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Methods for Assessment of Effects of Habitual Exercise on the Autonomic Nervous Function Using Plethysmogram

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***Abstract*—The present paper has proposed two methods for obtaining the linear correlation of the baroreflex system without measurement of blood pressure. One is based on the pulse wave transit time which needs both the electrocardiogram and the photoplethysmogram. The other is based on the photoplethysmogram only. The results from the experiments showed that the effect of habitual exercise and the Valsalva maneuver can be verified quantitatively. The proposed methods are possible to be used for a test of the autonomic nervous function at home.**

I. Introduction

JAPAN is being a super-aging society, and thus the inflation of nationwide medical cost can be predicted exactly in the very near future. To prevent the crisis in the nation's deficit-ridden health insurance system, we should seriously consider some strategies for protecting people's health.

In this situation, one of the most effective methods is to entrench people to exercise habitually, which may be valid especially for people suffering from metabolic syndrome instructed to the specific medical checkup. To promote habitual exercise, some indices representing the effect of exercise should be fedback to the person after the exercise.

It has been indicated that the index corresponding to linear correlation of the baroreflex system is useful for expressing the autonomic nervous function [1,2]. We adopted this index as information fedback to the person exercising to settle it a habit.

Unfortunately this index needs measurement of continuous blood pressure to calculate. However it is not easy to measure continuous blood pressure because its sensor is too expensive and bulky to use at an ordinary home.

In this article, two alternative methods without measuring continuous blood pressure are introduced. One is a method in which the pulse wave transit time (PTT [ms]) is used instead of continuous blood pressure, and PTT is obtained from electrical cardiogram (ECG) and photoplethysmogram (PPG). The ECG is also difficult to measure at home and should not be used if possible. The other method does not need the ECG signal but linear correlation can be still obtained on the basis of only PPG signal.

In the use of these methods, the effect of habitual exercise on the index was evaluated and Valsalva maneuver was employed to ascertain the capability of the proposed method to extract individual difference from the calculated index.

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II. Methiods

A. Method Based on Pulse Wave Transit Time

Monitoring device

For home use, a measurement device should be wireless with less constraint. There are many monitoring systems but RF-ECG (Micro Medical Device, Inc.) is unique as a very small (40mm×35mm×7.4mm) and light (11.8g including electrical cell) wireless monitoring sensor to measure not only ECG but also acceleration and temperature as shown in Fig.1a).

Fig. 1 Wireless sensors for measuring a) ECG signal and b) photo-plethysmographic signal

However, there is no small sized wireless device which can measure both ECG and PPG signals. In this study, we developed a sensor based on RF-ECG whose input terminal can acquire the PPG signal by attenuating its voltage level as shown in Fig.1b). To avoid the effect of body motion, the PPG signal was measured at the ear lobe and the sensor itself was inserted into a pocket on the chest of the subject's cloth. Another RF-ECG was used simultaneously to measure the ECG signal. Thus, both ECG and PPG signals can be measured in a wireless fashion at the sampling rate of 204Hz with less restriction.

The heart rate HR [bpm] was obtained from the reciprocal of the ECG signal, and PTT was calculated as the interval from the peak time of R-wave of the ECG signal to the peak time of the velocity of the PPG signal. Both PTT and HR were band-pass filtered with a pass band between 0.08Hz and 0.12Hz to be limited to the Mayer wave-related frequency components. After the processing, cross-correlation coefficient $\rho(\tau)$ between these signals was calculated time-discretely as follows:

$$\rho(\tau)=\frac{\phi_{PTT,HR}(\tau)}{\sqrt{\phi_{PTT,PTT}(0)\cdot\phi_{HR,HR}(0)}} \quad (1)$$

where $\phi_{PTT,HR}(\tau)$ is the cross-correlation function between PTT and HR, and $\phi_{PTT,PTT}(\tau)$ and $\phi_{HR,HR}(\tau)$ are auto-correlation functions of PTT and HR, respectively. In this study, $\rho(3)$, i.e., the value of $\rho(\tau)$ at $\tau=3$ s was obtained as an index which represents the linear correlation of the baroreflex system from PTT to HR. The index $\rho(3)$ is more stable value than the conventional index $\rho_{\max}$ which is defined as the maximum value of $\rho(\tau)$ in spite of its lower value.

