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Estimating blood pressure using the pulse transit time of the two measuring from pressure pulse and PPG

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Abstract

Blood pressure (BP), one of the most important vital signs, is used to identify an emergency state and reflects the blood flow characteristics of the cardiovascular system. The conventional noninvasive method of measuring BP is inconvenient because patients must wear a cuff on their arm and the measurement process takes time. This paper proposes an algorithm for estimating the BP using the pulse transit time (PTT) of the photoplethysmography (PPG) and pressure pulse from finger at the same time as a more convenient way to measure the BP. After recording the electrocardiogram (ECG), measuring the pressure pulse, and performing PPG, we calculated the PTT from the acquired signals. Then, we used a multiple regression analysis to measure the systolic and diastolic BP indirectly. Comparing the BP measured indirectly using the proposed algorithm and the real BP measured with a sphygmomanometer, the systolic pressure had a mean error of ±3.240 mmHg and a standard deviation of 2.530 mmHg, while the diastolic pressure had a satisfactory result, i.e., a mean error of ±1.807 mmHg and a standard deviation of 1.396 mmHg. These results are more superior than existing method estimating blood pressure using the one PTT and satisfy the ANSI/AAMI regulations for certifying a sphygmomanometer i.e., the measurement error should be within a mean error of ±5 mmHg and a standard deviation of 8 mmHg. These results suggest the possibility of applying our method to a portable, long-term BP monitoring system.

Key Words : pulse transit time, blood pressure

1. Introduction

Blood pressure (BP), one of the major vital signs, provides valuable information about cardiac output, the elasticity of the blood vessels, and physiological variation. BP measurements help the physician to understand and diagnose the integrity of the cardiovascular system. In 1773, Stephen Hales[1], an English theologian and scientist, measured the mean BP of a horse directly by inserting an L-shaped brass tube into the horse's carotid artery and connecting a glass tube vertically to it. Since then, various methods of measuring BP have been introduced. Invasive methods involve inserting a catheter into an artery to accurately measure the arterial pressures. This has the disadvantages causing pains, the possibility of infection, and side effects arising from inserting a catheter tip into the patient's blood vessel. Various indirect methods of measuring BP have been developed to solve these problems, such as the Riva-Rocci, oscillometry, ultrasound, and tonometry methods [2-4]. However, the necessity of attaching a cuff to the patient's arm and the limitations in measuring the BP continuously pose drawbacks. In the past few decades, several studies have reported on continuous and noninvasive BP measurements using the pulse transit time (PTT), which has an inverse linear relationship with the BP. Franchi et al.[5], Park et al.[6], and Lass et al.[7] estimated the BP using the time interval between the R-peak of the electrocardiogram (ECG) and characteristic points of the pulse wave signal, such as the baseline of the pulse wave, maximum point, and point indicating 50 % of the pulse wave amplitude. Teng and Zhang[8] estimated the BP using the systolic and diastolic peaks of the photoplethysmograph (PPG) signal, and the width of the pulse wave. Despite the simplicity of the measurement, however, BP measurements using the pulse wave require

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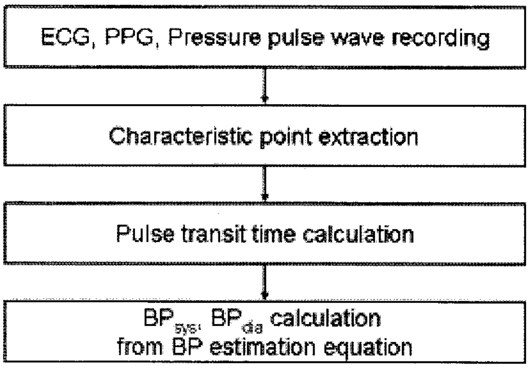


Fig. 1. Flowchart of the signal processing used to estimate the systolic and diastolic BP.

additional information, such as body parameters, high, length of leg, sex, weight, percent body fat, body fat, arm circumference and length etc, to improve the accuracy. In this report, we estimated the blood pressure using only the ECG and pulse wave without additional information such as body parameters to solve the problems and to measure the blood pressure using the convenient method. We propose minimum estimation error by using each of the two PTT calculated from pressure pulse and PPG at the same point.

