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Wearable Cuff-less PTT-based System for Overnight Blood Pressure Monitoring

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Abstract— **A wearable cuff-less pulse transit time (PTT) based monitoring device is developed for ambulatory blood pressure (BP) monitoring. Ten healthy subjects (aged 27±4 years old) underwent 24-hour ambulatory BP monitoring using 1) a standard brachial cuff-based oscillometric device as reference and 2) the proposed cuff-less PTT measuring system. Raw PTT and BP measurements were linearly interpolated and then smoothed by a low-pass filter to remove aliasing effect caused by the low sampling rate and synchronized. Resampled PTT and BP were assessed for correlation using correlation coefficients and Bland-Altman plots. Our study showed that PTT estimated systolic BP most accurately within 4.8 ± 4.3 mmHg on healthy young subjects during sleep time. We conclude from this study that the proposed cuff-less PTT-based BP monitoring system has potential to be a less intrusive alternative to standard oscillometric method for long-term overnight BP monitoring.**

I. Introduction

Blood pressure (BP) is an important health indicator to diagnose cardiovascular diseases and to assess the effectiveness of antihypertensive treatment. Since BP varies from beat to beat and is affected by many factors such as stress, anxiety, illness and exercise, a single BP measurement is insufficient to reflect the BP profile of an individual. Clinical studies have proven that 24-hour ambulatory BP can provide more comprehensive information about BP, such as the diagnosis of white-coat hypertension. It has also been validated that nighttime BP, night-day BP ratio and day systolic BP (SBP) variability are strong independent predictors of cardiovascular events [1, 2]. Nevertheless, conventional BP devices are predominantly cuff-based, which may cause discomfort to the users due to the inflation of the cuff, and therefore are not suitable for long-term, especially nighttime BP monitoring. Therefore, a cuff-less approach based on the measurement of pulse transit time (PTT) are being studied as a less intrusive alternative [3, 4]. Since PTT and related parameters can be conveniently estimated from electrocardiogram (ECG) and photoplethysmogram (PPG) by wearable devices, this proposed cuff-less method provides a promising solution for long-term BP monitoring.

Most recent studies focused on the relationship between BP and PTT during a short period, i.e. within a few minutes or hours [5-7]. A limited number of long-term studies were conducted in controlled laboratory environment. One recent study investigated the relationship between beat-to-beat BP and PTT, focusing on their correlation within 5 minutes at different sleeping stages during the night [8]. Bia *et al.* recorded 24-hour PTT and ambulatory BP every 15 min during waking and every 30 min during sleeping in both hypertensive and healthy subjects, and found the association between the circadian profile of PTT and BP with the high occurrence of cardiovascular events in the morning [9].

To our best knowledge, this study presents for the first time on the relationship of BP and PTT over a 24-hour period in an unattended out-of-laboratory setting.

II. System Design

A strap-based wearable monitoring device was developed for ambulatory ECG and PPG measurement as shown in Fig. 1. It contains two straps which connected by a wire. The strap on the left is the main part of the device which is mounted with all processing circuits, two textile-based ECG electrodes, a LED emitter and photo-detector for PPG sensing. The strap on the right contains the third textile-based ECG electrode. The two straps will be separately wrapped around two arms for long-term ECG and PPG recordings. The total weight of the device is 56 g, and the power consumption is estimated to be 52.5 mW excluding the Bluetooth module.

III. Experiment

A. Protocol

Oscar 2™, SunTech Medical® is a standard brachial cuff-based oscillometric ambulatory BP monitor used to measure SBP and diastolic BP (DBP). The cuff of the

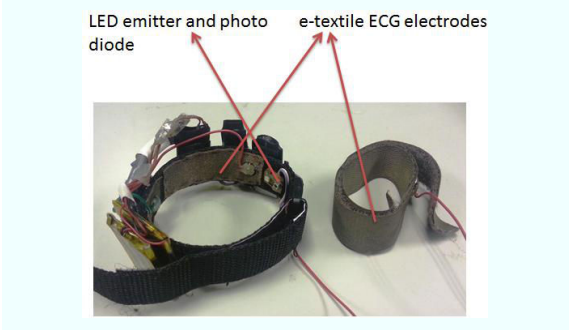

Figure 1. A strap-based wearable monitoring device for ambulatory ECG and PPG measurement

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ambulatory BP device was wrapped on the subject's non-dominant upper arm. The device was set to take measurement automatically every 30 minutes during daytime (8:00-23:00) and every 45 minutes during nighttime. The strap mounted PTT device was also wrapped on the arms of the subject, the main strap on the upper arm at different side of the BP cuff and the other strap on the forearm at the same side of the BP cuff. 1 min of ECG and PPG signal would be automatically recorded every 30 minutes during the experiment and then transmitted to a mobile device through Bluetooth at baud rate of 57600 Bd. All data is further processed offline in MatLab.

