An Armband Wearable Device for Overnight and Cuff-less Blood Pressure Measurement

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Abstract—24-hour blood pressure (BP) has significant prognostic value for cardiovascular risk screening, but the present BP devices are mainly cuff-based, which are unsuitable for long-term BP measurement, especially during nighttime. In this paper, we developed an armband wearable pulse transit time (PTT) system for 24-hour cuff-less BP measurement and evaluated it in an unattended out-of-laboratory setting. Ten healthy young subjects participated in this ambulatory study, where PTT was measured at 30-minute interval by this wearable system and the reference BP was measured by a standard oscillometric ambulatory BP monitor. Due to the misalignment of BP and PTT on their recording time caused by the different measurement principles of the two BP devices, a new estimation method has been proposed: transients in PTT were removed from the raw data by defined criteria, and then evenly interpolated, low-pass filtered and resampled to synchronize at the time when BP was recorded. The results show that with the proposed method, the correlation between PTT and systolic BP (SBP) during nighttime with dynamic range of 21.8 ± 14.2 mmHg has improved from -0.50 ± 0.24 to -0.62 ± 0.20 (p<0.1), and the difference between the estimated and reference SBP has improved from 0.7 ± 10.7 mmHg to 2.8 ± 8.2 mmHg with root mean square error reduced from 10.7 mmHg to 8.7 mmHg. In addition, the correlation between a very low frequency component of SBP and PTT obtained from the proposed method during nighttime is -0.80 ± 0.10 and the difference is 2.4 ± 5.7 mmHg for a dynamic BP range of 13.5 ± 8.0 mmHg. It is therefore concluded from this study that the proposed wearable system has great potential to be used for overnight SBP monitoring, especially to measure the averaged SBP over a long period.

Index Terms— 24-hour ambulatory blood pressure, pulse transit time, cuff-less, wearable devices, mobile health.

I. INTRODUCTION

CARDIOVASCULAR disease (CVD) remains the number one cause of death worldwide [1]. In 2008, CVD caused 17 million deaths globally, accounting for nearly one third of all deaths [2], and the number is estimated to reach up to 23.3 million by 2030 [1]. Blood pressure (BP) is one of the most important risk factors for predicting CVD events. Nevertheless, clinic BP has been questioned as it may not reflect the normal BP level due to the white-coat effect [3]. 24-hour ambulatory BP monitoring is being increasingly adopted in clinical diagnosis and treatment of hypertension [4]. Other related parameters, such as nighttime BP and BP variability, have been proved to be capable of providing independent clinical values in the prediction of CVD events [5, 6].

Though the significance of ambulatory BP monitoring in the clinical practice has been recognized, the present BP measurement devices are mainly cuff-based, which may cause discomfort due to the inflation of cuff during measurement, and are thus unsuitable for long-term BP monitoring, especially during nighttime. Pulse transit time (PTT), defined as the time for the pulse to travel from the heart to a peripheral site, has been proposed to be a potential surrogate of BP [7-10]. Since PTT can be readily derived from electrocardiogram (ECG) and photoplethysmogram (PPG) by wearable devices [11-13], it provides a very practical solution for ambulatory BP monitoring. Most of the present studies, however, focused on the short-term correlation between BP and PTT, aiming to validate the potential of PTT for beat-to-beat BP estimation. For example, two recent studies reported continuous BP and PTT overnight in a laboratory setting, but only the correlation between beat-to-beat BP and PTT within a few minutes rather than overnight correlation was investigated [14, 15]. To the best knowledge of the authors, no study has investigated the correlations between BP and PTT within 24 hours or overnight in an out-of-laboratory daily life setting. Therefore, this study aims to investigate whether PTT can be a surrogate of 24-hour BP in an unattended environment.