2. The BP estimation algorithm

After recording the ECG, pressure pulse, and PPG signals from the study subjects, the PTT with respect to each cardiac period for each pulse wave was calculated and averaged. Then, the systolic and diastolic BP were estimated using the derived formula for estimating the blood pressure. Fig. 1 shows the flowchart for the proposed signal processing used to estimate the BP.

2.1. Measure ECG, pressure pulse and PPG

Figure 2 showed sensor attachment and hardware construction to measure ECG, pressure pulse and PPG. ECG sensor is attached at the two arms and pressure and PPG sensors is attached by integrated belt type at the finger.

Bio-signal amplifier is ECG amplifier(PhysioLab, Korea) to acquire the ECG and pulse amplifier is PPG-Amp(PhysioLab, Korea). We used Bridge-Amp(PhysioLab, Korea) to monitor pressure pulse and record the signals at the personal computer using iDAQ400(PhysioLab, Korea). We perform A/D(analog to digital) trans-

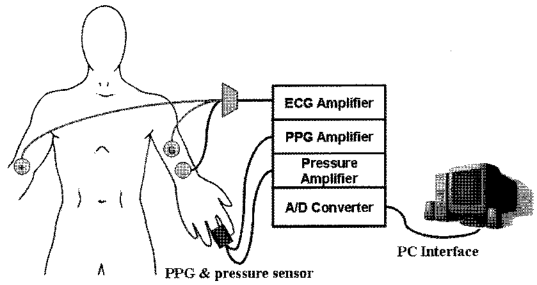
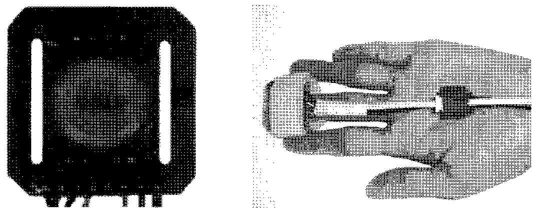


Fig. 2. Measurement of ECG and PPG and pressure pulse signal.



(a) External appearance of the sensor

(b) the sensor attached on the finger

Fig. 3. The pulse wave sensor integrated with pressure pulse wave and PPG sensor.

form using 12 bit quantization and 1 kHz sampling rate. Figure 3 sshow used integrated sensor.

2.2. Detecting the characteristic points in the pulse wave signal

It is generally difficult to detect the foot of the pulse wave because the systolic and diastolic waveforms of the pulse wave change continuously due to various factors, such as the characteristics of the blood vessel wall, viscosity of the blood, influence of the pulse wave, and vibrations of arterial tissues. Any characteristic point of the pulse wave should reflect the beginning of the pulse wave, and should not be influenced by the transmission characteristics of the blood vessel or frequency distortion. Therefore, characteristic points of the pulse wave that minimize the calculation error arising from the change in the form of the pulse wave have been identified in research on the PTT calculation. The characteristic points of the pulse wave generally used are the maximum, minimum, average point between the maximum and minimum of the pulse wave signal (RM50), maxima of the first and maximum second derivatives of the pulse wave, intersection of a line tangent, and intersection of two line tangents. In this study, we used the

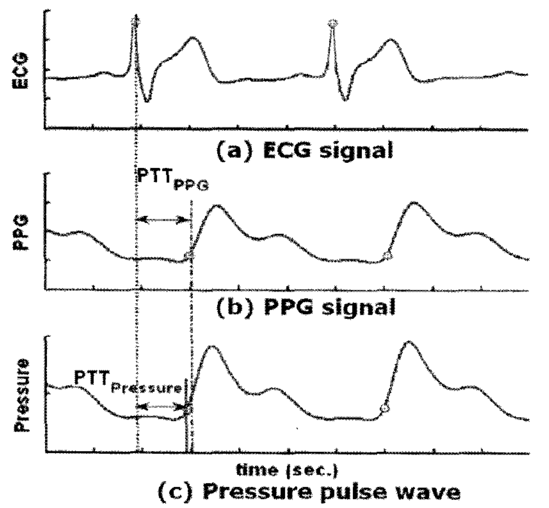


Fig. 4. Calculation of the pulse transit time.

maximum of the second derivative of the pulse wave as the characteristic point of the pulse wave for calculating the PTT because it was noise resistant, gave stable results, and was easily obtained[9].