Ten healthy young subjects aged 27±4 years old participated in this study. Subjects' demographics and medical history is collected. All subjects underwent 24-hour BP and PTT measurement on a normal working day without vigorous exercise. Subjects were reminded by an alarm on the PDA to keep still as much as possible during measurement to minimize the effect of motion artifacts. Asleeping and wake-up time were self-reported. All participants signed informed consent form, and the study was approved by the Joint Chinese University of Hong Kong - New Territories East Cluster Clinical Research Ethics Committee.

B. *Data Analysis*

The acquired ECG and PPG were filtered by low-pass filter with cutoff frequency at 30 Hz and 16 Hz, respectively. After excluding the episodes of ECG and PPG with poor signal quality, 417 episodes of data in total were used in the following analysis. For each episode, the R-peak of ECG and the peak of the first derivative of PPG (dPPG) were detected. PTT was then derived beat by beat as the time interval from R-peak of ECG to the peak of dPPG. Distorted ECG and PPG waveform due to motion artifacts was manually removed and the corresponding PTT values were excluded from the analysis.

Since two independent devices were used to measure PTT and BP, it is technically difficult to synchronize them to record data exactly at the same minute every half hour. Therefore, the raw data should be interpolated to investigate the relationship between BP and PTT within 24 hours. The raw data of BP and PTT were firstly linearly interpolated at the interval of 30 minutes (i.e. sample rate = 1/30/60 Hz) and then smoothed by a low-pass filter with cutoff frequency of 1/30/60/3 Hz. Then the smoothed BP and PTT data were resampled at the time when BP were recorded. In addition, we removed the interpolated samples between transition periods due to change in posture, i.e. when subject lay down to sleep and woke up from bed, since these fast changes in both BP and PTT would not be able to be picked up by the sampling intervals of 30 minutes.

To evaluate the ability of PTT in BP estimation, a previous BP-PTT model proposed by Poon et al. [4] was adopted in this study, and the arterial stiffness related parameter was set to be 0.017 $mmHg^{-1}$ in the model [10]. The first pair of SBP/DBP and PTT during sleeping of each subject was used for individual calibration.

IV. RESULTS

A. *ECG and PPG recordings during nighttime*

ECG and PPG showed satisfactory signal quality during sleeping and most of the time during waking. Fig. 2 shows a typical example of a one-minute recording of ECG, PPG and the derived PTT during sleeping from one subject.

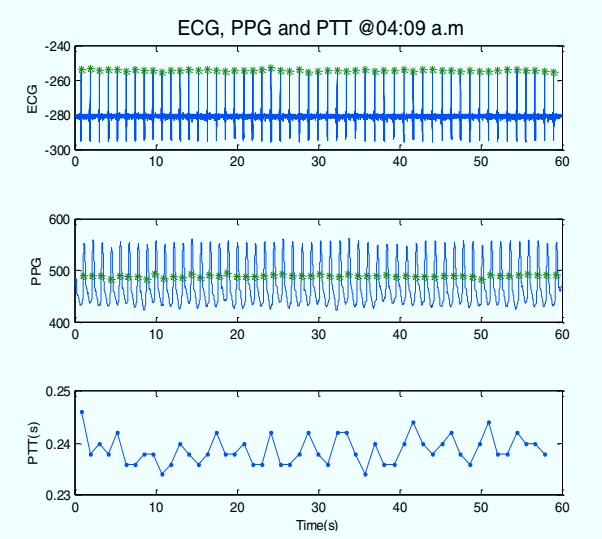


Figure 2. Typical example of 1min recording of ECG, PPG and the derived PTT during sleeping from one subject

