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Cuffless Blood Pressure Estimation using only Photoplethysmography based on Cardiovascular parameters

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***Abstract*— This study provides cuffless blood pressure estimation. In general, blood pressure changes when the subject's condition changes, and it is important to estimate it continuously and noninvasively. In many previous studies, they used PTT (Pulse Transmission Time) for estimating. However, PTT needs both electrocardiogram and photoplethysmography to be measured. Our method needs only a finger type photoplethysmographic sensor for estimating. We use the features obtained only from photoplethysmography for estimating, instead of PTT obtained from electrocardiogram. The features used are accelerated plethysmography's waveform, Heart Rate Variability and the rate of photoplethysmography's drift. Blood pressure is modeled as the product of CO (Cardiac Output) and TPR (Total Peripheral Resistance) in general. Then, we estimated blood pressure as the product of eCO and eTPR estimated by proposed photoplethysmography's features with Stepwise multiple regression analysis. Therefore, our proposed method provides not only blood pressure, but also CO and TPR. As of result, we estimated blood pressure based on eCO and eTPR, and we obtained $r = 0.71$. Therefore, we could obtain the result closer to Finometer in accuracy.**

I. Introduction

Monitoring blood pressure is important. Blood pressure is an index of people's health condition, and blood pressure changes when the subject's health condition changes.

Blood pressure is usually measured by a cuff. However, the method using a cuff has a low degree of usability for the subjects. Therefore, a method of blood pressure estimation having a higher degree of usability without a cuff is necessary.

In previous studies, Pulse Transmission Time (PTT) was mainly used for cuffless blood pressure estimation as a feature [1][2]. However, two kinds of biosignals which are electrocardiogram and photoplethysmography are necessary to measure PTT. Moreover, people have to wear multiple electrodes at some places on their body to measure electrocardiogram. So, we propose a method of cuffless blood pressure estimation using features obtained only photoplethysmography only, instead of PTT.

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II. Photoplethysmography

Photoplethysmography is the change of blood's volume in the vessel. Oxygenated hemoglobin in the vessel absorbs green lights (wave length: 400 - 550 nm) more than other lights. Therefore, human blood looks like red.

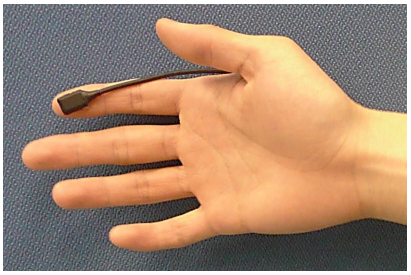

Fig. 1. Finger type photoplethysmographic sensor in this study

We can observe photoplethysmography noninvasively with irradiating LED (Light Emitting Diode) toward the vessel in the skin, and receiving the reflected light at PD (Photo Detector) (Fig. 1). We use only one wave length in this range to measure photoplethysmography [3].

III. Features for blood pressure estimation

A. Accelerated plethysmography

In general, it is difficult to detect the features of photoplethysmography's waveform because photoplethysmography's baseline is easy to drift. Then, differentiating the photoplethysmography's waveform is effective to detect the waveform's features easily [4]. Sano proposed the accelerated plethysmography obtained by differentiating photoplethysmography twice [5]. Accelerated plethysmography's peaks correspond to photoplethysmography's inflection points (Fig. 2(b)).

In this study, we use accelerated plethysmography's peaks as the features for blood pressure estimation. Each of the peak obtained in sequence is defined as the component wave a, b, $\cdots$, f. These features are defined as the distance between each component wave and the accelerated plethysmography's baseline. The component wave a is definitely positive as a feature, and b is negative. The other component waves' signs depend on the subject. In addition, we also use some compound features. For example, we use $\mathrm{APGindex} = (c + d - b)/a$, which is said to have correlation to the subject's age, proposed by Sano.

The time intervals of each accelerated plethysmography's component wave are also effective features that we use [6].