2.3. Calculating the PTT

The PTT was defined as the time interval between the R-peak of the ECG and the characteristic point of the pulse wave. The principle of the PTT is illustrated in Figure 4, which shows the (a) ECG, (b) PPG, and (c) pressure pulse wave signals. The measured PTT_{PPG} and $PTT_{pressure}$ are the time intervals between the R-peak of the ECG and the characteristic points of the PPG and pressure pulse wave signals, respectively.

3. The formula for estimating BP

3.1. The relationship between PTT and BP

The PTT is inversely proportion to the BP. A linear regression equation using the PTT as the input variable can be derived to establish the compensation coefficient from the measured BP and PTT[10]. The systolic and diastolic BP can be estimated using the PTT only, after deriving the linear regression equation for estimating the BP.The BP measurement method using the PTT has the advantage of allowingconvenient real-time monitoring of the BP without a cuff.

The correlation between the BP and the PTT calculated from simultaneous measurements of the ECG, pressure pulse, and PPG was determined using statistical techniques as follows. After measuring the ECG, pressure pulse, and PPG 20 times in the same person, the PTT was calculated as the time interval between the R-peak of the ECG and the characteristic point of the pulse wave of the PPG. Then, we determined the correlation between the detected PTT and the BP. The BP of subjects was altered by having them exercise to investigate a wide range of BPs. The standard BP was measured using the BP-1 (Casio, Japan) and the ECG, pressure pulse wave, and PPG signal were measured simultaneously.

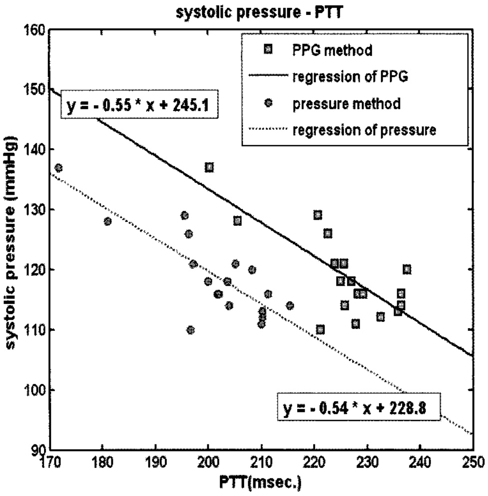
The standard BP measured in the subjects gave systolic BP ranging from 110 to 137 mmHg and diastolic BP ranging from 65 to 83 mmHg.

The correlation between the PTT calculated from the R-peak of the ECG and the characteristic point of the pulse wave signal, and the systolic and diastolic BP is summarized in Table 1. The correlation analysis was performed for the 95% confidence interval using MATLAB 7.0.

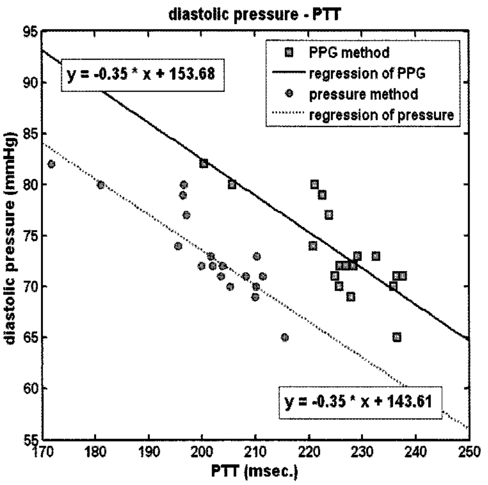
Table 1 indicates that the root mean square error (RMSE) is less than 5 mmHg, the value of the correlation coefficient exceeds 0.7, and the p-value for the systolic and diastolic blood pressures is less than 0.05. These results revealed that the BP has a close relationship with the PTT. The correlation coefficient between BP and PTT from the PPG was −0.7422 for the systolic BP and −0.8034 for the