Experiment

In the experiment, elderly people were used as test subjects classified into two groups. One is the Exercise Group consisting of 8 healthy people (age 52 to 73; mean 65.6±7.7; 4 males and 4 females) exercising habitually for over 15min a week. The other is the Control Group consisting of 8 almost healthy people (age 55 to 75; mean 67.6±6.5; 3 males and 5 females) exercising little

To give dynamic change in subject's hemodynamics by using change in his or her posture, the experimental protocol was as follows:

1) Supine position (5 min)
2) Upright standing position (2 min)
3) Supine position (3 min)
4) Upright standing position (2 min)
5) Supine position (3 min)

B. Method Based Only on Photoplethysmogram

Estimation of cross-correlation function

So far, many methods for obtaining blood pressure based on photoplethysmogram have been proposed, in which, for example, local maximum or minimum values of the acceleration of the signal are utilized. The purpose of these methods is usually to obtain the absolute value of blood pressure. However, if the purpose is to estimate the linear correlation of the baroreflex system, we can do it as shown below.

First, as shown in Fig.2, obtain the feature variables specifying the PPG signal at a certain beat such as the first extremum a and the second extremum b of the acceleration, the second extremum B of the velocity, the mean value MP and the difference PA between the maximum and minimum values of the signal within the beat. Since these variables are sampled every unequally-spaced interval, resample it every equally-spaced interval of 0.2s (5Hz) after the cubic spline interpolation. Let k be a discrete time which is incremented with the resampling, and produce a feature vector given by

$$x(k)=\left[a,b,b/a,a^2,b^2,ab,B/a,MP,PA\right]^T \quad (2)$$

Consider a multiple regression model in which an explanatory variable is $x(k)$ and an objective variable is heart rate $y(k)$ as follows:

$$\hat{y}(k)=\beta^T x(k)+\varepsilon(k) \quad (3)$$

where β is a coefficient vector to be identified with the least square method and $\varepsilon(k)$ is a residue. In general, it is expected that cross-correlation between blood pressure and heart rate whose frequency components are limited to the Mayer wave-related band is maximized a few second later. This phenomenon means that the baroreflex system has a delay. Let denote the delay as L [ms]. Unfortunately, the value of L is changed with time and subjects. Thus, find the optimal values β^* and L^* corresponding to β and L, respectively, so that the error between the $\hat{y}(k)$ and $y(k)$ can be minimized.

Instead of the value of (1), calculate a surrogate value that is obtained by letting $PTT=\hat{y}(k)$ and $HR=y(k)$ in (1). In this case, heart rate $HR=y(k)$ is calculated from the foot-to-foot interval (FFI [ms]) of the PPG.

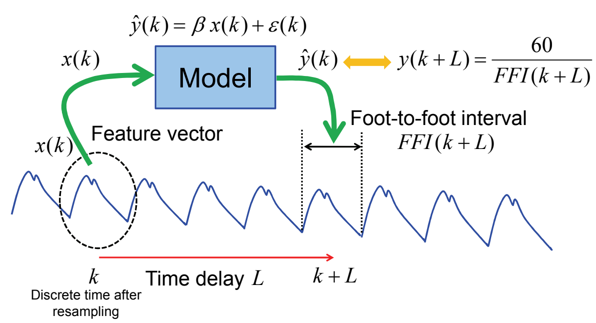

Fig.2 Multiple regression model with the input feature vector of pulse wave for estimation of heart rate.

The reason why the cross-correlation between heart rate and its estimate can be substituted by that between blood pressure and heart rate is shown below. It is known that heart rate correlates closely with blood pressure in the Mayer wave-rerated band at a resting state. If the output of the multiple regression model agrees well with the actual blood pressure, it is likely that the estimate obtained from the model also correlates well with heart rate.

On the other hand, the other method for estimation of blood pressure based on the PPG needs same calibration process using a blood pressure sensor. However, the proposed method employs the subject's heart rate as a reference value to identify the model parameters and does not needs any blood pressure sensor. While the method described in 2.1 which uses the PTT requires the ECG sensor to specify the position of the R-wave, the proposed method uses only the PPG sensor which is cheap and expected to be widely spread.

Estimation of cross-correlation function

Thirty-two healthy subjects (Age 23.1±3.6; 24 males; 8 females) were used in an experiment including the Valsalva maneuver with a protocol as follows:

1) Rest (5 min)
2) Respiration cease (1 min)
3) Rest (3 min)
4) Respiration cease (1 min)
5) Rest (5 min)

A photo sensor and an amplifier for (BIOPAC; PPG100C) was used to measure the PPG signal at the index finger and blood pressure sensor (Finapres; Portapres) was used to measure continuous blood pressure at the middle finger.

