A New Method for Unconstrained Pulse Arrival Time (PAT) Measurement on a Chair

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Abstract

A new method of measuring pulse arrival time (PAT), which is usually used for the estimation of systolic blood pressure, in an unconstrained manner using a chair, is proposed. The capacitive-coupled ECG (CC-ECG) measurement system and the air cushion with balancing tubes system were used for unconstrained PAT measurement. Firstly, the correlation between the standard PAT (S-PAT) from the photoplethysmography (PPG) and the PAT measured in an unconstrained manner (U-PAT) was evaluated. It was observed that U-PAT, which is the time delay from the R-peak of ECG to the steepest decent point of air cushion pressure wave, is significantly correlated with the S-PAT. Secondly, systolic blood pressure (SBP) measured by the radial tonometer is compared to the U-PAT. The ten-beat averaged U-PAT removed respiration effects and demonstrated a high intra-subject correlation with SBP in all participants. Finally, the tonometry SBP was estimated from these U-PAT values for one participant intermittently during half a day.

Key words : pulse arrival time (PAT), blood pressure, unconstrained, ubiquitous healthcare

I. INTRODUCTION

PULSE arrival time (PAT) can be defined as the duration from the R-peak of the electrocardiogram (ECG) to a feature point of the pressure or volume pulse waves measured in the peripherals. The PAT is usually being studied to estimate the systolic blood pressure (SBP) continuously, which is based on the several previous studies about the significant correlations between the blood pressure and the PAT [1-8]. Bramwell and Hill explained the relationship between the PAT and the SBP using the equation,

$$PWV^2 = (L/PAT)^2 = (\Delta P \cdot V)/(\Delta V \cdot \rho)$$

where PWV = pulse wave velocity, L = length, PAT = pulse arrival time, ΔP = change in pressure, V = initial volume, ΔV = change in volume, and ρ = density of fluids. This equation shows that the higher BP, the shorter PAT [9].

For the non-invasive PAT measurement, the volume pulse wave was generally recorded using the ECG and the photoplethysmography (PPG) [8, 10, 11]. The PAT measurement methods as a non-invasive parameter, however, limit long-term monitoring because of the attachment of ECG electrodes, PPG sensors, and cables. These constraints may be similar even to those of the oscillometric method. For the ubiquitous healthcare, unconstrained PAT measurement techniques will be required without any constraints. In this study, a new method for the minimally constrained measurement of PAT using a chair, which is one of the objects used most in daily life, is proposed.

The minimally constrained (unconstrained) PAT (U-PAT) using a chair can be measured using the capacitive-coupled ECG (CC-ECG) measurement system and the air cushion system with balancing tubes as shown Figure 1. The CC-ECGs are detected from two insulated capacitive sensors on the back of the seat and conductive sheet below the hips as the reference [12].The R-peaks of the CC-ECG agreed perfectly with the R-peaks of a standard ECG in the previous experiments using the same filter settings [12]. The air cushion system under the femoral arteries emits the differential signal from another air cell connected by the balancing tubes [13, 14]. This

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signal is thought to reflect not only the ballistocardiogram, but also the volume and pressure variation of femoral arteries and other arteries following the heart beats.

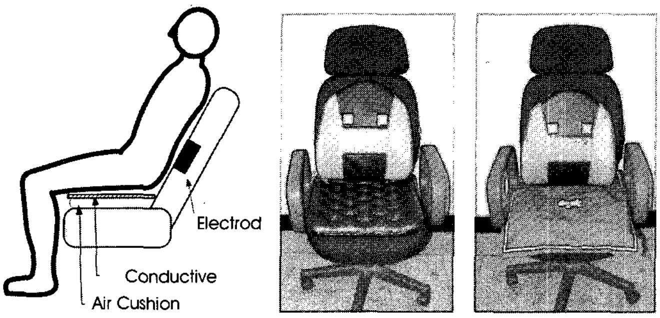


Fig. 1. Unconstrained PAT measurement on a chair with capacitive-coupled ECG (CC-ECG) measurement system and air cushion balancing tubes.