Table 1. Result of Correlation Analysis berween 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

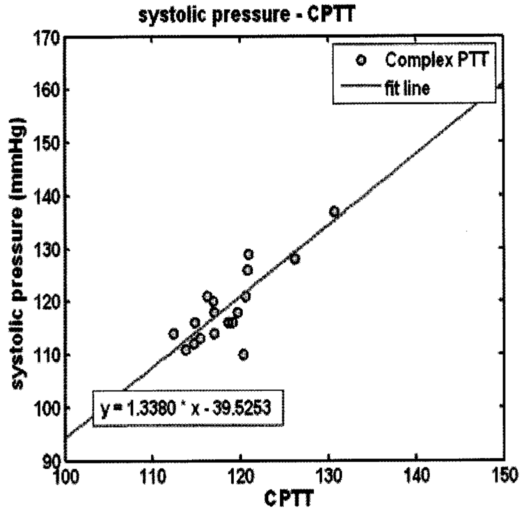


(a) Systolic blood pressure vs. PTT

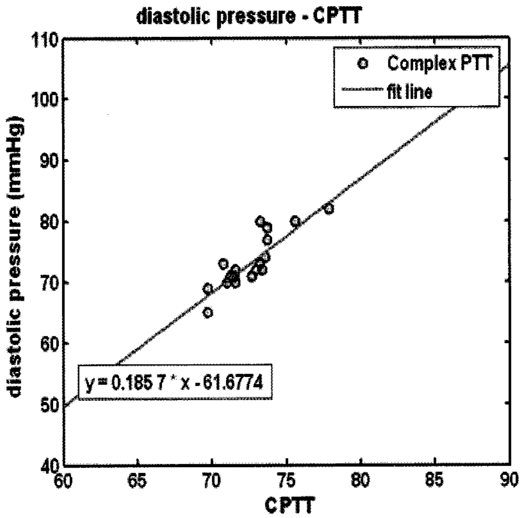


(b) Diastolic blood pressure vs. PTT

Fig. 5. Correlation between BP and the PTT.



(a) Systolic BP



(b) Diastolic BP

Fig. 6. Linear regression lines for estimating the BP.

diastolic BP. The correlation coefficient between the BP and PTT using the pressure pulse wave for the systolic and diastolic BP was −0.7422 and −0.8034, respectively. These results are in accord with several previous studies showing that the pulse waveform has an inverse relationshipwith the PTT and is proportional to the BP. Moreover, the PTT was more closely correlated with the diastolic BP than with the systolic BP. The distributions of the diastolic and systolic BP with regard to the PTT are plotted in Figure 5, with the linear regression line derived statistically. The PTT obtained using the PPG gives a higher estimation error for the systolic and diastolic BP (i.e., the degree of dispersion) than the PTT using the pressure pulse wave signal. As shown in Table 1 and Figure 5, the systolic and diastolic BP have linear regression lines with similar slopes with regard to PTT, although the y-intercepts differ markedly. This arises because the pressure pulse wave is transferred faster than the PPG signal, indicating 29.5 ms for the systolic BP and 28.7 ms for the diastolic BP.

3.2. Formulat for estimating BP

We propose a formula for estimating the systolic and diastolic BP using the PTT calculated from the pulse pressure and PPG measured simultaneously. The R-

Table 2. The Results of the r^2 Regression Analysis for Calculatingand Evaluating the BP Estimating Equation

		Systolic pressure	Diastolic pressure
Analysis of variance (ANOVA)	RMSE	4.455	3.021
	Adjusted r^2	0.4275	0.2621
	p-value	<0.0001	<0.0001
	Intercept	190.2 (<0.0001)	96.40 (<0.0001)
Parameter analysis	PTTPPG	0.2157 (0.0001)	0.2419 (<0.0001)
	PTTpressure	−0.5981 (<0.0001)	−0.3897 (<0.0001)

Table 3. Statistical Analysis for Calculating the Linearregression Lines to Estimate the Blood Pressure

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

square (r^2) selection method was used to verify the appropriateness of the model. The results of the r^2 selection method are summarized in Table 2.

