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An Evaluation of a PTT-Based Method for Noninvasive and Cuffless Estimation of Arterial Blood Pressure

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Abstract—**The aim of this study is to determine if a noninvasive and cuffless blood pressure (BP) estimation method using pulse transit time (PTT) can accurately track the changes in BP after a treadmill exercise. Experiments were conducted on 12 healthy subjects, who were directed to run on a treadmill at 10 kph for 4 minutes. For each subject, 13 trials were recorded in total, including 11 trials obtained immediately after exercise and during the 60-minute recovery period. BP was measured at the finger by the Finometer and at the brachial arteries by a sphygmomanometer respectively. PTT was determined as the time interval between the peak of the electrocardiogram R wave and the foot of the photoplethysmogram. Both PTT-based device and Finometer were calibrated initially and Finometer calibration was also performed after exercise to the sphygmomanometer. Experimental results showed that there was only occasional discrepancy between BPs measured by Finometer and PTT-based device during the recovery period, i.e., at 5 minutes after exercise (p = 0.008 for systolic BP and p = 0.03 for diastolic BP). At all other post exercise time spots there were no significant differences between BPs measured by Finometer and PTT-based device.**

I. Introduction

Noninvasive and cuffless measurement of arterial blood pressure (BP) is desirable for patient monitoring, whether in hospitals or at home. Several methods to measure BP noninvasively and continuously are arterial tonometry, volume clamp method, and pulse transit time (PTT)-based method.

Using an array of pressure transducers to press against the skin over an artery, arterial tonometry can measure BP continuously [1, 2]. The hold down pressure is less than arterial pressure; therefore, the artery is not occluded. Arterial pressure waveforms are transmitted directly to the transducer. The system must be calibrated and this can be done with systolic and diastolic measurements from a standard arm cuff oscillometric technique. However, the arterial tonometer suffers from relatively high cost when compared with a conventional sphygmomanometer and its accuracy is decreased by wrist movement [3].

Finometer continuously measures finger arterial BP using the volume clamp method proposed by Peňáz [4]. In this method, a small inflatable cuff containing an infrared photoplethysmograph is applied to one of the subject's fingers. The pressure in cuff first inflates to a pressure equal to the mean pressure in the artery, and the cuff pressure is continuously adjusted by a servo control system to maintain the transmural pressure at zero as determined by the finger photoplethysmograph. Finometer enables beat-to-beat non-invasive assessment of BP and therefore it has been used to track BP changes [5-7].

An alternative method for continuous measurement of BP is the evaluation of the relationship between PTT and BP [8-12]. The PTT-based method has several advantages over volume clamp method because it requires only the electrocardiogram (ECG) and the photoplethysmogram (PPG) and there is no danger of cessation of perfusion to the finger due to the long-time applying pressure on finger in Finometer measurement. It is believed that PTT-based method also has the potential in tracking BP changes. Therefore, the aim of this study is to evaluate the accuracy and reliability of the PTT-based method in tracking BP changes after a treadmill exercise by comparing with simultaneous Finometer measurements.

II. Methodology

Experiments were conducted on healthy, non-smoking and normotensive subjects aged 21-28 years old (24.3±2.8 years), including 8 males and 4 females. The experiment was carried out in a temperature-controlled room (24±2°C). Upon their arrival, subjects were asked to sit down and relax for 10 min in order to allow their BP to become stable. Later on all subjects were directed to run on a treadmill (Model C956, Precor, USA) at 10 kph for 4 min.

In the experiment, the ECG and the PPG were recorded simultaneously at a sampling rate of 1 kHz for each channel and digitized by a 12-bit A/D converter. ECG was monitored by standard lead I. Reflective PPG was recorded at the fingertip of the index finger of the right hand. BP was measured by the Finometer (FMS, Finapres Medical Systems BV, The Netherlands) from the middle finger of the right hand simultaneously. BP recordings obtained from Finometer were converted to digital form at a sampling rate of 1 kHz by a 12-bit A/D converter. BP was also measured by a sphygmomanometer (TXJ-10, Desk Model, Japan) at brachial arteries by an experienced registered nurse. Measurements were carried out at 2-minute interval for two times before exercise, restarting "immediately" after exercise (as soon as practically possible). During the 60-minute recovery period BP measurements as well as the ECG and the PPG recordings were made at 5 min, 9 min, 15 min, 20 min, 25 min, 30 min, 40 min, 50 min, 55 min, and

60 min. Each trial was recorded for 20 sec, except for the one obtained immediately after exercise, which was recorded for 5 min.