II. SYSTEM AND METHOD

A. System Design

An armband-based wearable monitoring device shown in Fig. 1 was developed for ambulatory ECG and PPG measurement. ECG was measured by three electrodes. This wearable device is an improved version of the system we reported in [16]. In this system, to avoid long wires across the body, two e-textile electrodes were sewed in the armband wrapped around the left arm, and the other one adopted the adhesive Ag-Ag/Cl electrode which was placed on the right side of the subject’s thorax. One electrode on the armband works as a common electrode with the right leg driven circuit to actively cancel common-mode interference. PPG was measured by near-infrared LED emitter and a phototransistor in reflective mode. The acquired ECG and PPG were amplified and filtered by band-pass filters with frequency band of 0.5-17 Hz and 0.5-10 Hz, respectively. The filtered analog signals were digitalized by a micro-controller unit (MCU, ATmega 8) at the sample rate of 500 Hz and resolution of 8-bit, and then stored in...
Sensors &
electrodes
Amplifiers
Filters
Flash
memory
Power
On/off
MCU
(A/D and Control)

(a)

(b)

(c)

Stretchable
armband
Circuit
protecting
cover
Infrared
PPG sensor
Two e-textile
ECG

Fig. 1. The armband wearable device for 24 hour ECG and PPG measurement. (a) The block diagram of the system; (b) the circuitry of the system; (c) final package in a stretchable armband.

A flash memory module mounted on the armband. To save power, the MCU was programmed to switch on the powering circuit of the system every 30 minutes and then switch off after 1-minute data recording. A buzzer was used for reminding the subject to keep still during signal recording to avoid motion artifacts.

B. Protocol

Ten healthy young subjects (27±3 years old) were recruited in this study. No severe physical activities were involved during the monitoring. The subjects were required to keep still during the measurement to avoid motion artifacts. Oscar 2 oscillometric ambulatory blood pressure monitor (SunTech Medical) which is the standard device for 24 hours ambulatory BP measurement was used in this study to measure reference BP. The device was set to automatically take measurements of systolic BP (SBP) and diastolic BP (DBP) every 30 minutes during the whole day according to the clinical guidelines [3]. One minute of ECG and PPG were recorded every 30 minutes by the wearable device. After 24-hour monitoring, the subjects came back to the laboratory and removed all the sensors to finish the study. The starting, ending, sleeping and waking time were self-reported by each subject. All subjects signed informed consent form and the study was approved by the University Ethics Committee.

C. Measurement of the reference blood pressure

Finapres and Portapres were often used as the reference BP measurement devices in previous in-laboratory studies [14, 15]. Since these devices are bulky, a standard 24-hour ambulatory BP meter was chosen to be the reference in the current study. The reference device measures intermittent BP at intervals of around 30 minutes to evaluate the performance of the PTT-based method over a 24-hour period.

The measurement principle of this 24-hour ambulatory BP monitor, however, makes it difficult to obtain synchronized BP and PTT measurements during a 24-hour period. First, although the two devices were set to have the same sampling rate (one sample per 30 min), they tend to be out-of-sync a few hours after the start of the study due to the built-in sampling pattern of the 24-hour ambulatory BP monitor. Second, using a cuff inflation to trigger the recording of PTT can better synchronize the two devices but such a design was not adopted due to other practical issues: a) if a physical cable was used to connect the two devices that were placed on the two arms of a subject, it would cause great inconvenience to the subject and therefore the design is not recommended by the doctor; b) if wireless communication such as Bluetooth was used, the heavy power consumption of the wireless module is found to be impractical for the 24-hour study. Third, it is essentially difficult to synchronize PTT with BP at exactly the same beat due to the intermittent nature of the oscillometric measuring principle of this ambulatory BP monitor. Specifically, the oscillometric BP device, which measures BP by detecting the maximal oscillation in a sphygmomanometer cuff caused by blood flow, assumes that BP do not vary a lot during the measurement period [17]. This may be reasonable for a well-control protocol in laboratory settings which requires the subject to keep still during the whole procedure. However, for the ambulatory 24-hour study, BP may change transiently within a few seconds during daily activities such as walking, eating or drinking, deep breathing and posture change [18-20], as shown in Fig. 2. Since it is difficult to know when the BP readings displayed on the device actually occur within the cuff inflation period, it is impossible to synchronize BP and PTT with precision in second. Therefore, resampling is needed to synchronize BP and PTT.

