A Method to Estimate Peripheral Systolic Blood Pressure using Pulse Transit Time during Bicycle Ergometer Exercise of Healthy Korean Subjects in their Twenties

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Abstract

A simple algorithm that can be used to estimate a healthy person's blood pressure using pulse transit time is proposed in this paper. Fifty healthy students participated in the experiment that was conducted in line with the study. The subjects were asked to exercise on several exercise levels using a bicycle ergometer. Their blood pressures during the succeeding rest period were measured.

A simple method was proposed to illustrate the relationship between blood pressure and pulse transit time. The systolic blood pressures as well as the heights and weights of the subjects were regarded as the proper parameters, and a second-order regression curve was produced to estimate the subjects' blood pressures. The mean error of estimation was less than 10 mmHg, which was the mean error of manual measurement. Although our estimation model is so simple, it can be used to estimate continuous blood pressure measurement for bicycle ergometer exercise. The electrocardiograms, photoplethysmograms, and blood pressures, however, could not be measured simultaneously. As such, their estimation may be slightly different from the results taken from simultaneous measurements.

Key words : blood pressure, pulse transit time, photoplethysmogram, bicycle ergometer

I. INTRODUCTION

A person's blood pressure can provide information about his cardiovascular state during exercise or when in a normal state. Especially, in the exercise state, the alarm system can prevent the exerciser from getting a heart attack, and can also prevent other urgent, critical situations from occurring. Nevertheless, however, blood pressure cannot be measured while a person is exercising.

In this paper, a blood pressure estimation method during exercise, using pulse transit time (PTT) and a bicycle ergometer, is proposed.

The measurement of the blood pressure (BP) can be classified into invasive and non-invasive methods. The invasive method measures the blood pressure through the insertion of a catheter into the peripheral artery. This method is very direct and accurate, but is not easy to use, especially for continuous, long-term measurement. One of the non-invasive methods, on the other hand, measures the blood pressure by wrapping a cuff around the arms or legs [10]. This method is simple and easy to use, but is indirect and, therefore, inaccurate. But with such a method, long-term observation is possible.

In this study, the non-invasive method was used to estimate the peripheral blood pressure because the subjects were healthy and monitoring can be easily conducted on them. This means that a lower degree of accuracy of the estimation of their blood pressures can be allowed as compared with unhealthy patients, and also means that it is a useful method in carrying out regular check-ups of one's health.

The parameter that was used for blood pressure estimation was pulse transit time (PTT), which is the time difference between an r-peak of electrocardiogram and a subsequent characteristic point of photoplethysmogram (PPG) [1]. The wave of PPG is easily affected by various clinical conditions, such as its sensing point and the subject's posture [3, 7, 8, 12]. As such, the subject should not move while the wave of PPG is being measured.

Several researches used PTT to estimate blood pressure [2, 11], but the methods that were used in such studies were too difficult and complex for commercial applications. Thus, a simple model for estimating blood pressure using PTT was proposed in this study. The problem of exercising on the bicycle ergometer that might be commercialized to complement

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one's personal fitness is so specific that it does not need to be too complex. Estimation of blood pressure in such condition-specific exercise for healthy young people can be simplified and easily conducted.

Therefore, in this paper, we propose a simple algorithm of blood pressure estimation and report several results obtained from the experiment and estimation procedures.

II. MATERIALS AND METHODS

A. Subjects

Fifty healthy 24 ± 2.3-year-old students (45 men and 5 women) participated in the experiment that was conducted in line with this study. In the first experiment, 10 subjects participated in the same way for 10 days (1 experiment per day, for a total of 10 days). In the second experiment, 40 subjects took part in a single measurement, which was the same as the first experiment's protocol.