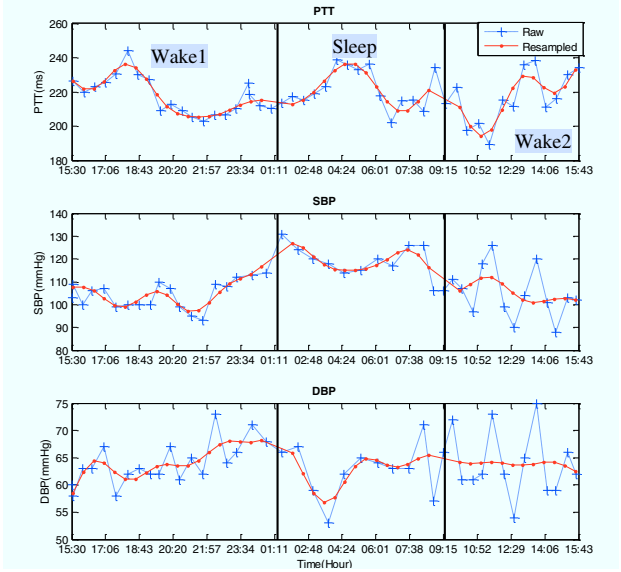
B. *Correlation between BP and PTT*

Table 1 summarized the correlation coefficients of SBP/DBP and PTT in 24 hours and three segmented periods of all subjects. Nighttime data of Subject 7 was missing because the device accidently powered off during nighttime. The correlation data during wake1 or wake2 in some subjects were missing due to the subjects' special experimental time so that few data points were available during this period to calculate the correlation. From Table 1, it can be seen that very weak correlation was found between SBP/DBP and PTT in 24 hours among most of the subjects. When data of each subject were segmented according to his/her sleeping/waking time into wake1, sleep and wake2, significant negative correlation (R<-0.5) between SBP and PTT was found during sleep and sometimes during waking in all subjects. Only some subjects showed strong negative correlation between DBP and PTT.

Fig. 2 shows a typical recording of the raw and resampled data of SBP/DBP and PTT in 24 hours of one subject, and the correlation of SBP/DBP and PTT at three segmented periods of the same subject. The strong correlation during sleeping in nearly all subjects indicates that PTT can be a surrogate of SBP in a stable state, and therefore we did the estimation on totally 80 pairs of SBP and PTT in the eight subjects who have sleeping data. The dynamic range of SBP in the estimation for eight subjects was 14.6 ± 7.3 mmHg. The results of this study showed that the difference between the estimated SBP and the reference was calculated to be 4.8 ± 4.3 mmHg. The relationship between the estimated and reference SBP during sleeping was shown in the Bland-Altman plot in Fig. 3.

TABLE I. CORRELATION COEFFICIENTS OF SBP/DBP AND PTT IN 24 HOURS AND THREE SEGMENTED TIME PERIODS OF 10 SUBJECTS

Subject No.	SBP_PTT				DBP_PTT			
	24hour	Wake1	Sleep	Wake2	24hour	Wake1	Sleep	Wake2
1	-0.61	--	-0.51	-0.27	-0.69	--	-0.45	-0.02
2	-0.33	--	-0.61	-0.61	-0.80	--	-0.91	-0.95
3	0.27	0.65	-0.80	0.39	0.35	0.37	-0.70	0.67
4	0.40	0.15	-0.86	0.35	0.29	-0.15	-0.89	0.53
5	0.25	0.35	-0.86	-0.53	0.23	0.46	0.24	-0.51
6	-0.35	--	-0.52	-0.36	-0.48	--	-0.00	-0.54
7	0.51	0.38	--	-0.60	0.53	0.28	--	0.19
8	0.08	--	-0.97	0.19	0.33	--	0.16	0.56
9	-0.06	-0.07	-0.40	-0.97	-0.02	-0.10	-0.66	-0.55
10	-0.11	-0.09	-0.81	-0.94	-0.47	-0.64	-0.37	-0.37



(a) Raw and resampled data of the 24-hour PTT and SBP/DBP of one subject;

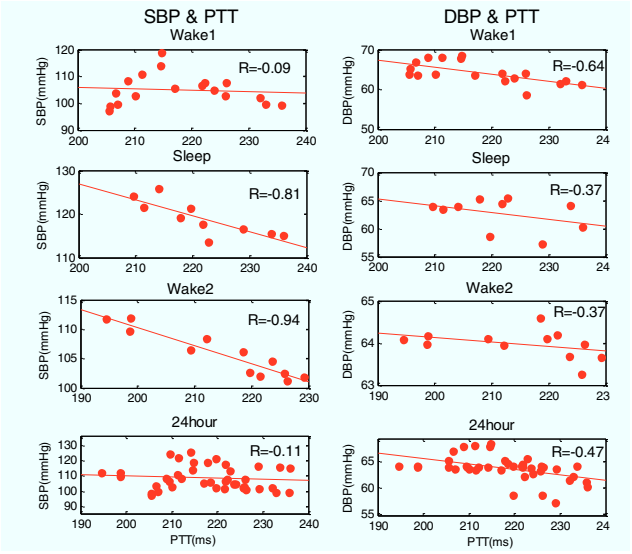


Figure 3. (b) The correlation between SBP/DBP and PTT at three segemented periods of the same subject.

