Separate Estimation of Long- and Short-term Systolic Blood Pressure Variability from Photoplethysmograph

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Abstract—**This paper proposed a method to monitor systolic blood pressure (BP) variability without using a cuff during the daytime. In this method, BP variability of long-term and short-term were separated and estimated respectively from features of phoplethysmograph (PPG) through the use of a frequency filter. Then, total variability was obtained from the combination of long-term and short-term. BP by using a cuff (ground truth) and PPG of nine healthy young subjects were measured during the daytime; then BP variability was estimated from PPG to verify the validity of our method. As a result, the correlation coefficients between measured BP variability and estimated BP variability was improved from r = 0.35 in previous method to r = 0.41 in proposed method. In particular, the estimation results in short-term BP variability showed good accuracy (r = 0.67). This method of estimating BP variability has the potential to be a simple and continuous BP monitoring system during the daytime.**

I. Introduction

Blood pressure (BP) is an important index in health care, since it is influenced by cardiovascular diseases and stress. Measurement of BP is usually done using a cuff as shown in Fig. 1(a). However, measurement by cuff cannot discover state of rapid BP variation in daytime because measuring by cuff is difficult under continuous measurement regime amid movement. Therefore, many research of estimating BP without a cuff have recently been reported [1][2][3][4] for the continuous and wearable BP measurement.

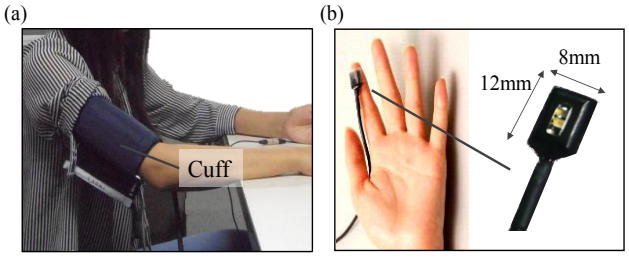

Figure 1. Instrument to measure BP and pulse wave by (a) sphygmomanometer, and by (b) PPG sensor

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Zheng and others reported the estimation of BP variability using the pulse transit time (PTT) computed from an electrocardiogram and photoplethysmographic (PPG) sensor [3]. Their Experimental results estimated BP variability during the nighttime with high accuracy. However, they reported that estimating BP variability during the daytime had comparatively low accuracy. Therefore, one aim of this research is to improve the accuracy of estimating BP variability during the daytime. Our research does not use an electrocardiogram which means, we estimate BP variability by using only PPG sensor as shown in Fig. 1(b). Since PPG can be measured by a single sensor, it enables a near-wearable measurement rather easily. Since PPG can also extract many features from waveform, Suzuki reported the validity of classifying them according to a subject's characteristic and learning [4]. This research focuses on the difference in the variation factors of BP as the characteristic to classify. Though BP variation is caused by many factors such as physical load and room temperature, this research only considers the temporal factor (long, short) of BP variation.

II. Estimating BP Variability from PPG

BP varies by various factors. Generally, causes of high BP include atherosclerosis advancing with aging, and causes of low BP include reduction of cardiac pumping function. However, BP greatly changes constantly throughout the day. Sometimes gradual variation occurs over a period of hours and sometimes a rapid variation arises in seconds. The factors of long-term variation are physiological things such as room temperature, circadian clock and digestive activity. The factors of short-term variation are physical and psychological stress such as exercising and thinking. These variations have different effects on the heart and blood vessels [5]. As a result, they influence to a form of the pulse wave. In this study, we therefore separate BP variability into long-term and short-term variability and estimate BP variability from accelerated plethysmograph features. The processing flow of training and generalization to estimate BP variability is shown in Fig. 2.

A. Photoplethysmography and BP variability

Photoplethysmography is defined as the change of blood volume in the capillary vessels under the skin. The PPG sensor observes the green light with the built-in LED (Light Emitting Diode), and receives the reflected light with the built-in Photo Detector. Oxygenated hemoglobin in the vessel absorbs green light more than other lights. Thus, we could measure PPG noninvasively as the time series residual light using the finger type sensor.