In this study, a novel processing algorithm is proposed to overcome the synchronizing issue aforementioned. Based on this method, the correlation between BP and PTT within 24 hours and the estimation accuracy of this wearable device is investigated.

Fig. 2. Principle of BP measurement by automated oscillometric method
changes of around 5% on PTT [12], so the threshold to exclude the transients in PTT is determined to 9 milliseconds for all subjects. 2) Repeat the steps (low pass filtering and resampling) in Method 1 on PTT obtained from step 1 of Method 2 to get a new smoothed PTT (solid triangles in Fig. 3). 3) Remove the interpolated points in SBP and PTT which were located in the transitional period between daytime and nighttime. Interpolations between two neighboring raw data points whose interval were longer than 3 hours were discarded.

The correlation between SBP and PTT obtained by Methods 1 and 2 were computed for each subject, respectively.

3) Nonlinear model for BP estimation

To assess whether PTT has potential to be a surrogate of BP, a nonlinear BP-PTT model, which was firstly proposed in our previous work [10], is adopted in this study and elaborated as follows: The fundamental concept of relating BP with PTT is based on Moens-Korteweg equation which expressed PWV in terms of the elastic modulus of the artery wall for lateral expansion ($E_m$), the thickness of the arterial wall (h), the radius of the artery at the end of diastole (r) and the density of blood (ρ), i.e.,

$$PWV = \frac{E_m h}{2 \rho r}$$

(1)

In addition, the mathematical representations of the elasticity or compliance of arterial wall as a function of BP are needed to arrive at an equation that allows the estimation of BP from PWV. A very commonly used experimental finding is based on the in vivo and in vitro studies on 12 anaesthetised dogs by Hughes et al. [21]. This study concluded that the elastic modulus ($E_m$) increased exponentially with the mean BP (MBP) of the dogs’ descending thoracic aorta in vivo, i.e.,

$$E_m = E_0 e^{Pr}$$

(2)

where P is MBP. The exponential dependence of elasticity modulus on BP was also reported on human arteries [22] and is reproduced in Fig. 4. Based on (2) and the in vivo experimental data from Fig. 4, the coefficients in (2) can be fitted as follows: $E_0$=1429 mmHg and γ=0.031 mmHg⁻¹.

Substituting (2) into (1), MBP is derived to be logarithmically related to PTT, i.e.

$$MBP = MBP_0 + \frac{2}{\gamma} \ln \left( \frac{PTT}{PTT_0} \right)$$

(3)

On the other hand, according to Bramwell-Hill equation,

$$PWV = \sqrt{\frac{\Delta P}{\rho \Delta V}}$$

(4)

for a given pulse, if $\Delta P$ is the pulse pressure (PP), i.e., the difference between SBP and DBP, and it is assumed that the changes of the arterial diameter are negligible, PP is found to be proportional to 1/PTT², i.e.

$$PP = PP_0 \left( \frac{PTT}{PTT_0} \right)^2$$

(5)

where PP₀, MBP₀ and PTT₀ can be obtained from calibration.

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**Fig. 3. Illustration of the proposed method for the analysis of SBP and PTT.** Symbols and lines are denoted as follows: open circle - raw SBP and PTT; cross symbol - removed transients; dotted line - smoothed data by Method 1; solid line - smoothed data by Method 2; open triangle - SBP smoothed and resampled to the time of BP measurements; solid triangle - PTT smoothed by Method 2 to the time of BP measurements.
Since MBP is often estimated as $1/3 \cdot SBP + 2/3 \cdot DBP$, SBP and DBP can be estimated from (3) and (5), respectively,

$$\begin{align*}
DBP &= \frac{1}{3}SBP + \frac{2}{3}DBP + \frac{2}{\gamma} \ln \left(\frac{PTT}{DBP} \right) \left(\frac{SBP - DBP}{3} \right) \left(\frac{PTT}{PTT} \right)^{3/2}, \\
SBP &= DBP + (SBP - DBP) \left(\frac{PTT}{PTT} \right)^{3/2}.
\end{align*}$$