B. Experimental Procedure

The experiment consisted of five exercise periods alternating with five rest periods (blood-pressure measurement was conducted twice). A normal-exercise ECG measurement method was applied to the subjects. PPG sensors (PPG Kit v2.4, Physiolab Co., Ltd, Korea) were attached to the left ears of the subjects, because other part such as finger tip is more affectable than ear against motion artifacts. If the motion artifacts are not eliminated, it is difficult to detect the characteristic point of PPG, therefore, to reduce the motion artifacts more, we fixed the lead to the lower jaw and the ergometer. Their signals were transmitted by physiography (PowerLab/800, ADInstruments, Australia) and were converted to digital signals (400 Hz). The subjects' blood pressures were measured using a cuff-type blood pressure measuring system (MEK PI-z30526). The mean error of this module was about 10 mmHg.

The subjects were made to exercise, using bicycle ergometers (Spokhan 6300, SpotecKorea Co., Ltd, Korea), to produce a change in their bodies' blood pressure. Different, gradually increasing exercise load levels were assigned to five exercise periods. The levels were called 1, 2, 3, 4, and 5 (no unit), respectively.

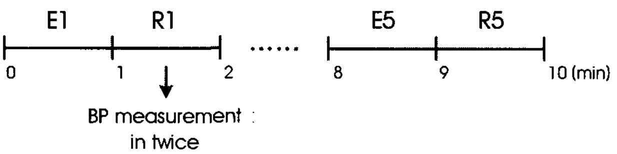

Fig. 1. Experimental protocol (Ei: i-th exercising period; Ri: i-th resting period)

The experiment lasted for a total of 10 min. It consisted of five exercise stages, where the ECG and PPG were simultaneously measured, and five rest stages, where the subjects' blood pressures were measured twice.

C. Calculation of Pulse Transit Time

The PTT was calculated from the ECG and PPG data that were obtained. It was calculated based on the time difference between the r-peak of the ECG and the second derivative point of the PPG (Fig. 2). The second derivative point of the PPG was regarded as an adequate characteristic point of the PPG signal because this point can be easily detected and has relatively small variations in the PTT calculation in a single data set [5]. The PTT was regarded as the mean value of all the PTT data in a session.

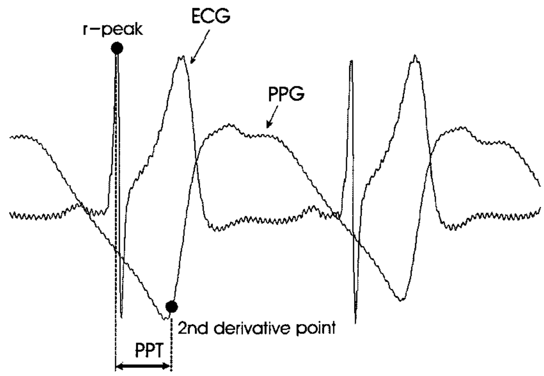

Fig. 2. Characteristic points of ECG and PPG for PTT calculation

D. PTT Normalization

The PTT can be affected not only by blood pressure but also by other factors, such as the elasticity of the vessel, the viscosity of the blood, and the subject's posture, height, and weight. Thus, these factors must be controlled when estimating the BP using the PTT. This is called the normalization of the PTT.

Many methods can be used to normalize the PTT value. In this paper, the subjects' heights and weights were used as normalizing factors. The elasticity of the vessel and the viscosity of blood should be measured using invasive methods, and can pave the way for more exact results when estimating blood pressure. The setting used in this experiment coincided with what were assumed to be the everyday exercise conditions of a healthy person. Thus, in this setting, the invasive variables of the subjects usually could not be measured. Moreover, it was assumed that the subjects' weights were related to the viscosity of their blood, as seen in the fat present in their blood vessels; that the subjects' heights reflected the absolute propagation time of the blood from the subjects' hearts to their ears; and that the elasticity of the blood vessels is not easily changed in the short-term estimation setting, which resembles the experimental setting in this paper as well as routine exercise environments. Consequently, the normalization of the PTT using the heights and weights of the subjects (sec/meter/kg) has an advantage: generic models of blood pressure estimation can be made across the subjects. The person-specific estimation model of blood pressure make the error rate lower, but we want to propose a general estimation model, which can be used for most healthy people.

E. BP Estimation Model using the Normalized PTT

Models that estimate the blood pressure measured after the exercise were constructed, using the mean PTT value measured during the exercise session.

