error of ±5mmHg and the standard deviation of 8mmHg. These results are suggest the possibility of applying to portable and long time blood pressure monitoring system hereafter.

***Keywords*—**Blood pressure, Systolic, Diastolic, Pulse transit time.

I. INTRODUCTION

BLOOD pressure (BP) acts as one of the vital signs providing the useful information about cardiac output and elasticity of the blood vessel, and physiological variation. Therefore, the measurement of BP is helpful for a physician to understand and diagnose the integrity function of the cardiovascular system. The invasive method of measuring the blood pressure by inserting a catheter into the blood vessel to measure the arterial pressures accurately, still has the disadvantage of accompanying pain and contamination, and the side effects arising from inserting the catheter-tip into a patient's blood vessel. The various indirect methods of measuring BP such as Riva-Rocci and oscillometric and ultrasound, and tonometry method, etc. were developed to solve these problems [1]-[2]. However, there is the inconvenience of using the cuff attached to the patient's arm for non-invasive BP measurement and also the limitation in measuring the blood pressure continuously. Recently, the continuous and non-invasive the BP measurements using PTT, in inversely linear relationship with blood pressure, have been extensively accomplished in the past few decades. Park [3], and Lass [4] estimated the blood pressure using time interval between the R-peak of electrocardiogrm (ECG) and the characteristic points of the pulse wave signal, such as the base line point of pulse wave, maximum point, and point indicating 50% of the pulse wave amplitude. Also Teng [5] estimated the blood pressure using the systolic and the diastolic peak of PPG signal, and the pulse width of the pulse wave. The blood pressure measuring method using these pulse waves induces the inconvenience of needing additional information, such as body parameter to improve the accuracy despite simplicity of measurement. In this study, the estimating algorithm of the BP was proposed using the PTT calculated from the time difference between peculiar points of pressure pulse and photoplethysmography measured at identical region with QRS peak of ECG.

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II. THE BP ESTIMATING ALGORITHM

After recording the ECG and pressure pulse, and photoplethysmography signals from the experimental objects, the PPT with respect to each cardiac period as for each pulse wave was calculated and averaged. Thereafter, the systolic blood and the diastolic blood pressure were estimated using the derived blood pressure estimating formula. Fig. 1 shows the flowchart of the proposed signal processing to estimate the BP.

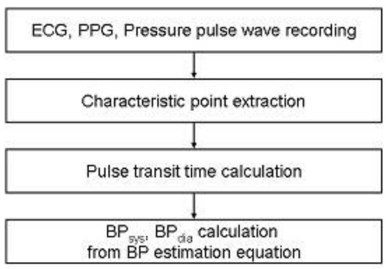


Fig. 1. Flowchart of signal processing for estimation of the systolic and diastolic pressure.

A. Detection of the characteristic point in the pulse wave signal

In general, it is not easy to detect the foot of the pulse wave because the systolic and diastolic waveforms of the pulse wave change every moment due to various factors such as the characteristics of the blood vessel wall, viscosity of the blood, influence reflected in the pulse wave, proper vibration of tissue in the artery system, etc. The characteristic point of the pulse wave should reflect the beginning point of the pulse wave, and should not be influenced by the transmission characteristic of the blood vessel and the frequency distortion. For this reason, the characteristic point of the pulse wave to minimize the calculation error generating from the form change of the pulse wave was detected in most researches on the PTT calculation. The characteristic points of the pulse wave generally used are the maximum, the minimum, the average point between the maximum and the minimum of pulse wave signal (RM50), the maximum of first derivative and the maximum of the second derivative of the pulse wave, the intersection of a line tangent, and the intersection of two line tangents. In this study, the maximum point of the second derivative of the pulse wave providing noise resistance, the stable result and easy implementation was used as the characteristic point of the pulse wave for the calculation of PTT.

B. Calculation of pulse transit time(PTT)

PTT was defined as the time interval between the R-peak of ECG and the characteristic point of the pulse wave. The principle of PTT can be represented as shown in Fig. 2. Fig. 2(a) indicates ECG signal, Fig. 2(b) PPG signal, and Fig. 2(c) pressure pulse wave signal. The measured PTTPPG implies the time interval between the R-peak of ECG and the characteristic point of PPG signal. PTTpressure implies the time interval between the R-peak of ECG and the characteristic point of the pressure pulse wave signal.