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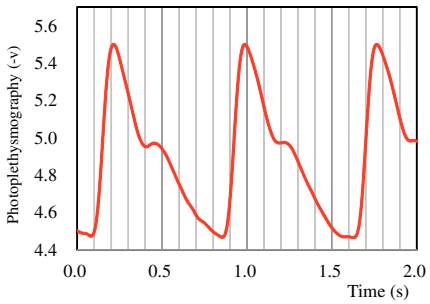
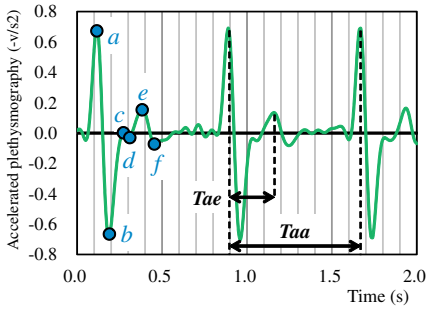


(a) Photoplethysmography



(b) Accelerated plethysmography

Fig. 2. Photoplethysmography and accelerated plethysmography obtained by differentiating photoplethysmography twice.

For every heart beat, there is a component wave i and j. T_{ij} is defined as the time interval between these component waves. We use six component waves (a, b, $\cdots$, f) in total, then the number of the time interval's pattern is ${}_6C_2 = 15$. For example, Fig. 2(b) shows a feature T_{ae}, which is the time interval between the component wave a and e.

T_{aa} is a particular feature which is the time interval between the current wave's a and the next wave's a. We regard T_{aa} as the inverse of pulse rate.

B. Heart Rate Variability

Measuring photoplethysmography, we can obtain Heart Rate Variability (HRV) by detecting the inverse of T_{aa} continuously. This time series data can be regarded as R-R Interval (RRI) obtained from electrocardiogram. We can obtain Sympathetic Nerve Activity (SNA) by transforming this data to a frequency sequence using Fast Fourier Transform (FFT).

Low Frequency (LF) is defined as the integrated value whose range is [0.03 - 0.15] Hz of obtained Heart Rate Variability's frequency band (a range of frequency sequence). In the same way, High Frequency (HF) is defined as the integrated value whose range is [0.15 - 0.43] Hz. Then, SNA is defined as (1).

$$\mathrm{SNA} = \frac{\mathrm{LF}}{\mathrm{HF}} \tag{1}$$

In this study, we also use SNA obtained from accelerated plethysmography as a feature for blood pressure estimation.

C. Drift rate of photoplethysmography

Photoplethysmography's base line is easy to drift when the subject's mental condition changes. The more the subject feels stress, the more the photoplethysmography's base line drifts [7].

$P(f)$ is defined as the photoplethysmography's frequency sequence calculated by FFT. $P(f)$ is the power spectrum of photoplethysmography. The photoplethysmography's base line corresponds to the lower frequency band than pulse rate in $P(f)$ (Fig. 3).

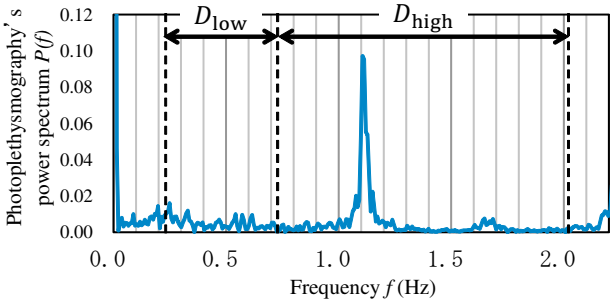


Fig. 3. Photoplethysmography's frequency bands corresponding to its drift and pulse rate are obtained from the frequency sequence $P(f)$, which is the photoplethysmography's power spectrum.

We define $P(f)$'s range [0.2 - 0.7] Hz as the frequency band corresponding to photoplethysmography's drift, considering the influence of pulse rate's frequency. D_{low} is defined as equation (2a). In the same way, D_{high}, which corresponds to pulse rate, is defined as (2b), considering pulse rate's harmonic frequency.

$$D_{\mathrm{low}} = \int_{0.2}^{0.7} P(f)\,df \tag{2a}$$

$$D_{\mathrm{high}} = \int_{0.7}^{2.0} P(f)\,df \tag{2b}$$

Therefore, Drift rate D is defined as equation (3).

$$D = \frac{D_{\mathrm{low}}}{D_{\mathrm{high}}} \tag{3}$$

We also use Drift rate, which is the ratio of photoplethysmography's drift, as a feature for blood pressure estimation.