In this study, two models were used, namely: the second-order regression curve in the normalized PTT and the BP domain; and the first-order regression curve in the log-log domain (its order was decided empirically).

The second-order regression curve in the normalized PTT and BP domain was obtained using the data derived from the first experiment. The same is true for the first-order regression curve in the log-log domain.

The estimated value of blood pressure can be calculated by regression curve model. After we designed a regression curve from the obtained data, the blood pressure related to specific PTT can be estimated through the regression curve not through the obtained data, like a function.

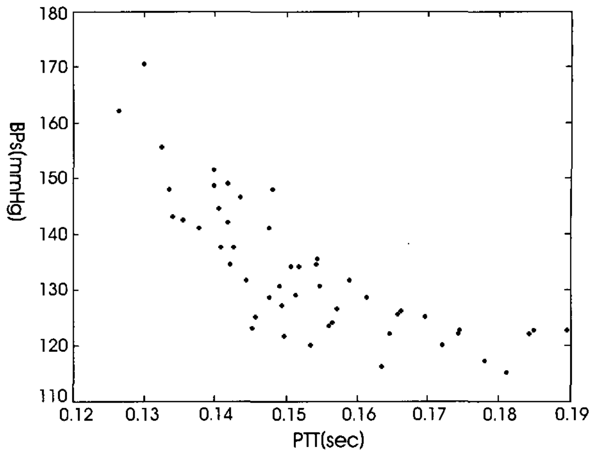

Fig. 3. Relation between PTT and systolic blood pressure

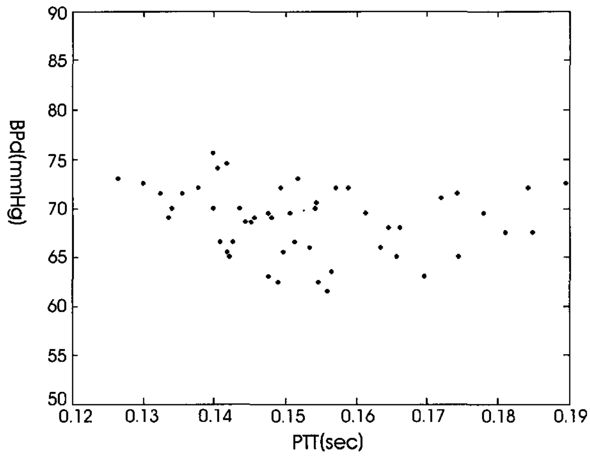

Fig. 4. Relation between PTT and diastolic blood pressure

Ⅲ. RESULTS

Among the 140 experimental cases (10 repeated experiments involving 10 subjects, and one experiment involving each of 40 subjects), two cases were omitted in the analysis by technical mistakes.

A. Correlation between Blood Pressure, Exercise Level, and PTT

Figs. 3 and 4 and Table 1 show the relations between the systolic BP and the PTT, the diastolic BP and the PTT, and the systolic BP and the exercise level, respectively. These show that the systolic BP can be estimated using the PTT, and that the exercise level may be a useful variable for estimation purposes. The diastolic BP, however, cannot be estimated using the PTT.

Table 1. Relation between Systolic Blood Pressure and Exercising Level (strength)

Exercising Level	Systolic Blood Pressure
1	116 ± 9 mmHg
2	120 ± 9 mmHg
3	126 ± 11 mmHg
4	133 ± 12 mmHg
5	144 ± 17 mmHg

B. Blood Pressure Estimation using the Normalized PTT

The data that were obtained from the first experiment were used as a training set, and the data that were obtained from the second experiment were used as a test set.

The indices of the estimation error are the mean and standard deviation of the different values between the real systolic blood pressure and the estimated systolic blood pressure calculated from regression curve.

C. PTT Normalization using Height and Weight

Based on the results of the preliminary analysis, the normalization method using both height and weight was chosen over that using height alone. Fig. 5 shows the second-order regression curve with respect to the normalized PTT by both height and weight.

The first-order regression curve in the log-log domain shows larger errors (more than 10 mmHg) than those shown by the second-order regression curve in the normalized PTT and the BP domain.