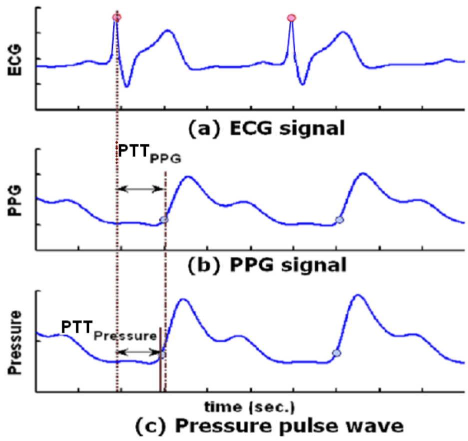


Fig. 2. Principle of pulse transit time calculation.

C. Estimation of the BP using PTT

PTT decreases as the BP increases, while BP increases as PTT decreases. A linear regression equation using PTT as an input variable can be derived establishing the compensation coefficient according to correlation, after the BP and PTT are measured using the inverse relation between the BP and PTT [6]. The systolic and the diastolic BP can be estimated using PTT only after the linear regression equation estimating the BP is derived. The BP measurement method using PTT has the advantage of providing the convenient real-time monitoring of the BP without the cuff.

III. Calculative Method of the Blood Pressure Estimating Formula

A. Relation between PTT and blood pressure

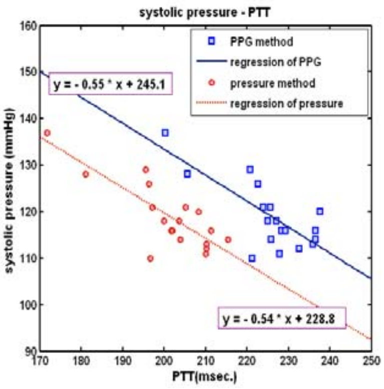
Correlation between the blood pressure and PTT calculated from simultaneously measured the signals such as, ECG, pressure pulse, and photoplethysmography was performed and investigated using the statistical technique. The experimental method was accomplished as the following. After the ECG, pressure pulse, and PPG signals were measured 20 times on the identical subjects, PTT was calculated as the time interval between the R-peak of ECG and the characteristic point of pulse wave of PPG. And the correlation between detected PTT and the blood pressure was observed. The blood pressure of object was controlled through physical exercise to investigate the wide range of blood pressure. The standard BP was measured using the BP-1 (Casio, JAPAN), simultaneously with the measurement of ECG, pressure pulse wave, and PPG signal. The standard BP measured from objects indicated that the systolic blood pressure was in the range of 110 ~ 137 mmHg, while the diastolic blood pressure was in the range of 65 ~ 83 mmHg.

The correlation of PTT calculated between the R-peak of ECG and the characteristic point of pulse wave signal, and the systolic and the diastolic blood pressure can be analyzed as shown in TABLE1. The correlation analysis was performed in the confidence interval of 95% using Matlab 7.0.

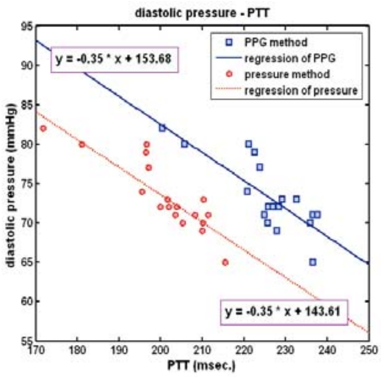
TABLE I Result of correlation analysis between the blood pressure and pulse transit time

Blood pressure		Systolic pressure		Diastolic pressure	
Method		PPG	Pressure	PPG	Pressure
Regression line	Slope	-0.5582	-0.5454	-0.3558	-0.3501
	Intercept	245.1	228.9	153.7	143.6
RMSE		4.389	4.362	3.317	2.113
Correlation coefficient		-0.7422	-0.8053	-0.8034	-0.8691
p-value (95% confidence interval)		0.0004	< 0.0001	< 0.0001	< 0.0001