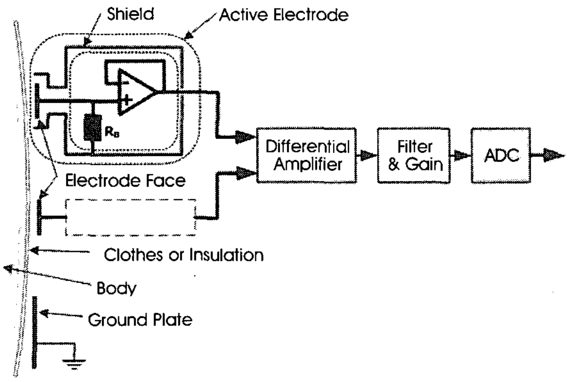
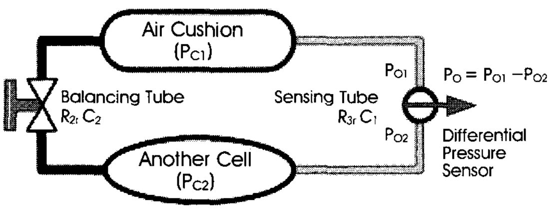


Fig. 2. Diagram of capacitive-coupled (CC-ECG) measurement system



$$R_1C_1\frac{dP_O}{dt}+P_O=P_{C1}-P_{C2}$$

$$R_2C_2\frac{dP_{C2}}{dt}+P_{C2}=P_{C1}$$

Fig. 3. Schematic diagram of air cushion system with balancing tubes

In this paper, the U-PAT obtained from the CC-ECG and air cushion system is compared with the typical PAT using the photoplethysmography (PPG), and then the intra-subject correlation between U-PAT and SBP is investigated during conditions of changing blood pressure.

II. METHODS

A. Participants

Three healthy males participated in this study. Their ages were 25, 27, and 29 years and they had no history of cardiovascular disease. One volunteer participated in experiments for the comparison of U-PAT to S-PAT, and the study of U-PAT in intermittent BP monitoring.

B. Materials

The ECG and air cushion pressure wave are needed to obtain a U-PAT. The ECG was measured by a capacitive-coupled measurement system on a chair as shown in Figure 1. This system has two active electrodes and a capacitive ground within the seat cushion. The two active electrodes are shielded and have their own pre-amplifier which transfers the displacement current through the insulation into the voltage. These signals from two pre-amplifiers are differentiated by a differential amplifier and the differential signal is filtered with the bandpass a filter of which bandwidth is 1 to 200 Hz. The capacitive ground is used for the reference electrode that is conductive sheet within the seat cushion. Figure 2 is the block diagram for the capacitive-coupled ECG (CC-ECG) measurement.

The air cushion system for measuring the pressure wave is constructed with a main air cushion, another air cell, and balancing tubes which is performed as the high pass filter to the DC offset such as the motion or the respiration. The schematic diagram of the sir cushion system shows as the Figure 3.

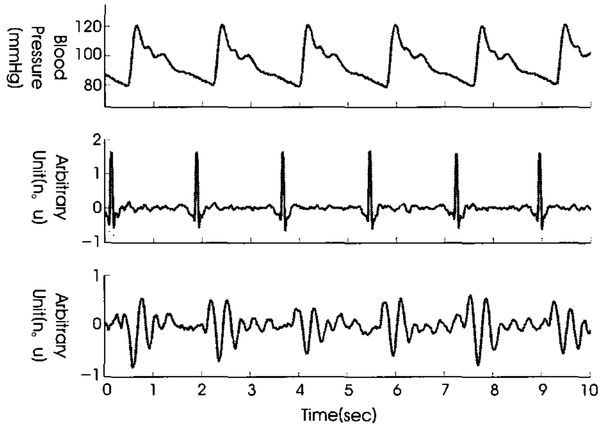


Fig. 4. Radial artery tonometer output signal, CC- ECG, and air cushion pressure wave, respectively.

The R-peaks can be detected in the ECG signal measured from the CC-ECG measurement system, and the pulse pressure wave was recorded from the air cushion system with balancing tubes. The pressure wave was post-processed by a digital high-pass filter having a cutoff frequency of 1 Hz to remove respiration activities and artifacts. The bandwidth of the pressure wave used in this study was 1 to 40 Hz. The time difference between this R-peak and a certain point of the air cushion pressure pulse is used as the U-PAT.