IV. Method to Estimate Blood Pressure

A. Cardiovascular parameters

In general, blood pressure is modeled as equation (4). BP is mean blood pressure. CO (Cardiac Output) is defined as the amount of blood ejected from heart, and TPR (Total Peripheral Resistance) is the resistance against the blood flowing in the peripheral vessels.

$$\mathrm{BP} = \mathrm{CO} \times \mathrm{TPR} \tag{4}$$

BP is the product of CO and TPR. Therefore, blood pressure is a physiological index related to the other significant cardiovascular parameters, especially CO and TPR. In this study, we estimate mean blood pressure with estimating CO and TPR using photoplethysmography based on the model of equation (4).

B. Regression based on model (4)

We estimate eCO and eTPR using proposed features obtained from photoplethysmography (Fig. 4). Then, we estimate mean blood pressure by multiplying eCO and eTPR together based on the model (4). It is expected that the photoplethysmography's waveform is influenced by TPR, which is Total Peripheral Resistance, especially because photoplethysmography is measured at the peripheral vessel.

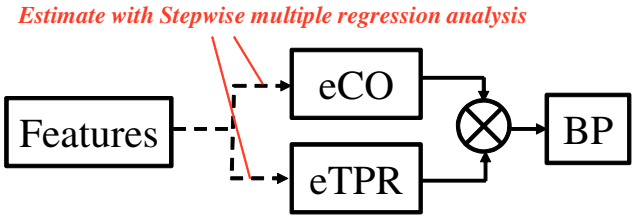


Fig. 4. We estimate BP as the product of eCO and eTPR, which are estimated by proposed features obtained from photoplethysmography only with Stepwise multiple regression analysis.

We use stepwise multiple regression analysis to estimate eCO and eTPR ($p_{\text{in}} = 0.05$, $p_{\text{out}} = 0.05$).

V. Experiment

A. Condition of measuring biosignals

The purpose of this experiment is to verify the proposed method. The proposed method has two steps. The first step is to estimate eCO and eTPR with our proposed photoplethysmography's features using stepwise multiple regression analysis. The second step is to estimate BP with estimated eCO and eTPR before.

We measured photoplethysmography, CO, and TPR together from three females and two males (aged 21.0 ± 1.2) sitting on a chair, after obtaining the informed consent. Photoplethysmography was measured using a finger type sensor shown in Fig. 1. This photoplethysmographic sensor's sampling rate is 1 kHz, and this is a product made by Japanese corporation.

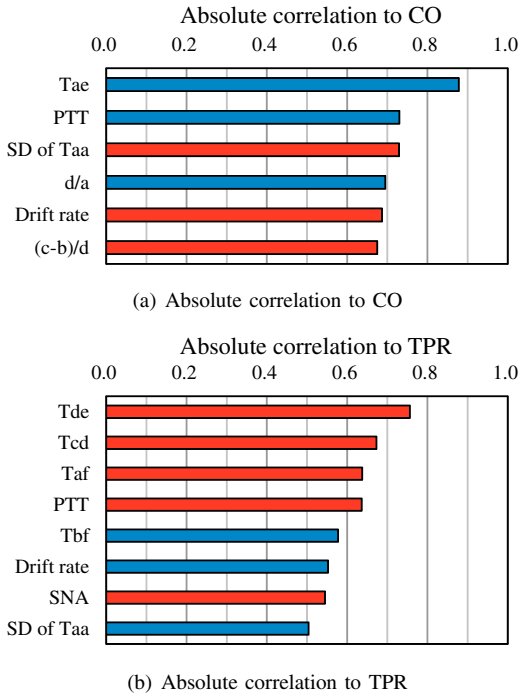
Then, CO and TPR were measured by Finometer Pro, which is a product made by Finapres Medical Systems Corp. [8]. Finometer is a finger type cuff.

We measured the biosignals while they were resting, and also while they raised their leg. The number of data is 28 in total.