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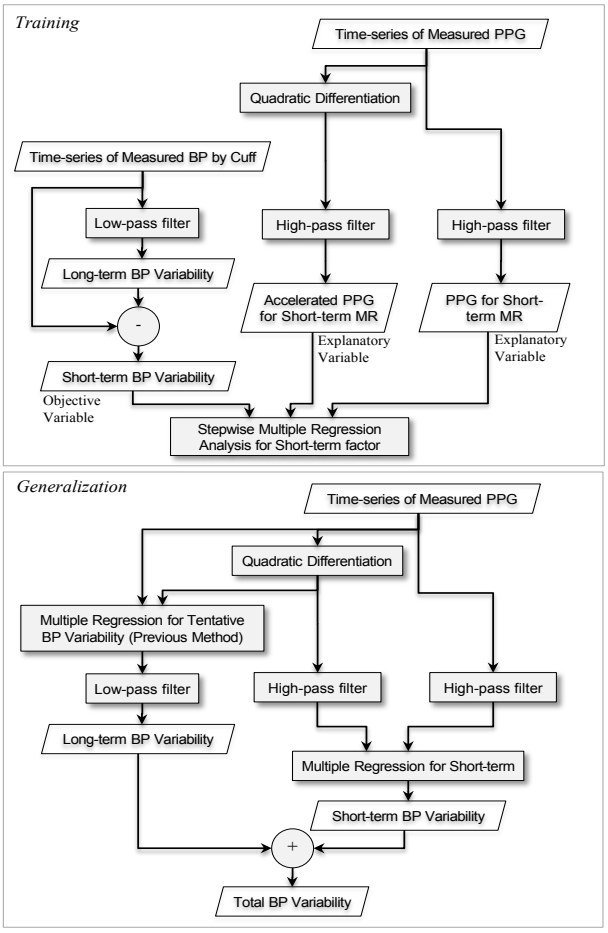

Figure 2. Processing flow of training and generalization to estimate BP variability

Both BP and PPG are used as indexes of the cardiovascular system in general, for example, the stiffness of the blood vessel [6]. Both of them are affected by the cardiovascular system, and PPG has a relationship with BP.

Therefore, we estimate BP variability using PPG in this study. We define BP variability as the distance of systolic BP between the standard condition and each current one. For example, BP variability is -5.2 mmHg when the subject's current systolic BP is 132.5 mmHg and his/her standard systolic BP is therefore 137.7 mmHg. Standard systolic BP means the systolic BP measured by a cuff at rest in the beginning.

B. *Separation of BP Variability for Training of Multiple Regression Analysis*

First, we measure BP values for a long duration by using a cuff to make this training data (ground truth). Then the low-frequency component of time-series BP variability is defined as variability caused by long-term factor, i.e., a long-term BP variability V_{Long} can be extracted by low-pass filtering the measured BP variability. On the other hand, variability caused by short-term factors V_{Short} is defined as the difference between the measured BP variability and the long-term BP variability V_{Long} for the training of the multiple regression analysis.

Based on this definition, Fig. 3 shows an example of separating measured BP variability into two variability components caused by long-term and short-term factors. True BP value for training is measured every 15 minutes. A cutoff frequency of the low-pass filter is set up at 1/7200Hz. Short-term BP variability obtained in this manner is considered an objective variable in the training of the multiple regression analysis.

C. *Extraction of Photoplethysmographic Features*

Many features were extracted from PPG to estimate BP variability. PPG has two typical peaks which are ejection wave (P1) and reflected wave (P2) in Fig. 4(a). P1 is occurred by heart beating, and P2 is occurred by the pulse reflecting at the other vessel. The PPG's periodic waveform could be detected from every heart beating. PPG's waveform is simple, and it is difficult to extract features of the raw waveform in general. So differentiating the waveform is effective to extract features. Sano has suggested using accelerated PPG which is defined as the quadratic differential PPG [7]. An accelerated PPG is commonly used for evaluation of the peripheral blood circulatory system because it relatively easily changes with an age group or an illness. We use accelerated PPG's peaks *a*, *b*, *c*, *d* and *e* wave in sequence in Fig. 4(b) as the features to estimate BP variability. These peaks in accelerated plethysmograph correspond to PPG's inflection points, and are used as indexes of blood vessels [8].

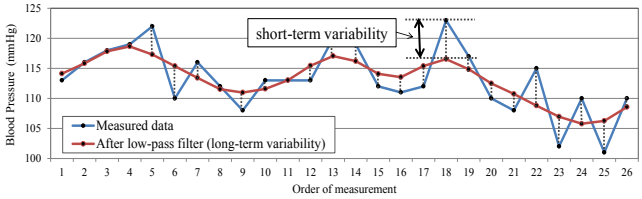

Figure 3. Separation of long-term and short-term BP variability from measured BP

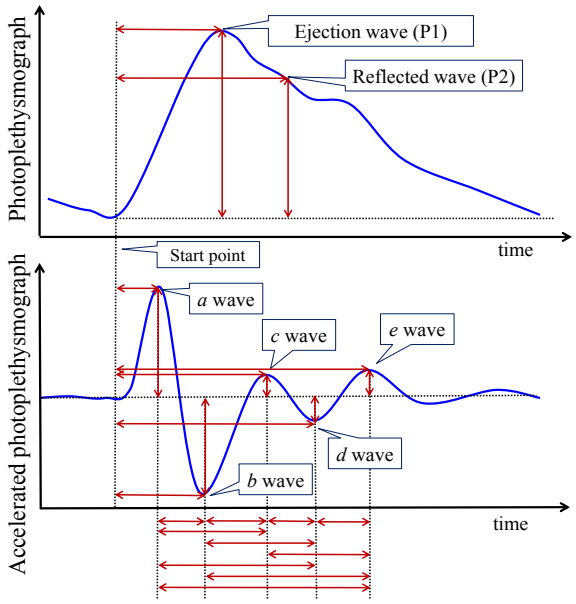

Figure 4. Extracted features from PPG. (a) PPG showing P1 and P2, (b) accelerated PPG showing *a,b,c,d, and e waves*