Using the peak of the ECG R wave and the foot of the PPG, the beat-to-beat PTT and the mean of the PTT for the 20-second period were calculated for each trial. For the trial recorded immediately after exercise, which lasts for 5 min, data recorded in the first 20 sec were analyzed.

An initial calibration of the PTT-based device and Finometer was performed by entering the reference BP values obtained from the sphygmomanometer, which is considered by many to be the gold standard in general practice. For PTT-based device, the recordings of the first trial were used for calibration and the remaining trials were used for BP estimation. Additional calibration was carried out for Finometer after exercise when finishing the initial signal recording of 5 min.

Student *t*-test was used to determine the differences between the measurements obtained by two methods. $p < 0.05$ was considered statistically significant.

III. Results

The BP measured before exercise was used as the baseline. As shown in Fig. 1, immediately after exercise, brachial systolic blood pressure (SBP) measured by the sphygmomanometer was elevated from the baseline of 110.1±12.6 mmHg to 149.0±21.0 mmHg ($p < 0.001$) and by 5 min after exercise SBP was only slightly higher than pre-exercise baseline ($p = 0.057$). Brachial diastolic blood pressure (DBP) was reduced from the pre-exercise baseline of 72.3±8.6 mmHg to 63.8±10.7 mmHg immediately after exercise ($p = 0.045$) and by 5 min after exercise it was only slightly lower than pre-exercise level ($p = 0.539$). Table 1 gives the BP measurements obtained at specific times after exercise.

Blood pressure was measured at the finger by volume clamp method and also estimated by PTT-based method. Fig. 2 shows the changing trend of post exercise BP obtained by these two methods respectively. SBP measured by Finometer was significantly higher than the baseline immediately after exercise ($p = 0.009$) and by 5 min after exercise ($p = 0.032$). The responses of DBP to exercise were similar to SBP. DBP significantly higher than pre-exercise immediately after exercise ($p = 0.003$) and by 5 min after exercise ($p < 0.001$). For PTT-based method, immediately after exercise BP was significantly higher than pre-exercise ($p = 0.012$ for SBP and $p = 0.016$ for DBP). However, no differences in SBP and DBP were noted when comparing the baseline and BP readings obtained by 5 min after exercise ($p = 0.473$ for SBP and $p = 0.484$ for DBP).

The differences between BP measured by volume clamp method and PTT-based method at specific times were assessed by *p*-value (Table 2). Besides the measurements made by 5 min after exercise, there was no significant difference between the measurements obtained by these two methods.

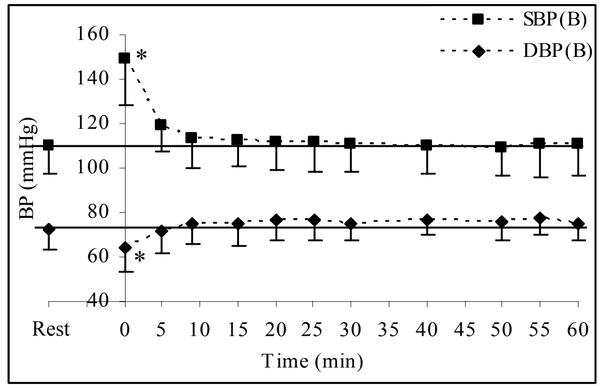

Fig. 1. Blood pressure measured by sphygmomanometer before and after exercise. Blood pressure different from the baseline at rest,* $p < 0.05$.

TABLE 1
BRACHIAL BLOOD PRESSURE MEASURED BY SPHYGMOMANOMETER AT SPECIFIC TIMES AFTER EXERCISE

Time (min)	SBP (mmHg)	DBP (mmHg)
0	149.0±21.0	63.8±10.7
5	119.5±12.0	71.3±9.6
9	113.0±12.8	74.8±8.8
60	110.8±14.5	75.3±7.6

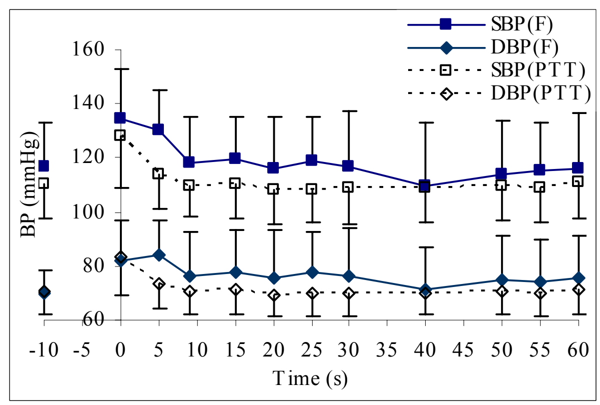

Fig. 2. Blood pressures measured by Finometer and estimated by PTT-based method before and after exercise. Finometer (F), PTT-based method (PTT).