TABLE 1 indicates that RMSE below 5 mmHg the and maximum value of correlation coefficient over 0.7, and p-value of the systolic and the diastolic blood pressures below 0.05. These results revealed the close relation with PTT. The correlation coefficient between BP and PTT from PPG was -0.7422 in the systolic BP, and -0.8034 in the diastolic BP. And, the correlation coefficient between the BP and PTT using the pressure pulse wave was -0.7422 in the systolic BP, and -0.8034 in the diastolic BP. It was certain that PTT was inversely proportional to the BP since all correlation coefficients indicated negative values. These results are in accord with the previous studies of many researches that PWV having an inverse relation with PTT is proportional to the blood pressure. Moreover PTT was more closely connected with the diastolic BP than the systolic BP, indicating that the PTT using the pressure pulse wave was better correlated than the PTT by means of the PPG signal. The distributions of the diastolic and the systolic blood pressure with regard to PTT, with the linear regression line derived by the statistic analysis in the pressure pulse wave and PPG are illustrated in a graphic form as shown in Fig. 3. PTT using PPG in the systolic and the diastolic blood pressure has higher estimation error, namely the degree of dispersion, than PTT using the pressure pulse wave signal. As shown in Table 1 and Fig. 3, the systolic and the diastolic blood pressure have a similar slope of the linear regression line with regard to PTT, but there are remarkable differences in the intercept of the y-axis.



(a) Systolic pressure



(b) Diastolic pressure

Fig. 3. Correlation relation of the blood pressure and pulse transit time.

These phenomena are interpreted as a result that the pressure pulse wave is conducted faster than PPG signal, indicating 29.5 ms in the systolic blood pressure and 28.7 ms in the diastolic blood pressure.

B. *Estimating formula of the blood pressure*

A model formula estimating the systolic and the diastolic blood pressure are proposed using PTT calculated from the pulse pressure and PPG measured simultaneously. The R-Square selection method was carried out to verify the appropriateness of the model. Results of the R-Square selection method can be summarized as shown in TABLE 2.

TABLE II RESULT OF R-SQUARE REGRESSION ANALYSIS FOR ESTIMATION AND EVALUATION OF THE BLOOD PRESSURE MODEL EQUATION

		Systolic pressure	Diastolic pressure
Analysis variance (ANOVA)	Root MSE	4.455	3.021
	Adj R-square	0.4275	0.2621
	p-value	< 0.0001	< 0.0001
Parameter analysis	Intercept	190.2 (<0.0001)	96.40 (<0.0001)
	PTT_{PPG}	0.2157 (0.0001)	0.2419 (<0.0001)
	$PTT_{pressure}$	-0.5981 (<0.0001)	-0.3897 (<0.0001)

As the statistic significance is represented below 0.05 in the systolic and the diastolic blood pressure, a model formula of R-squared regression turned to have a significant feasibility. Although the root mean square error (RMSE) of 4.550 in the systolic blood pressure was higher than that of 3.021 in the diastolic blood pressure, R2 in the systolic blood pressure was 4.275, representing the significance of calculated R-squared regression formula.

Model formula for estimation of the systolic and the diastolic blood pressure was derived by combining PTTPPG due to PPG and PTTpressure due to pressure pulse wave signal on the basis of the calculated R-Square selection method. The proposed model formula for estimation of the systolic and diastolic blood pressure is as follows.

$$CPTT_{sys} = 190.2 + 0.2157 \times PTT_{PPG} - 0.5981 \times PTT_{pressure} \quad (1)$$

$$CPTT_{sys} = 96.41 + 0.2419 \times PTT_{PPG} - 0.3897 \times PTT_{pressure} \quad (2)$$

$CPTT_{sys}$, variable determined by mathematical model, is derived through the systolic blood pressure and linear regression line, while $CPTT_{dia}$, variable determined by mathematical model, is derived through the diastolic blood pressure and linear regression line. The blood pressure was estimated using the derived linear regression line. The analysis result of the linear regression line can be summarized as shown in TABLE 3.

TABLE III STATISTIC ANALYSIS FOR EXTRACTION OF LINEAR REGRESSION FOR THE BLOOD PRESSURE ESTIMATION

Blood pressure		Systolic pressure	Diastolic pressure
Regression line	Slope	1.338	1.858
	Intercept	-39.53	-61.68
RMSE		3.824	2.367
Correlation coefficient		0.8126	0.8562
p-value (95% confidence interval)		< 0.0001	< 0.0001