The U-PAT was compared with the standard PAT (S-PAT). The same R-peak in the CC-ECG was used, and the volume pulse wave was recorded using photoplethysmography (PPG) on a toe for the S-PAT. During PPG measurement, a NONIN sensor of transmitted type was used with an amplifier bandwidth of 0.5 to 30 Hz.

For the investigation of the correlation between U-PAT and SBP, beat-by-beat blood pressures and the U-PAT were recorded simultaneously. In this study, SBP parameter was monitored continuously using a Colin CBM-7000 radial artery tonometer in a seated position with the wrists at heart-level. The sampling rate for all data was 2 kHz, and the time resolution of the PATs was 0.5 msec. The amplitude resolution is 16-bit and the measured signals are shown in Figure 4.

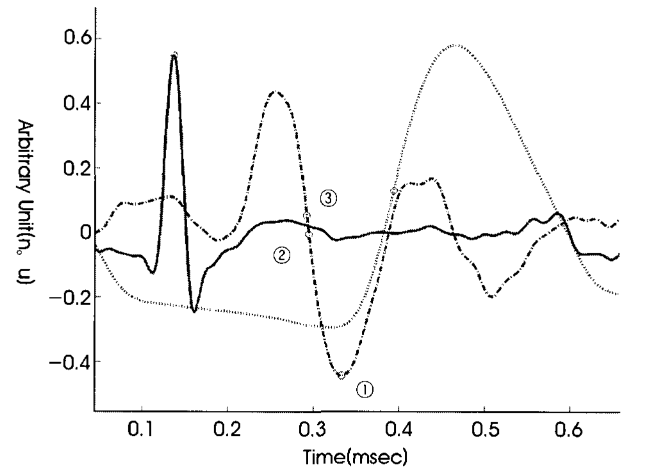


Fig. 5. One-interval waveforms of CC-ECG (—), pressure wave of air cushion (- - -), and PPG on a toe (----).

Table 1. Correlations between S-PAT and three different U-PATs obtained from three feature points of the air cushion pressure wave

Air Cushion Pressure Wave Points	r
1st minimum point	0.6318
zero crossing point	0.8621
steepest descending point	0.9663

All p−values < 0.001

C. Procedures

The U-PAT measured as unconstrained measurement method were evaluated by the following three procedures: 1) the comparison between the U-PAT and S-PAT during varying BP, 2) correlation of the U-PAT with SBP, and 3) the intermittent estimation of SBP using U-PAT over a period of half a day.

To compare the U-PAT with S-PAT, each participant ran up and down stairs for five minutes to change their blood pressure and PAT. After the variation of PAT and BP, U-PAT and S-PAT measurements were conducted for five minutes simultaneously.

To determine the correlation of U-PAT and SBP, each participant performed the following: 1) Baseline: after five minutes resting, the U-PAT and BP were recorded quietly on a chair in a sitting position for five min. 2) Valsalva: after each participant performed a Valsalva maneuver, the parameters were monitored for the recovery of BP and PATs. 3) Static exercise: participants maintained a horse riding position for three minutes and data were recorded for BP and PAT recovery on a chair. Between tasks, each participant took at least a ten-minute rest.

One volunteer participated in the experiment for intermittent SBP estimation using U-PAT. The experiment was performed the day after the above experiments for a more reliable evaluation. The intermittent recording was performed from 13:00 (after lunch) to 22:00 for one min every hour. The participant was drowsy between 13:00 and 14:00, had dinner at 17:30, and performed light exercise for ten min at 19:30.