The advantage of this model is that only one calibration point is needed to determine the individual parameter, which is important for the practical use of this method. In this study, the first measurements of BP and PTT were adopted for calibration, and the rest of the data were used for validating the accuracy of this model. The difference between the PTT-based estimation and the reference device were compared between the two methods (Methods 1 and 2) as well as between different references (raw and smoothed SBP).

### III. RESULTS

#### A. Correlation during 24 hours, daytime and nighttime

Very weak correlation was found between 24-hour SBP/DBP and PTT in most subjects. When 24-hour data were segmented into daytime and nighttime, all subjects showed negative correlation between smoothed SBP and PTT during nighttime as shown in Table I.

**Table I** Comparison of correlation coefficients between the smoothed SBP and PTT by two analysis methods at different periods for each subject

<table>
<thead>
<tr>
<th>Sub No.</th>
<th>Daytime</th>
<th>Nighttime</th>
<th>24-hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Method 1</td>
<td>Method 2</td>
<td>Method 1</td>
</tr>
<tr>
<td>1</td>
<td>-0.29</td>
<td>-0.28</td>
<td>-0.11</td>
</tr>
<tr>
<td>2</td>
<td>-0.61</td>
<td>-0.57</td>
<td>-0.61</td>
</tr>
<tr>
<td>3</td>
<td>0.30</td>
<td>0.35</td>
<td>-0.79</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0.27</td>
<td>-0.59</td>
</tr>
<tr>
<td>5</td>
<td>0.33</td>
<td>0.25</td>
<td>-0.86</td>
</tr>
<tr>
<td>6</td>
<td>-0.29</td>
<td>-0.81</td>
<td>-0.54</td>
</tr>
<tr>
<td>7</td>
<td>0.60</td>
<td>0.18</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>0.23</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>9</td>
<td>-0.10</td>
<td>-0.24</td>
<td>-0.14</td>
</tr>
<tr>
<td>10</td>
<td>-0.38</td>
<td>-0.30</td>
<td>-0.69</td>
</tr>
</tbody>
</table>

On the other hand, no consistent correlations were found between SBP and PTT during daytime, i.e., some subjects showed positive correlation, some showed negative correlation or no correlation. The correlation of SBP and PTT during daytime did not show significant improvement by Method 2 for most subjects. Very few subjects showed significant correlation between DBP and PTT, which is not shown in this paper. One typical example of the 24-hour SBP and PTT data processed by two methods and the correlations between smoothed SBP and PTT during daytime, nighttime and 24 hours are given in Fig. 5.

**Fig. 5.** (a) A typical example of the reference SBP and PTT in 24 hours. (b) Correlation between smoothed SBP and PTT during three periods by Method 1 and 2.

The ranges of BP change, the correlation coefficients between PTT and SBP as well as the differences between the reference BP and PTT-based estimation by Methods 1 and 2 are summarized in Table II. The correlation between raw SBP and
PTT was significantly improved by Method 2 from \(-0.50 \pm 0.24\) to \(-0.62 \pm 0.21\) (\(p < 0.1\)). In addition, the correlations between the smoothed SBP and PTT were significantly stronger than that of raw SBP and PTT for both methods \((-0.61 \pm 0.24\) vs \(-0.50 \pm 0.24\) for Method 1, and \(-0.80 \pm 0.10\) vs \(-0.62 \pm 0.21\) for Method 2, \(p < 0.05\)).