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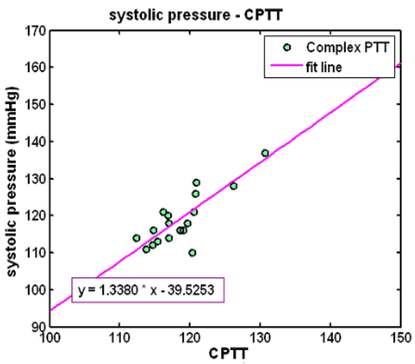
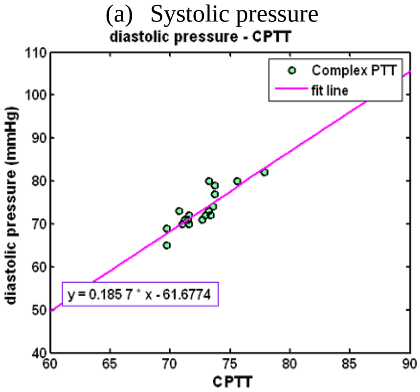
According to TABLE 3, correlation is very high since the statistical signification is lower than 0.05 in the systolic and the diastolic blood pressure. The diastolic blood pressure with correlation coefficient of 0.8562 revealed a higher coincident indicator than the systolic blood pressure with correlation coefficient of 0.8126. In addition, RMSE of two linear regression lines indicated the systolic blood pressure of 3.824 and the diastolic blood pressure of 2.367, suggesting the possibility of estimating a stable blood pressure.

The linear regression line for estimation of the systolic and the diastolic blood pressure, and distribution of the blood pressure with respect to CPTTsys and CPTTdia are described in the graph as shown in Fig. 4. Fig. 4 illustrated the improved result of RMSE which decreased approximately 0.5, compared to that in Fig. 3. Since estimation of the blood pressure was carried out using PTT calculated from pressure pulse and PPG signal simultaneously, a more excellent result was obtained than the result estimating the blood pressure using a kind of PTT.



(a) Systolic pressure



(b) Diastolic pressure

Fig..4 Linear regression line for estimation of the blood pressure.

The linear regression line (3) estimating the systolic blood pressure using $CPTT_{sys}$ and $CPTT_{dia}$, and the linear regression line (4) estimating the diastolic blood pressure are described as the following.

$$BP_{sys} = 1.338 \times CPTT_{sys} - 39.53 \tag{3}$$

$$BP_{dia} = 1.858 \times CPTT_{dia} - 61.68 \tag{4}$$

The estimating equation of the blood pressure with regard to PTT can be derived from substituting (1) and (2) for (3) and (4) respectively. The estimating equation of the systolic and the diastolic blood pressure, compose of two PTT calculated from the pressure pulse wave and PPG signal, are expressed as the following.

$$BP_{sys} = 215.0 + 0.2886 \times PTT_{PPG} - 0.8002 \times PTT_{pressure} \tag{5}$$

$$BP_{sys} = 123.0 + 0.4493 \times PTT_{PPG} - 0.7239 \times PTT_{pressure} \tag{6}$$

IV. Experimental Result and Consideration

The ECG, pressure pulse, and PPG were measured 20 times on an identical object. In addition, after measuring the real blood pressure using BP-1 (Casio, JAPAN), the availability of estimating the blood pressure by using the pulse transit time was evaluated, by comparing the real blood pressure and the blood pressure estimated by indirect blood pressure measurement using the proposed PTT. For this experiment, the ECG-Amp (PhysioLab, Korea) was used for the signal amplifier to obtain the ECG signal. The PPG-Amp (PhysioLab, Korea) for acquiring the PPG signal and Bridge-Amp (PhysioLab, Korea) for monitoring pressure pulse wave were utilized for amplification of the pulse wave signal. Measuring data was recorded at a personal computer by A/D converting at a rate of 12 bit and at a sampling rate of 1 kHz, using iDAQ400 (PhysioLab, Korea). The integrated sensor was used for detecting PPG and the pressure pulse wave in order to measure at identical body position. Objects were healthy adult males of the average age of 30 years without cardiovascular disease, and measurements were carried out by increasing or decreasing the blood pressure through physical exercise and relaxation. RMSE and mean error, and error standard deviation of the real blood pressure measured by the standard sphygmomanometer and the blood pressure estimated using the proposed method are summarized in TABLE 4.

TABLE IV RMSE, ERROR MEAN AND ERROR SD BETWEEN REAL BLOOD PRESSURE AND BLOOD PRESSURE ESTIMATED USING PROPOSED METHOD IN THIS STUDY OR METHOD APPLIED IN ANOTHER STUDY (Unit : mmHg)

Method	Ⅰ PPG and pressure (in this study)		Ⅱ PPG (another study)		difference (Ⅱ - Ⅰ)	
BP	Systolic	Diastolic	Systolic	Diastolic	Systolic	Diastolic
RMSE	4.068	2.260	4.389	3.317	0.321	1.057
Error mean	±3.240	±1.807	±3.694	±2.616	0.454	0.809
Error STD	2.530	1.396	2.855	2.226	0.325	0.830