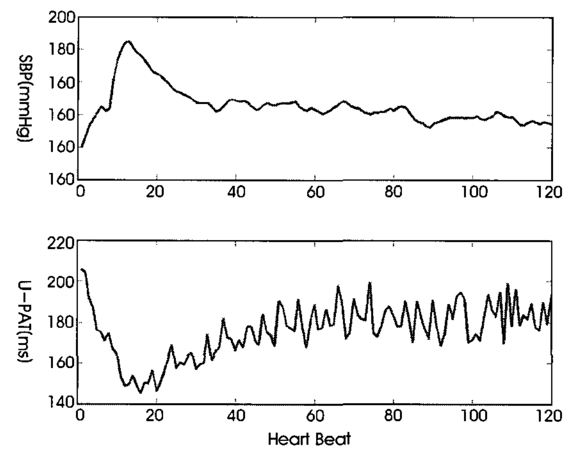


Fig. 6. The beat-by-beat SBP and U-PAT during Valsalva maneuver. The U-PAT pattern agrees with the SBP pattern oppositely. However, the respiration artifact is included in the beat-by-beat U-PAT signal.

D. Data Analysis

The U-PAT was calculated as the difference between the R-peak and a certain point on the air cushion pressure wave, and the S-PAT was calculated between the R-peak and the steepest ascending point of the PPG signal. The best point of the air cushion pressure wave was selected from three possible

Table 2. Correlations between beat-by-beat U-PAT and SBP of each participant in three activities, and correlations between ten-beat averaged U-PAT and SBP of each participant in all conditions

U-PAT vs. SBP	Participant I		Participant II		Participant III	
	r	p	r	p	r	p
Baseline	−0.0013	n.s.	−0.0600	n.s.	−0.0827	n.s.
Valsalva Maneuver	−0.7307	< 0.001	−0.5447	< 0.01	−0.7479	< 0.01
Static Exercise	−0.5367	< 0.001	−0.3491	< 0.001	−0.3020	< 0.001
All conditions	−0.6484	< 0.001	−0.4260	< 0.001	−0.5621	< 0.001
All conditions after ten-beat averaging	−0.8584	< 0.001	−0.5963	< 0.01	−0.8101	< 0.001

n.s. = not significant

feature points by correlation between the U-PAT and S-PAT. Figure 5 shows the three feature points: 1) first minimum point, 2) zero crossing point, and 3) steepest descent point of the air cushion pressure wave. The correlation coefficients between the S-PAT and the three different U-PATs were as follows: (a) 1st minimum point (r = 0.6318), (b) zero crossing point (r = 0.8621), and (c) steepest descent point (r = 0.9663) of the air cushion pressure wave (Table 1). The correlation between the U-PAT and the S-PAT was highest at the steepest descent point for U-PAT, and this point was used (with U-PAT) for the following PAT analysis.

For data analysis of the Valsalva and static exercise conditions, which caused large variation in PATs and BPs, data were measured during the participants' descending or ascending recovery period. The PAT and SBP detected from the distorted CC-ECG, tonometer, or air cushion pressure wave signals in which detection of the feature point was difficult were rejected. A beat-by-beat correlation analysis of U-PAT and SBP was performed for each result and condition. The beat-by-beat U-PAT includes the respiratory artifact, as in Figure 6, since the air cushion pressure wave is also sensitive to respiration activities. Figure 6 shows that even though the respiration effect is still observed in the U-PAT signal after high pass filtering, the beat-by-beat U-PAT during the Valsalva maneuver is in good agreement with the SBP pattern. After averaging of continuous several beats, which cover a few respiration periods, improvement of the correlation of the U-PAT and SBP was shown. By averaging ten beats of data, statistically improved data were obtained and used for the correlation analysis. Because inter-participant correlation was not adequate as in previous studies [4],an intra-participant correlation analysis was performed in this study. The linear regression equations for each participant could be obtained with the averaged U-PATs and SBP during various changing BP conditions.

The linear regression equation from the ten-beat averaged U-PAT and SBP data was needed for intermittent SBP estimation. For this estimation, continuous ten-beat samples of one-min intervals every hour were selected, and SBP was estimated with the ten-beat averaged U-PAT using the above