**B. PTT-based BP Estimation**

After excluding the first point, which was used for individual calibration, 90 and 70 pairs of SBP and PTT during nighttime were included in the estimation for Method 1 and 2, respectively. The estimation performance was evaluated by mean and SD of the difference as well as the root mean square error (RMSE) between the estimation and reference SBP. Table II shows that using Method 2, the RMSEs between the estimated and reference SBP was reduced from 10.7 to 8.7 mmHg for raw SBP and from 8.9 to 6.2 mmHg for smoothed SBP, respectively. The differences between the PTT-based estimated and raw SBP were 0.7 \pm 10.7 mmHg and 2.8 \pm 8.2 mmHg for Methods 1 and 2, respectively. For the smoothed reference SBP, the differences were 0.5 \pm 8.9 mmHg and 2.4 \pm 5.7 mmHg for Methods 1 and 2, respectively. The dynamic ranges of overnight SBP for all subjects are from 80 to 145 mmHg and from 91 to 141 mmHg for raw and smoothed SBP, respectively. The Bland-Altman plots of the differences between the PTT-based estimations and the different references are shown in Fig. 6.

**IV. DISCUSSION**

The correlation between BP and PTT has been studied extensively in the past to explore the potential of PTT as a surrogate of BP. According to Moens-Korteweg equation, it is known that when BP changes, the pressure-dependent vascular elasticity will change, thus inducing a change on pulse wave velocity and a reverse change on PTT. This pulse wave propagation-based model described the physiological basis of the negative correlation between beat-to-beat BP and PTT. It is however unknown whether this relationship still holds for BP and PTT over a much longer period. In this paper, the 24-hour ambulatory study was conducted to explore the relationship between intermittent BP and PTT within 24 hours in an unattended out-of-laboratory setting. Due to the differences in measuring principles of the cuff-based and PTT-based cuffless BP measurement methods, it is impossible to measure the two BP exactly at the same time point. Therefore, resampling is needed to calculate the correlation between PTT and BP. Limited by the very low sampling rate, i.e. sampling at 30-min interval, it would be unable to capture the high-frequency fluctuations in both BP and PTT, as known to the sampling theorem. Therefore, BP and PTT should be first low-pass filtered before interpolating. It is found that the correlation between the smoothed SBP and PTT was larger than that between the raw SBP and PTT, which suggests that the relationship between SBP and PTT is frequency-dependent. This result is consistent with the conclusion of Liu’s study [23], which found that the ratio of low frequency (LF) and high frequency (HF), i.e., LF/HF ratio, of SBP was about four times higher than that of PTT.

Two previous studies investigated the nighttime BP-PTT relationship in laboratory settings [14, 15]. In Chua’s study, the overnight data were segmented into 5-min non-overlapping epochs and the correlation between SBP and PTT within these epochs was reported to be around -0.2 [14]. This result is very different from our study, which may be caused by two factors: 1)
the frequency band of interest in Chua’s study is 0-0.15 Hz, while this study focuses on 0-0.00019 Hz; 2) the reference BP were measured by Portapres in Chua’s study, which is known to provide relative changes of continuous BP instead of absolute BP levels, while this study used standard ambulatory BP device which is based on automated oscillometric measuring principle [24]. In Vlahandonis’ study, Finapres was adopted as the reference, and good negative correlation (r = -0.57 — 0.65) was found between SBP and PTT. However, this study also only investigated the short-term correlation, i.e., 500 sec of each sleep stage, rather than overnight correlation [15]. In addition, neither of the two studies evaluated the performance of BP estimation according to standards. In this respect, this study is the first one to investigate overnight BP-PTT relationship and shows the potential of PTT for cuff-less and overnight BP estimation in unattended settings.