The comparison between estimated blood pressure and real blood pressure is represented in Fig. 5. The comparison of estimated blood pressure in TABLE 4 and real blood pressure measured by the standard sphygmomanometer indicates that mean error of ±3.240 ㎜Hg, and standard deviation error of 2.530 ㎜Hg were observed in the systolic blood pressure. On the other hand, mean error of ±1.807 ㎜Hg and standard deviation error of 1.396 ㎜Hg were observed in the diastolic blood pressure which was small compared to those in the systolic blood pressure. The estimating capacity of sphygmomanometer can be evaluated from the various points of view such as RMSE and average error, and standard deviation of error. The results of the systolic and the diastolic blood pressure by estimating algorithm proposed in this work are satisfied in accord with the regulation of American National Standards of the Association for the Advancement of Medical Instrumentation (ANSI/AAMI) that the mean error and the standard deviation should be smaller than ±5 ㎜Hg, and 8mmHg respectively, for the certification sphygmomanometer. Compared to the result of estimating the blood pressure, the result of estimated the blood pressure using only one parameter, that is, PTT among methods for estimation of the blood pressure, the results of the estimated the blood pressure by algorithm proposed in this research indicated an excellent performance in RMSE and average error, and standard deviation. Namely, experimental errors were observed as low as 0.321 ㎜Hg in the systolic blood pressure as well as 1.057 mmHg in the diastolic blood pressure in the point view of RMSE. Experimental errors were observed as low as 0.454 ㎜Hg in the systolic blood pressure as well as 0.809 mmHg in the diastolic blood pressure in the point view of mean error. Experimental errors were observed as low as 0.454 ㎜Hg in the systolic blood pressure as well as 0.809 mmHg in the diastolic blood pressure in the point view of average error. And experimental errors were observed as low as 0.325 mmHg in the systolic blood pressure as well as 0.830 mmHg in the diastolic blood pressure in the point view of standard deviation. These results now propose the possibility of estimating blood pressure more accurately, using two kinds of PTT such as PTT_{PPG} and $PTT_{pressure}$, rather than PPT.

There are currently lots of existing researches on estimating the blood pressure by a non-invasive method using PTT, and also research result[7] that the diastolic pressure can-not be accurately estimated. As shown in TABLE 4, our research result indicates that RMSE of 2.260 in the diastolic blood pressure are significantly lower than RMSE of 4.068 in the systolic blood pressure. These results are due to the insufficiency of experimental objects and times out of acquisition number. As shown in Fig. 5, even though the range of the blood pressure used in experiment is very limited, there is a clear possibility of estimating the diastolic blood pressure only using PTT. According to another research, it is reported that accurate measurement of the blood pressure could be obtained by correcting the individual differences in the case of estimating the blood pressure by using the PPG signal. In this study, the method of estimating the blood pressure was only suggested, however, the correction method for applying the derived equation of estimating the blood pressure to various objects was not considered. When considering in reproduction between intra-group and inter-group, reproduction in the intra-group was very high as shown in TABLE 4. The method of estimating the blood pressure in this work was non-invasive, without using the cuff. And the blood pressure was estimated using PTT (PTTPPG, PTTPRESSURE) calculated from the ECG and pulse wave signal. This technique will be extended to the development of portable real-time system and system capable of continuously monitoring patients for a long period of time.

V. Conclusion

Comparison of the blood pressure indirectly measured by the proposed algorithm of estimating the blood pressure and real the blood pressure measured by the standard sphygmomanometer indicated the satisfactory result of the error mean of ±3.24 ㎜Hg and the standard deviation of 2.530 ㎜Hg in the systolic blood pressure, while the error mean of ±1.807 ㎜Hg and the standard deviation of 1.396 ㎜Hg in the diastolic blood pressure. The results of the systolic and the diastolic blood pressure by the estimating algorithm proposed in this work are fully satisfied in accord with the regulation of American National Standards of the Association for the Advancement of Medical Instrumentation (ANSI/AAMI) that the error mean and the standard deviation should be smaller than ±5 ㎜Hg, and 8 ㎜Hg respectively, for the certification sphygmomanometer. The method of estimating the blood pressure was non-invasive without using the cuff. The blood pressure was estimated using two PPT calculated from PPG signal and pressure pulse wave. This technique will be extended to the development of a portable real-time system and system capable of continuously monitoring patients for a long period of time.

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