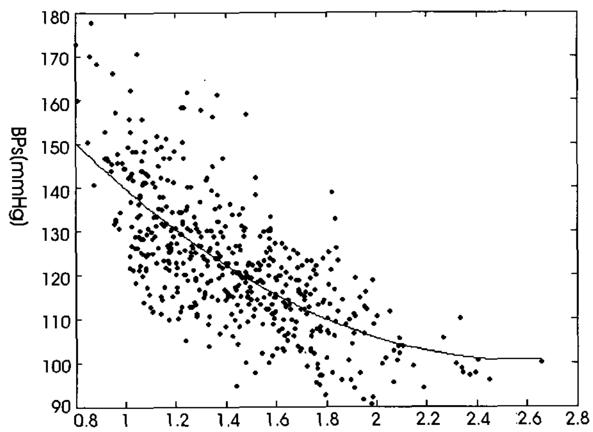

Fig. 5. 2nd regression curve between normalized PTT and systolic blood pressure.

In Fig. 6, the estimation results and the error of estimation, both using the mean PTT and the near-PTT, are compared. Near-PTT refers to the several latest PTT values before the BP was measured. Interestingly, the result shows an estimation using the mean PTT, which has lesser estimation errors than that observed with using near-PTT. The estimation errors obtained by using mean-PTT was 5.89 ± 0.72mmHg, and near-PTT was 6.61 ± 0.94mmHg (p-value < 0.1).

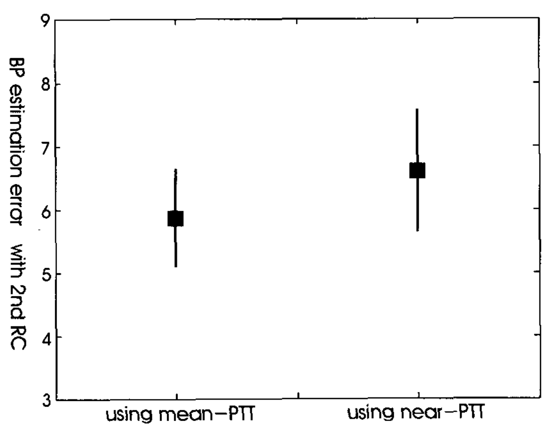

Fig. 6. Blood pressure estimation error for mean-PTT and near-PTT

IV. DISCUSSION AND CONCLUSION

The estimation of blood pressure during exercise can be useful not only in preventing an emergency situation during exercise but also in determining the proper amount of exercise that individuals should have.

Height and weight were found to be significant parameters for the estimation of blood pressure, but the exercise level was not. Sex of subjects was not considered, because we want to propose a simple and general model to estimate blood pressure. Ages of subjects was not also considered in that our age of interest is limited to young person. Ifwe want to propose an age-independent general model, the estimation error may be increased. In that case, the general model may be designed for several groups according to the ages, such as, twenties, thirties, forties, and others. Or estimation model have to be sophisticated.

It was likewise found that second-order regression is a suitable method for estimation in the normalized PTT and the BP domain. Its mean error of estimation is less than 10 mmHg.

An attempt was made to estimate the systolic blood pressure through non-invasive methods using the subjects' PTT, heights, and weights. First, the PTT was normalized, using the heights and weights of the subjects, to come up with a generic estimation model. The second-order regression shows the best estimation result within an allowable error. The mean estimation error is smaller than 10 mmHg for the reference, and the mean error of the manual measurement of the BP is around 10 mmHg.

The protocol that was used in the experiment, however, has a limitation. The blood pressure, PPG, and ECG could not be measured simultaneously. As a result, the PPG and ECG data obtained in the exercise session can therefore be used to estimate the blood pressure during the rest session.

For a more precise study, the ECG and the PPG have to be measured simultaneously with the blood pressure in the experiment. At bottom, the PPG signal has to be easily and robustly measured irrespective of the motion of subject by selecting of the proper sensing point. And more proper parameters, which can reduce the estimation error and easily measured, have to be proposed.

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