We selected the heights and the times as the features to estimate BP variability. The height indicates the difference between each peak and the baseline. The time indicates an interval between each peak in PPG and accelerated plethysmograph. The features are summarized in TABLE I. For example, $P1_{Value}$ is defined as the distance between P1 and the PPG's baseline, $P1_{Time}$ is defined as the time interval between P1 and the start point of PPG, and T_{ab} is defined as the time interval between *a* wave and *b* wave in accelerated plethysmograph. Heart rate is defined as the number of time a heart beats in a minute. Heart rate could be obtained by PPG [9]. We use these features obtained from PPG and accelerated plethysmograph to estimate BP variability as explanatory variables in the training of the multiple regression analysis.

D. Estimation of Short-term BP Variability by Multiple Regression Analysis

We tentatively estimate BP variability from PPG features first using the previous method [10] as shown in Fig. 2. Therefore, the regression equation (1) is created to estimate a tentative BP variability using proposed features as shown in TABLE I.

$$y = \sum_{i=1}^{m} s_i x_i + s_{m+1} \tag{1}$$

where, y is the objective variable which corresponds to BP variability, m is the number of selected features, x_i is the explanatory variable which corresponds to the i-th proposed feature, s_i is the coefficient for x_i, and s_{m+1} is the intercept. We optimize every s_i using the database with the stepwise multiple regression analysis.

A long-term BP variability V_{Long} can be extracted by low-pass filtering the tentative BP variability. A short-term BP variability V_{Short} is estimated from the PPG by another multiple regression equation. The regression equation is created by using features in TABLE I as well as by using tentative BP variability.

Then, the total BP variability V_{Total} is defined as the sum of long-term and short-term variability as shown in equation (2).

$$V_{Total} = V_{Long} + V_{Short} \tag{2}$$

As mentioned above, long-term variability, short-term variability and total variability of BP are obtained only from time-series of measured PPG continuously.

TABLE I. FEATURES TO ESTIMATE BP VARIABILITY

Waveform	Features
Photoplethysmograph	$P1_{value}$, $P1_{Time}$, $P2_{Value}$, $P2_{Time}$, Heart rate
Accelerated plethysmograph	a_{Value}, a_{Time} ,b_{Value}, b_{Time}, c_{Value}, c_{Time}, d_{Value}, d_{Time}, e_{Value}, e_{Time} T_{ab}, T_{ac}, T_{ad}, T_{ae}, T_{bc}, T_{bd}, T_{be}, T_{cd}, T_{ce}, T_{de}

III. EXPERIMENT

A. Data Measurement Protocol

To verify the proposed method, we estimated BP variability during the daytime. For nine healthy test subjects (five males and four females, aged 22.6±0.88), their BP and PPG in daytime were measured after obtaining their informed consent. BP (for ground truth) was measured at an interval of every 15 minutes by a cuff shown in Fig. 1(a) at the right upper arm, and PPG was measured by the PPG sensor shown in Fig. 1(b) on the left index finger. The PPG sensor's sampling rate was 1 kHz. The sphygmomanometer TM-2425 was produced by A&D Company Ltd. The PPG sensor used is a product made by a Japanese corporation.

The subjects spent their day as they usually do with the measuring device on for about 16 hours from their getting up in the morning until sleeping at night. Their stable PPG were measured for 2 minutes duration during the cuff measurement while they were resting at ease.

B. Evaluation

We use three indices to evaluate a relation between measured BP by using a cuff and estimated BP from PPG in the experiments. r is the correlation coefficients between measured BP and estimated BP, μ is the average of error, and σ is the standard deviation of error. We evaluated accuracy of estimation using these variables. The correlation coefficients should be close to +1.0, μ and σ should be ±0.0 mmHg.

In the evaluation, we used leave-one-out cross validation method for each subject. This means that when estimating the BP variability of one subject, we developed the regression equation with eight other subjects.

C. Result

After the measurements were done, PPG features were first extracted from PPG. Then, variability of true BP and PPG were calculated. Finally, BP variability (Long-term, Short-term and Total value) was estimated. Fig. 5 shows estimated results of BP variability (V_{Long}, V_{Short}, V_{Total}) by using our proposed method and the previous method [10]. TABLE II summarizes r and σ of measured BP variability by using a cuff and estimated BP variability using PPG for all nine test subjects.