As the statistical significance is below 0.05 for the systolic and diastolic BP, the r^2 regression formula is feasible. Although the RMSE is higher for the systolic BP than for the diastolic BP (4.550 vs. 3.021), r^2 for the systolic BP was 4.275, indicating the significance of the calculated r^2 regression formula.

The model formula for estimating the systolic and diastolic BP was derived by combining the PTT obtained from the PPG (PTTPPG) and the pressure pulse wave signal ($PTT_{pressure}$) using the r^2 selection method. The derived formulas for estimating the systolic and diastolic BP are

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

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

The variables CPTTsys and CPTTdia, determined by the mathematical model are derived from the respective linear regression lines for the systolic and diastolic BP. The analysis of the linear regressions is summarized in Table 3.

According to Table 3, the correlations were very high since the statistical signification was less than 0.05 for the systolic and diastolic BP. The correlation coefficient was higher for the diastolic BP (0.8562 vs. 0.8126). In addition, the RMSE for linear regression lines for the systolic and diastolic BP was 3.824 and 2.367, respectively, implying that the BP estimates are stable.

$$BP_{sys} = 1.338 \times CPTT_{sys} - 39.53 \quad (3)$$

$$BP_{dia} = 1.858 \times CPTT_{dia} - 61.68 \quad (4)$$

Substituting equations (1) and (2) into (3) and (4), respectively, gives the following equations for estimating the systolic and diastolic BP from the pressure pulse wave and PPG signal:

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

$$BP_{dia} = 123.0 + 0.4493 \times PTT_{PPG} - 0.7239 \times PTT_{pressure} \quad (6)$$

4. Experimental results

The ECG, pressure pulse wave, and PPG were measured 20 times in the same subject. In addition, the real BP was measured using BP-1 (Casio), which allowed comparison with the BP estimated using the PTT. In this experiment, the ECG (ECG-Amp PhysioLab, Korea), PPG (PPG-Amp PhysioLab), and pressure pulse wave (Bridge-Amp PhysioLab) were recorded and the signals stored on a personal computer.

The subjects were healthy adult males (average age 30 years) with no cardiovascular disease and measurements were made while altering the BPthrough physical exercise. The RMSE, mean error, and standard devia-

Table 4. RMSE, Mean Error, and Error Standard Deviation between the Real BP Measured with a Sphygmomanometer and the BP Estimated using our Proposed Method or Method Used in Another Study (units: mmHg)

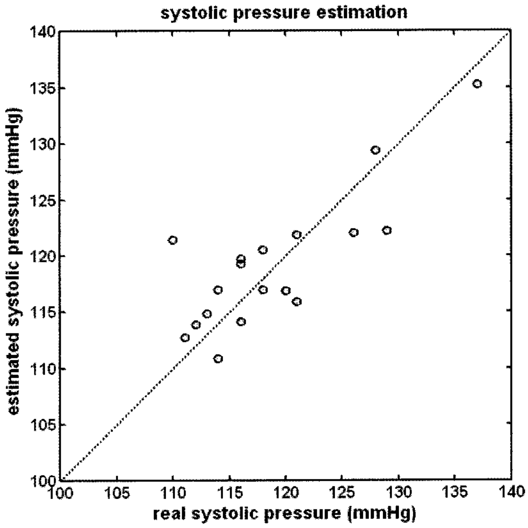
	I		II		Difference	
Method	PPG and pressure (this paper)		PPG (another study)		(II-I)	
BP	Sys.	Dia.	Sys.	Dia.	Sys.	Dia.
RMSE	4.068	2.260	4.389	3.317	0.321	1.057
Mean error	±3.240	±1.807	±3.694	±2.616	0.454	0.809
STD	2.530	1.396	2.855	2.226	0.325	0.830

tion betweenthe real BP measured using a standard sphygmomanometer and the BP estimated using the proposed method are summarized in Table 4.