TABLE 2
COMPARISON BETWEEN THE BP MEASUREMENTS OBTAINED FROM FINOMETER AND PTT-BASED DEVICE AFTER EXERCISE

Time (min)	Finometer SBP (mmHg)	PTT-based SBP (mmHg)	*p* value
0	134.8±18.2	128.1±19.3	0.391
5	130.2±15.0	113.7±12.5	0.008
9	117.9±17.4	109.8±11.7	0.193
60	116.1±20.2	110.8±13.4	0.457

Time (min)	Finometer DBP (mmHg)	PTT-based DBP (mmHg)	*p* value
0	82.1±14.6	83.3±13.9	0.830
5	84.3±12.9	73.6±9.3	0.030
9	76.2±16.6	70.7±8.3	0.314
60	75.6±15.9	71.3±9.2	0.432

IV. Discussions and Conclusions

The results show that the BP measured by volume clamp method and PTT-based method had similar decreasing trend after a treadmill exercise. Significant difference between the measurements made by these two methods was found only at 5 min after exercise. At that time spot, BP estimated by PTT was not significantly different from the readings obtained by sphygmomanometer (p = 0.262 for SBP and p = 0.568 for DBP). Whereas, the differences between the BP measured by Finometer and sphygmomanometer were not significant for SBP (p = 0.067) but significant for DBP (p = 0.011).

Resting SBP measured by Finometer was slightly but not significantly higher than that measured by sphygmomanometer (117.0±16.4 mmHg vs. 110.0±12.6 mmHg, p = 0.195), whereas DBP was slightly but not significantly lower (69.7±8.5 mmHg vs. 72.3±8.6 mmHg, p = 0.792). These results were consistent with previously reported tendency for the Finometer to give slightly higher systolic but slightly lower diastolic readings than the brachial sphygmomanometer at resting stage [6]. Immediately after exercise, SBP measured by sphygmomanometer was higher than that measured by Finometer (p = 0.09), after which the two measurements returned to their pre-exercise relationship. Brachial arterial pressure thus exceeded finger arterial pressure only when SBP was acutely elevated. Immediately after exercise, DBP measured by sphygmomanometer was significantly lower than that measured by Finometer ($p < 0.001$), and slightly but not significantly lower by 9 minutes after exercise (p = 0.799), and then they tended to return to their original relationship.

The BPs estimated by PTT-based method was not different from those measured by sphygmomanometer at resting stage. Immediately after exercise, the measured brachial SBP was significantly higher than the estimated SBP (149.0±21.0 mmHg vs. 128.1±19.3 mmHg, p = 0.019) and the measured brachial DBP was significantly lower than the estimated DBP (63.8±10.7 mmHg vs. 83.3±13.9 mmHg, p<0.001), after which, i.e. 5 min after the exercise, the estimated BP followed the BP measured by the sphygmomanometer.

It was observed that after exercise SBP dropped very quickly within 5 min. The discrepancy between the brachial BP measured by sphygmomanometer and BP measured by volume clamp method as well as PTT-based method in the early post exercise stage may partly attribute to the following two reasons. First, brachial BP was measured immediately after exercise with almost no time delay. However, time was needed to set up the Finometer, therefore, Finometer recording as well as PPG and ECG recording were 1-2minutes later than brachial BP measurement. Second, the volume clamp technique employed by the Finometer and PTT-based method may have systematic differences from the auscultatory one used in sphygmomanometer. Moreover, the performance of Finometer and PTT-based device depends to some extent on the calibration. It is expected that calibration performed immediately after exercise may reduce the discrepancy between the BP measurements made by the sphygmomanometer and Finometer as well as PTT-based device.

Immediately after exercise, both PTT-based method and volume clamp method tended to give the DBP readings higher than those measured by sphygmomanometer. It has been reported in several previous studies [13-15] that DBP measured by auscultatory method showed that it decreased immediately after exercise. Such post exercise hypotension has been observed in response to large-muscle dynamic exercise, including walking and running. The discrepancy between the DBP measurements obtained by different devices is suspected due to different mechanism of BP measurement.

In summary, the results suggested that the responses of PTT-based method to the treadmill exercise were similar to that of the volume clamp method. Only occasional discrepancy between the BP measured by these two methods was found during the post exercise period. Although the performance of PTT-based method in more diverse experimental protocol remains to be determined, this approach shows a great potential as a noninvasive and cuffless alternative for developing wearable BP monitoring devices.

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