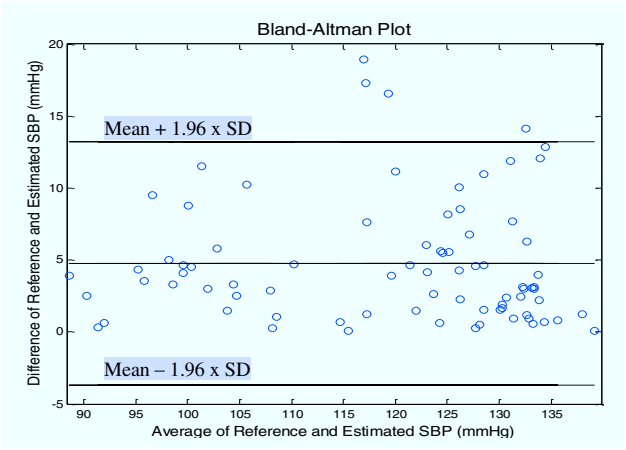


Figure 4. The Bland-Altman plot for SBP during sleeping of all subjects

V. DISCUSSION

To our best knowledge, this study presents for the first time the relationship of BP and PTT over a 24-hour period in an unattended out-of-laboratory setting. Different from the popular sites used for PPG measurement like finger, toe or wrist, which are encumbering and more frequently subjected to motion artifacts, this wearable device adopted the upper arm as the recording site of PPG and thus did not suffer from these problems as much. The recorded ECG and PPG showed good signal quality, especially during nighttime. In addition, PTT measured from this device showed very strong negative correlation with SBP during sleeping in nearly all subjects. The difference between the estimated SBP from PTT and the reference was 4.8 ± 4.3 mmHg. According to the subjects' feedback, this wearable device is significantly more comfortable to use compared to cuff-based 24-hour ambulatory BP meter.

We did not observe significant PTT drop at transitional period from waking to sleeping or significant increase from sleeping to waking as mentioned by Bia. et al [11]. This may be caused by the different measurement method of PTT adopted in their study, which took the last Korotkoff sound during the measurement of brachial BP by the ambulatory BP meter as the distal reference instead of PPG.

It is worth noting that the low sample rate 1/30/60 Hz is far from sufficient to preserve high frequency components of BP

and PTT induced by posture change or other normal activities, and therefore the interpolated BP and PTT were filtered by a low-pass filter to obtain the un-distorted low-frequency component of BP and PTT. Since posture change from waking to sleeping may induce significant changes on BP and PTT, the interpolated samples during the transitional periods of waking and sleeping were removed.

The poor correlation of SBP and PTT within 24 hours was mainly due to the weak correlation during daytime, which can be explained by the following two reasons: 1) daily activities such as walking may influence the vascular tone, i.e., vasoconstriction, thus changing the relationship between BP and PTT. The influence of vascular tone was also reported by other studies [12]; 2) pre-ejection period (PEP) which is part of the measured PTT may also have an impact on BP-PTT relationship. It has been found that PEP has great contribution in PTT change during daily activities such as posture change and dynamic exercise [13, 14]. Winokur *et al*. recently found that PEP may change in different directions with respective to vascular transit time during Valsalva maneuver [5]. This may explain why BP and PTT showed no significant correlation or even positive correlation in some subjects. On the other hand, during nighttime when the subjects have fallen asleep, the measurement is much more stable. BP, PTT and other related physiological parameters such as vascular tone, nervous activities will be more stable and have less significant transient changes. Therefore, the proposed processing algorithm and estimation algorithm of this study is capable of producing consistent results. It was also found that the correlation coefficients between SBP and PTT during nighttime were found to vary largely among subjects (-0.4~-0.97). It may be because that the physiological state may change due to neural or hormonal regulation during nighttime although no significant physical activities were involved, thus inducing changes on vascular tone and PEP.

VI. Conclusion

The strap-based wearable device was designed to explore the possibility of cuff-less ambulatory BP monitoring. The device was capable of prolonged ECG and PPG monitoring under natural settings. This study showed that a cuff-less PTT has potential to be a less intrusive alternative to standard cuff-based BP devices for overnight BP monitoring in natural settings. The aesthetics of the device can be enhanced in the future such as by replacing the strap with a terrycloth material to improve wearers' comfort. Another limit in this study is that the motion artifacts in signal acquisition were manually handled. In future work, advanced algorithms should be developed to automatically remove these artifacts to provide reliable PTT, thus promoting the practical use of this device in clinic or daily settings.

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