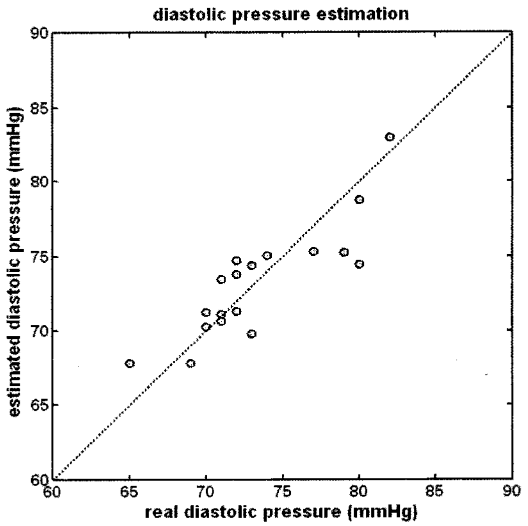
The estimated and real BP are compared in Fig. 7.

The comparison of the estimated BP in Table 4 and the BP measured using a sphygmomanometer gave a mean error of ±3.240 mmHg and a standard deviation of 2.530 mmHg for the systolic BP, while the respective values for the diastolic BP were ±1.807 and 1.396 mmHg, which were smaller than for the systolic BP. The degree of estimation of a sphygmomanometer can be evaluated using the RMSE, average error and standard deviation of the error. Results for the systolic and diastolic BP using our algorithm meet the American National Standards of the Association for the Advancement of Medical Instrumentation (ANSI/AAMI) for certification of a sphygmomanometer i.e., the mean error and standard deviation should be smaller than ±5 and 8 mmHg, respectively. Compared to the BP estimated using one parameter only (i.e., the PTT), our algorithm performed very well in terms of the RMSE, average error, and standard deviation. In the light of RMSE, the systolic and diastolic BP were 0.321 and 1.057 mmHg and in the light of the mean errors were 0.454 and 0.809. And the systolic and diastolic BP were 0.325 and 0.830 mmHg on the error of standard deviations. Therefore, the estimation of BP is more accurate using both PTT_{PPG} and $PTT_{pressure}$, rather than PTT alone.

Many studies have estimated the BP with noninvasive methods using the PTT, and suggested that the diastolic BP cannot be estimated accurately[11]. Nevertheless, as Table 4 shows, the RMSE for the diastolic BP using our method was much lower than for the systolic BP (2.260 vs. 4.068). The previous results were due to the small numbers of experimental subjects and the amount of data acquired. As shown in Fig. 5, although the range of BP examined in the experiment



(a) Systolic BP



(b) Diastolic BP

Fig. 7. Comparison of the BP estimated using the proposed method and that using a sphygmomanometer.

was limited, diastolic BP could be estimated using the PTT only. Another study reported that accurate measurement of the BP could be obtained by correcting the individual differences when estimating the BP using the PPG signal. That study only suggested a method of estimating the BP, and did not consider a correction method. On considering in the intra- and intergroup reproducibility of the results, the former was very high, as shown in Table 4. Our method of estimating the BP was noninvasive, and did not use a cuff. The BP was estimated using PTT_{PPG} and $PTT_{pressure}$ calculated from the ECG and pulse wave signal.

5. Conclusions

Comparison of the BP measured indirectly using the proposed algorithm and that measured using a sphygmomanometer gave a satisfactory result with a mean error of ±3.24 mmHg and standard deviation of 2.530 mmHg for the systolic BP, and ±1.807 and 1.396 mmHg, respectively, for the diastolic BP. The BP was estimated using two values of the PTT calculated from the PPG signal and pressure pulse wave.Our noninvasive method does not use a cuff and the estimates of the systolic and diastolic BP meet the American National Standards of the Association for the Advancement of Medical Instrumentation (ANSI/AAMI) for certification of a sphygmomanometer i.e., the meanerror and standard deviation should be smaller than ±5 mmHg and 8 mmHg, respectively. This technique will be extended to develop a portable real-time system capable of continuously monitoring patients for the long term without additional body information.

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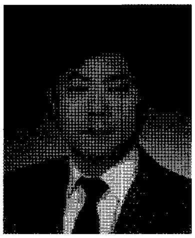

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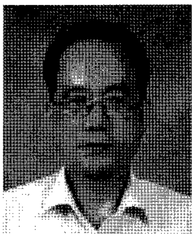

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