1) Rationale for removing PTT outliers

It is worth noting that the transients in PTT were removed from the raw data in Method 2 is not because they are incorrect, but rather to propose a more reasonable metric to compare the measurements from the two different devices. Specifically, the different measurement principles and other practical issues result in misalignment in the measurement time of the two BP devices. Therefore, resampling is necessary to synchronize BP and PTT before calculating the measurement differences. However, due to the very low sampling rate (1/30/60 Hz), only very low frequency components (within 1/30/60/2 Hz) of PTT can be reserved according to Nyquist sampling theorem. The linear interpolations near the transients are therefore unreliable. In this way, it is considered that the smoothed line obtained by excluding the transients might be more representative of the real PTT trend than the smoothed line when including the transients. For example, the solid line in Fig. 5 (a) was shifted downward to the blue dash line due to the existence of the second PTT outlier (open circle). It is thus suggested to remove the transients before resampling.

2) Rationale for disregarding interpolations during transitional periods

The rationale to disregarding interpolations during day-night transitional periods is that the interpolations around those transiently-changing PTT samples are not as reliable as those around slowly-changing PTT samples due to the very low sampling rate. Since a steep change of around 20% during day-night transitional periods occurred on the 24-hour PTT in healthy subjects [25], the linear interpolations during these periods are therefore inauthentic. To evaluate the correlation between PTT and BP, it is reasonable to remove this non-systematic error source. After removing these points, it was found that the correlation between SBP and PTT was significantly improved. Some subjects did not show significant improvement on the correlation by Method 2 since no transients were removed from the raw data during nighttime according to the defined criterion.

3) Correlation between BP and PTT: nighttime versus daytime, SBP versus DBP

We found that SBP and PTT showed much better negative correlation during nighttime than daytime. It can be explained by two factors which may have larger effects on PTT-BP relationship during daytime than nighttime: 1) vascular tone. Some in vivo experimental studies have investigated the effects of smooth muscle relaxation and contraction on PWV-BP relationship, and showed that the relationship can be significantly altered by the administration of vasoactive drugs [22, 26]. Daytime activities such as posture change, walking and working may regulate vascular tone and change the relationship of BP and PTT. 2) The time delay between R-peak of ECG and characteristic point of PPG contains two parts: pre-ejection period (PEP) and the transit time of the pulse wave from heart to periphery, i.e., vascular transit time. PEP is the time delay between the ventricular depolarization and opening of the aortic valve. It may change with venous return, cardiac contractility and arterial blood pressure [27] under different physiological status like stress, emotion and physical effort [28]. Some studies have shown that PEP has great contribution in the change of PTT during posture change and dynamic exercise [29, 30]. Under some situations, PEP and vascular transit time even changed in opposite direction [31, 32]. The above reasons can explain why SBP and PTT showed no significant correlation during daytime. On the other hand, unlike SBP which is determined by both the vasostate and left ventricular contraction, DBP is irrelevant of left ventricular contraction, which makes it uncorrelated with PEP. This is why weak correlation was found between DBP and PTT. Other studies have reported similar results, and suggested that vascular transit time instead of PTT is more correlated with DBP [32, 33].