TABLE II. COMPARISON OF ESTIMATION ACCURACY BY PREVIOUS METHOD, LONG-TERM, SHORT-TERM, AND TOTAL VARIABILITY

Subject ID	Previous method		V_{Long}		V_{Short}		V_{Total}	
	r	σ	r	σ	r	σ	r	σ
A	0.11	14.54	0.43	12.2	0.35	6.06	0.38	13.47
B	0.16	5.16	0.46	2.54	0.65	3.20	0.41	4.82
C	0.06	9.12	0.19	4.73	0.39	5.98	0.28	7.80
D	0.61	12.01	0.55	7.86	0.84	8.75	0.65	10.6
E	0.05	11.01	0.30	5.83	0.73	6.44	0.27	11.4
F	-0.07	7.81	-0.05	5.51	0.40	4.40	-0.02	7.93
G	0.09	7.59	0.42	3.53	0.14	4.66	0.29	6.11
H	0.24	7.59	0.09	5.66	0.24	5.61	0.23	8.06
I	0.55	6.89	0.67	3.75	0.74	5.12	0.58	6.62
Average	0.21	9.08	0.34	5.73	0.50	5.58	0.34	8.54

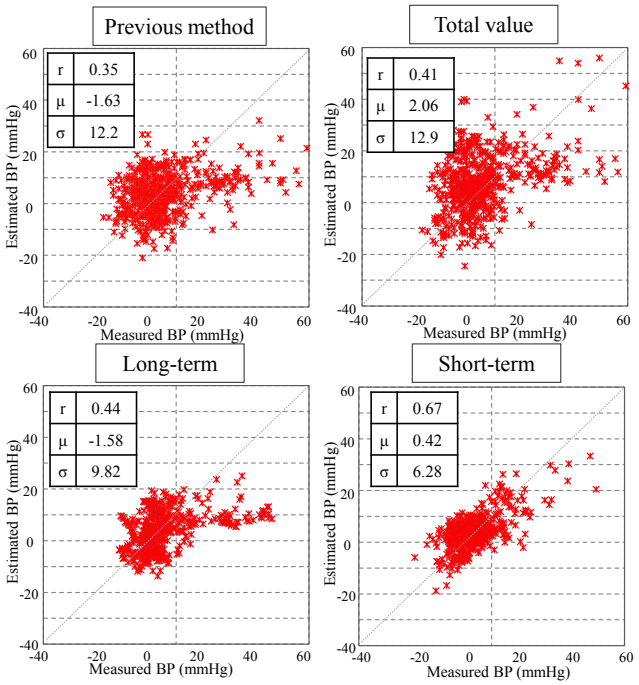

Figure 5. Results of estimating BP variability (From Top left, clockwise, Previous method; Total value; Short-term; Long-term)

D. Discussion

The correlation coefficients between measured BP and estimated BP improved from $r = 0.35$ in previous method to $r = 0.41$ in proposed method by focusing on temporal factors of BP variation. In particular, the estimation results in short-term showed good accuracy ($r = 0.67$). It has been reported that mental load, which is one of the factors in short-term variation, mainly increases total peripheral vessel resistance [11]. That is, short-term variation significantly appears in PPG through the total peripheral vessel resistance. However, decent accuracy was obtained for short-term and long-term BP variability, whereas errors of total BP variability showed a wider distribution despite improvement in accuracy as compared to previous method. This is to say that there were many samples with large error. Especially, it did not work in tracking large variations. One of the future works should aim to reduce this error.

In addition, large error of total BP variability remained but the estimation accuracy for each subject was more adequate than that of the previous method as a result of verification according to subjects. It is believed that this phenomenon was caused by instability of the baseline in measured BP. A slight difference for individual BP baseline may affect the creation of multiple regression equations and evaluation of correlation coefficients. Therefore, it is necessary to review and improve the way of decision of the robust BP baseline in this issue.

Moreover, estimation accuracy greatly differs among subjects as can be noted from TABLE II. For example, the subject F had little correlation for the long-term BP, and the subject G had a low correlation for the short-term BP. These differences suggest that the frequency and the factor of BP variation differ from one subject to another.

IV. Conclusion

This research proposed a method of estimating systolic BP variability, without using a cuff, to monitor BP continuously during the daytime. We focused on temporal variation of BP and PPG. Long- and short-term BP variability were separated and estimated respectively from PPG features. Experimental results confirmed that our proposed method has the potential to be a simple and continuous BP monitoring system through the daytime. Adding the measurements of some test subjects with various characteristics (e.g. age, sex, BP complaint) to the training data is left for a future work. We also have to separate long-term variation part from the source BP variation more successfully and evaluate accuracy of beat-to-beat estimation using Finometer and Nexfin to improve accuracy of estimating the total value of BP.

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