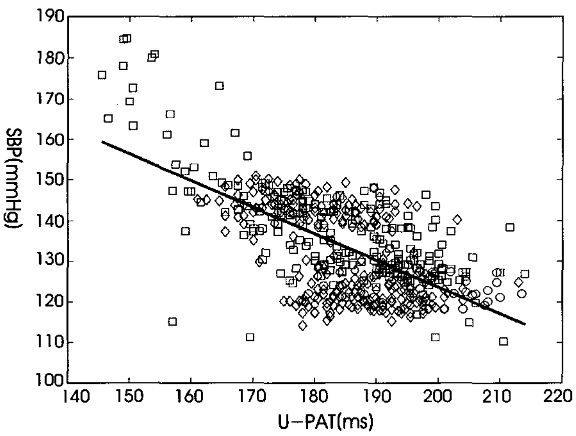


Fig. 7. Beat-by-beat U-PAT and SBP of participant I in three activities: 1. baseline (○), 2. Valsalva maneuver (□), and 3. static exercise (◇).

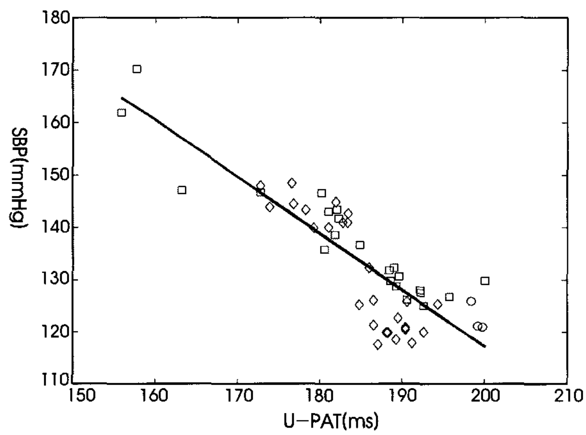


Fig. 8. Ten-beat averaged U-PAT and SBP of participant I in three activities: 1. baseline (○), 2. Valsalva maneuver (□), and 3. static exercise (◇).

regression equation. The estimated SBP was compared with the SBP measured simultaneously from the radial artery tonometer.

III. EXPERIMENTAL RESULTS

The intra-participant correlation analysis results are shown in Table 2 and Figure 7. The correlations of U-PAT and SBP are significantly high during Valsalva maneuver in all participants (r = -0.7303, -0.5447, and -0.7479 for participant I, II, and III, respectively). The static exercise data have a lower value of correlation than the Valsalva maneuver since the range of static exercise data is smaller than Valsalva data. However, the correlations of static exercise data with SBP is significantly high ($p < 0.001$). The important value in this analysis is the correlation coefficient in all conditions. All participants had a significant correlation in all conditions, as shown in Table 2, which agrees with previous results [2, 15, 16]. However, since this result was obtained from the U-PAT that included a respiration artifact, the correlation may improve if the ten-beat averaged data is used for reducing the error.

Table 2 and Figure 8show the result of correlation analysis with ten-beat averaged data. For all participants, the correlation with SBP was enhanced in all conditions. In this analysis, the correlation of averaged U-PAT and SBP was significantly high for all participants. From this analysis, linear regression equations for SBP estimation were calculated by ten-beat averaged data and used for the intermittent blood pressure estimation experiment. Each linear regression equation is as follows: 1) participant I ; SBP = 333.8 1.0832 U-PAT, 2) participant II; SBP = 342.5 1.0478 U-PAT, and 3) participant III ; SBP = 262.3 0.7298 U-PAT.

The intermittent measurement of SBP and U-PAT was performed for one minute every hour with participant I on the subsequent day. Figure 9 shows the result of the intermittent variation of SBP and U-PAT. The measurement was started after lunch, and the SBPs after lunch (13:00) and dinner (18:00) were relatively high. The SBP after exercise (17:30) was the highest. It could be said that the SBP decreases during a drowsy state as shown in Figure 9. The pattern of the U-PAT is oppositely similar to the SBP pattern. The estimated SBP, using the linear regression equation (SBP = 333.8 - 1.0832 U-PAT) from the U-PAT, were compared with the tonometry SBP shown in Fig. 9. The error between the tonometry SBP and the estimated SBP was 4.5±2.6 mmHg.