III. RESULTS AND DISCUSSION

A. Method Based on Pulse Wave Transit Time

Figure 3 shows a subject's data (Age 70; female; systolic/diastolic pressure=136mmHg/84mmHg) who was a member of the Exercise Group. The data are time courses of heart rate, HR, the normalized PTT to have zero mean and unit standard deviation, and the cross-correlation coefficient at $\tau = 3$, $\rho(3)$. At two parts of the upright standing position, HR increased like a rectangular shape, which corresponds to normal orthostatic baroreflex to regulate blood pressure. It is found that PTT also increased in the similar manner as HR but their shapes are not so similar. Decrease in $\rho(3)$ can be seen at the two parts around upright standing positions.

Figure 4 shows another subject's data (Age 72; female; systolic / diastolic pressure= 155mmHg / 102mmHg) who was a member of the Control Group. Unlike Fig.4, hear rate HR changed irregularly, which means the baroreflex did not work well. Moreover, the shape of PTT is very similar to that of HR. This fact may be caused by arterial sclerosis since she had light hypertension and she was taking depressor drug routinely. That is to say, the change in HR may be equal to that of PTT if blood vessel is like a lead pipe with less compliance. The absolute value of $\rho(3)$ was small and drifted around zero during the experiment, which implies that the regulation function manipulating HR based on blood pressure with 3 seconds delay was not well done by the autonomic nervous system.

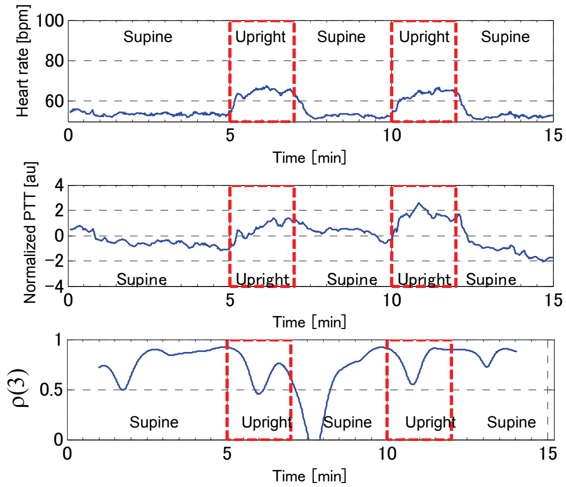

Fig.3 a)heart rate, b)normalized PTT and c)cross-correlation function $\rho(3)$ of a subject belonging to the Exercise Group (female; age 70; Systolic / diastolic pressure = 136mmHg/84mmHg).

Figure 5 shows the comparison of the mean value $\rho(3)$ between the Exercise and the Control Groups. It is found that the recovery speed of $\rho(3)$ of the Control Group was significantly lower than that of the Exercise Group in the interval between two upright standing positions. It can be guessed that this difference was caused by the effect of habitual exercise.

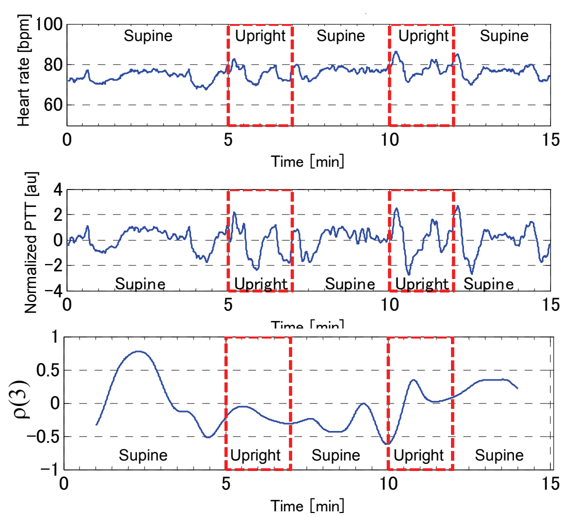

Fig.4 a)heart rate, b)normalized PTT and c)cross-correlation function $\rho(3)$ of another subject belonging to the Control Group (female; age 72; Systolic / diastolic pressure = 155mmHg /102mmHg).

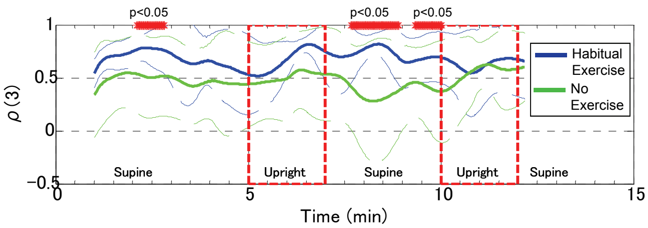

Fig.5 Comparison of $\rho(3)$ between the Exercise Group (n=8) and the Control Group (n=8). Solid line: mean. Broken line: S.D.