Photoplethysmography, CO and TPR are measured at the subject's left arm's fingers. In addition, we measured also their blood pressure defined as the correct value with a cuff (TM-2540R made by A&D Corp.) at their right arm during the same time. The correct mean blood pressure is calculated by measured systolic blood pressure and diastolic blood pressure.

B. Result of regression

Some of features which have greater absolute correlation to CO or TPR than the others are shown (Fig. 5). The red bar means a positive correlation between the corresponding feature and each cardiovascular parameter, and the blue one means a negative correlation.



(a) Absolute correlation to CO

(b) Absolute correlation to TPR

Fig. 5. Some proposed features obtained from only photoplethysmography have correlation to CO or TPR as well as PTT.

We also measured electrocardiogram simultaneously to obtain PTT, too. We do not use PTT as the feature for blood pressure estimation, however PTT has a great absolute correlation to CO or TPR relatively. In general, PTT is a significant index because PTT has the great inverse correlation to blood pressure [9].

Some of our proposed features obtained from only photoplethysmography have absolute correlations to CO or TPR, which is related to blood pressure, as well as with PTT. Therefore, it is effective to use these proposed features for blood pressure estimation.

The result of regression for each cardiovascular parameter is shown (TABLE I).

TABLE I
Result of regression for each cardiovascular parameter

	Correlation
CO vs. eCO	0.92
TPR vs. eTPR	0.87

The result of regression is the correlation between each cardiovascular parameter measured by Finometer and es-

timated parameter. We use these estimated parameters for blood pressure estimation at the next subsection V-C.

C. Result of blood pressure estimation

The result of blood pressure estimation is shown (Fig. 6). The result is the correlation between measured mean blood pressure by a cuff defined as the correct value and the product of eCO and eTPR estimated by stepwise multiple regression analysis using our proposed features obtained from photoplethysmography only.

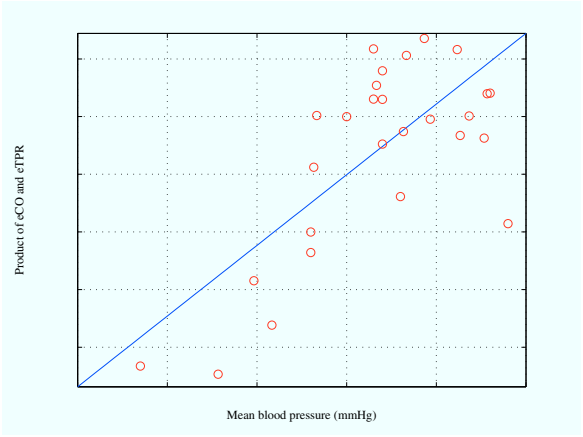


Fig. 6. The product of eCO and eTPR has a correlation to measured blood pressure.

The obtained correlation is shown (TABLE II). Then, the result obtained by measuring CO and TPR with Finometer is also shown.

TABLE II
CORRELATION TO MEASURED MEAN BLOOD PRESSURE

	Correlation
Measured	0.75
Estimated	0.71

The result estimated by photoplethysmography's features is $r = 0.71$. We obtained a result which is closer to the one obtained by Finometer, which is a finger type cuff.

VI. CONCLUSION

In this study, we propose a method of cuffless blood pressure estimation using only a finger type photoplethysmographic sensor. In many previous studies, PTT was used to estimate blood pressure, which needs also measuring electrocardiogram. However, we do not use PTT to have subjects' better usability.

We used the features, the waveform of accelerated plethysmography, SNA obtained by Heart Rate Variability, and Drift rate from photoplethysmography only.

Blood pressure is modeled as the product of CO (Cardiac Output) and TPR (Total Peripheral Resistance) in general. Then, we estimate mean blood pressure as the product of eCO and eTPR estimated by proposed photoplethysmography's features. Many previous studies propose to estimate blood pressure only in general. However, our proposed method can estimate CO and TPR also.

For the experiment, we measured five healthy human subjects' photoplethysmography, and estimated eCO and eTPR with stepwise multiple regression analysis. The result of blood pressure estimation by our proposed method is $r = 0.71$, which is rather close to $r = 0.75$ (the result measured by Finometer, which is a finger type cuff).

Our future work may include verifying with more human test subjects and improving the model to obtain a higher accuracy.

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