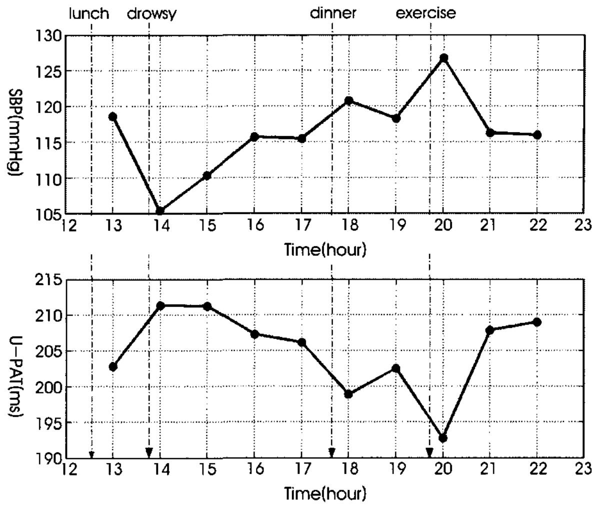


Fig. 9. Intermittent SBP and U-PAT

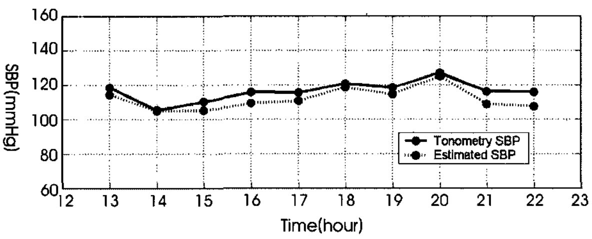


Fig. 10. Comparison of tonometry SBP with estimated SBP using U-PAT.

IV. DISCUSSION

The air cushion pressure wave induced from the heart beat is thought to be the summated signal of pulses from not only the femoral arteries, but also other large arteries in the body. This signal, used for blood pressure estimation, may provide a reliable index averaging the term of vessel stiffness in the extremities, which affects the PAT variation.

For obtaining a U-PAT from the air cushion pressure wave, the pressure signal should be processed with high pass filtering to remove the respiration effect. The U-PAT after filtering, however, was still affected by the respiration as shown in Figure 6 (e.g. the respiration effect was not effectively reduced by filtering). Averaging data covering several respiration periods was effective in reducing the respiration effect. Even though the accurate respiration period can be measured from the air cushion pressure wave by other filter settings, we simply averaged the data for ten beats. In this averaging method, participant I and III show that the correlation magnitudes are above 0.8, and the association of U-PAT and SBP was high, as demonstrated in Figure 8 and Table 2.

The correlation analysis for all participants did not show a sufficient correlation. The reason for this low correlation seems to be the small range of U-PAT and SBP values in the resting state. Furthermore, in addition to the effects of respiration, the BPs measured using the tonometer also have errors, and these are more dominant due to the small range of data.

In the previous study on the relationship of PAT and BP, the correlation between participants was not high [3]. In this paper, it is also demonstrated that the correlations between participants are not high enough to estimate SBP from PATs using a general estimation equation as in previous studies. However, the high correlation existing in the intra-subject data has significance for the use of PAT in the estimation of SBP on an individual basis. The correlation between U-PAT and PP was higher than that of U-PAT and SBP in all conditions for all participants. However, the intermittent BP estimation results showed that the estimated SBP with U-PAT had a very similar pattern with the SBP from the radial artery tonometer, and the error between the estimated PP and tonometry PP was larger than the SBP result.

Averaged U-PATs measured on a chair can be used to obtain intermittent BP estimation. However, the air cushion system and the CC-ECG system on a chair are very sensitive to the motion. Following the above experimental results, only continuous several-beat data is needed. If, although the motion artifact is dominant, the duration in which the several-beat U-PATs can be detected exist, the averaged U-PAT will be sufficient enough to estimate the SBP variation pattern intermittently. The extra sensor detecting patient motion will improve the properties of this system.

This BP estimation system will provide information regarding patients' health status by monitoring BPs in daily life without interrupting ordinary activities. An intermittent BP estimation system using a U-PAT measured on a chair can be applied to web-based telecare in which not only heart rate, but also the SBP from the U-PAT will be monitored. This telecare system of intermittent BP monitoring will help expand the range of healthcare in daily life, and is a step towards an era of ubiquitous healthcare.

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