B. Method Based Only on Photoplethysmogram

The mean value of thirty-two subjects' $\rho(3)$ obtained from the method based only on the PPG signal described in 2.2 are shown in Fig.6, accompanied by $\rho(3)$ calculated directly from measured blood pressure. The figure indicates that $\rho(3)$ based on the PPG is much lower than $\rho(3)$ based on the blood pressure and that the effect of respiration cease on the time trajectories was not clear in both two kinds of $\rho(3)$ s. The reason is that the data shown in Fig.6 includes the subjects whose $\rho(3)$ is low even in the resting state. It can be guessed that such subjects tend to have a dull autonomic nervous reflex function against the respiration cease.

Thus, the subjects were selected under the condition that the mean value of $\rho(3)$ in the resting state from 0min to 4min was higher than 0.5. There were 9 subjects who satisfy the condition, and the mean value of $\rho(3)$ of these subjects is shown in Fig.7. It seems that the decrease in $\rho(3)$ around the positions of the respiration cease got deep.

In the same way, when the threshold to select the subjects was increased to 0.7, four subjects survived and their mean value of $\rho(3)$ was shown in Fig.8. It can be found that the depth of the decrease around the respiration cease tended to get deeper and that the value of $\rho(3)$ based on the PPG in the resting state came closer to that based on the blood pressure.

These results suggest that the temporal change in the linear correlation of the baroreflex system can be estimated on the basis of the PPG signal only without measurement of the ECG or blood pressure. Moreover, it is possible that $\rho(3)$ based on the PPG is more sensitive to the effect of the respiration cease than $\rho(3)$ based on blood pressure.

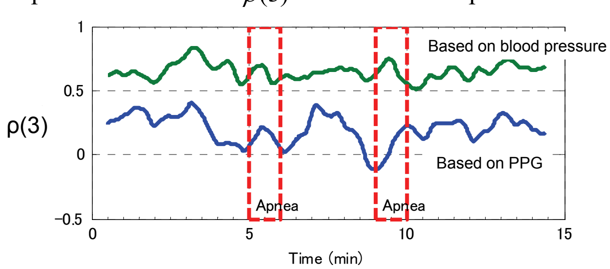

Fig. 6 Mean value of $\rho(3)$ over all 32 subjects.

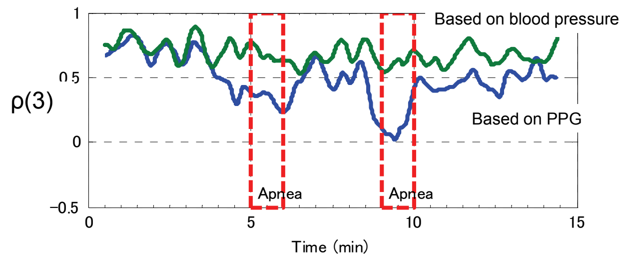

Fig.7 Mean value of $\rho(3)$ over 9 subjects whose mean value is larger than 0.5 from 0min to 4min.

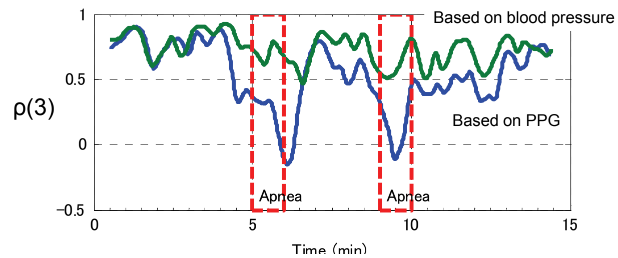

Fig.8 Mean value of $\rho(3)$ over 4 subjects whose mean value is larger than 0.7 from 0min to 4min.

IV. CONCLUSIONS

The present study has developed two methods for obtaining the linear correlation of the baroreflex system without measurement of blood pressure. One is based on the pulse wave transit time which needs both the ECG signal and the photoplethysmogram. The other is based on the photoplethysmogram only. The results from the experiment with the former method showed that the effect of habitual exercise can be verified quantitatively. The latter method indicated that the response of the linear correlation to the Valsalva maneuver can be estimated. The proposed methods are possible to be used for a test of the autonomic nervous function easily even at home.

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