4) Estimation error for raw and smoothed SBP

The differences between PTT-based estimation and the reference raw SBP were within 2.8 ± 8.2 mmHg, which is slightly beyond the difference recommended by Association for the Advancement of Medical Instrumentation (AAMI) standard, i.e., 5 ± 8 mmHg. The result is consistent with that as reported in Poon’s study (0.6 ± 9.8 mmHg) [10] and another recent comparative study (1.2 ± 9.7 mmHg) using the same model [34]. There are several sources of systematic errors of this model: 1) the elasticity-related parameter γ was set as a constant for all subjects. Since the elastic property of artery wall varies with age and gender, a feasible solution to reduce this error is to adopt different γ according to the gender and age of the subject [9]. 2) The changes of PTT are not only related to BP changes, but also PEP and vascular tone. This error can be reduced by taken into account these confounding factors in the BP-PTT model. Moreover, approximating MBP from fractions of SBP and DBP is another source of error. In addition, using smoothed PTT to estimate raw BP in this study may also cause errors. Since the relationship of BP and PTT was shown to be frequency-dependent [23], the smoothed PTT may be unable to accurately estimate high frequency components of BP. This explains the better results for smoothed BP estimation than raw BP. Nevertheless, the result is very close to the requirements of AAMI standard on evaluating BP measurement devices. Therefore, the wearable device and the proposed estimation method provide an effective and practical solution for overnight cuff-less BP estimation which is known with more
The difference between PTT-based estimation and the smoothed reference SBP, i.e., 2.4 ± 5.7 mmHg, is much smaller than that for raw reference SBP. Though no current studies have evaluated the clinical value of the smoothed BP, it actually contains different physiological meaning and important clinical significance. It is known that high frequency (HF) fluctuation (> 0.15 Hz) in BP is associated with mechanical influences from respiration, while low frequency (LF) fluctuation (0.05-0.15 Hz) is related to sympathetic nerve regulation on vasomotor tone [35]. Though the mechanism underlying very LF (VLF) fluctuation (< 0.05 Hz) is still unclear, it is suggested that VLF may depend on myogenic regulations or thermoregulation, which provides different information compared to HF and LF components [36]. In addition, the average value of two or three BP readings measured at intervals of 1 minute is commonly used in clinical diagnosis of hypertension [37]. Moreover, the mean value of 24-hour ambulatory BP measurements has been validated as independent risk factors to predict CVD death in many clinical studies [3, 38]. These facts implicate the clinical significance of smoothed BP.

This study has a few limitations: 1) BP and PTT were not aligned. Nevertheless, it must be noted that technically, it is difficult to perfectly align the measurements obtained from the two non-invasive BP devices with different measurement principles. 2) Low number of data samples. The number of data points is mainly limited by the sampling frequency of the reference BP device which was set to operate at every 30 minutes as outlined in most clinical guidelines of 24-hour ambulatory BP measurement worldwide [4, 39, 40]. Although after resampling, the number of sampling points has been reduced, it presents a fairer judgment to the measurement differences between the two methods. 3) The proposed method has limitation in estimating BP accurately with transient changes during daytime. The much better correlation during nighttime is likely due to the fact that there are fewer transient events during this period. Therefore, lack of synchronization has no big influence on BP-PTT correlation. But it is not the case for daytime when transient PTT and BP changes exist, and an exact synchronization is therefore necessary. In this respect, continuous BP and PTT should be measured simultaneously. However, two main practical issues make it difficult to evaluate the PTT-based method for continuous and long-term BP estimation in ambulatory settings: 1) the high power consumption of wearable device for continuous and long-term PPG measurement; 2) the availability of continuous BP reference device for ambulatory use. As far as we know, the current continuous BP devices are either invasive or non-portable. Based on these considerations, the present study, even though has the aforementioned limitations, is already the best one can achieve with the state-of-the-art technologies whilst complying with the clinical guidelines. In spite of its limitation in daytime BP estimation, this study is still of important clinical significance. The results of this study indicate that once calibrated at the beginning of nighttime, PTT can provide accurate estimation of overnight SBP without a cuff. As validated in many clinical studies, nighttime SBP is a better predictor of clinical outcome in the prediction of CVDs or events compared to daytime BP [5, 38].

V. CONCLUSION AND FUTURE WORK

In this study, an armband-based wearable device was developed for long-term BP measurement based on PTT method. 24-hour taking-home study was conducted to evaluate the accuracy of this device. To overcome the difficulties of misalignment in time between the recordings from the PTT-based wearable device and the oscillometric-based reference device, a new analysis method was proposed to preprocess PTT. The results showed that the correlation between SBP and PTT during nighttime was significantly improved by the proposed method to -0.62 ± 0.21 with the difference between the PTT-based estimation and the reference SBP in 2.8 ± 8.2 mmHg. The results were further improved to -0.80 ± 0.10 and 2.4 ± 5.7 mmHg after smoothing SBP. Therefore, this study provides a complete and effective solution for nighttime SBP measurement, which is known with significant clinical value for cardiovascular risk screening.

In future, a larger cohort study including more healthy subjects and patients with CVDs will be conducted to further validate this wearable device for overnight BP monitoring.

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