31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

A Novel Method for the Contactless and Continuous Measurement of Arterial Blood Pressure on a Sleeping Bed

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Abstract— **Nighttime blood pressure (BP) is found to best predict the 5-year risk of cardiovascular death in comparison to daytime BP, BP measured over a 24-hour period and clinical BP. In view of this, a novel contactless system has been developed on a sleeping bed for the cuffless and continuous estimation of BP at night. Experiments were conducted on 11 subjects to evaluate the contactless system, particularly its performance compared to a contact system. The results of this study showed that the accuracy of the contactless system to estimate BP by a cuffless approach is comparable to that of the contact system when measured at the same posture. More studies have to be conducted in order to understand the difference of the cuffless BP estimation approach when measuring at supine and sitting postures.**

I. Introduction

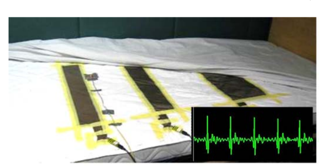
In 2008, the American Heart Association, American Society of Hypertension, and Preventive Cardiovascular Nurses Association jointly made a scientific statement to call to action on the use of home blood pressure (BP) monitoring, which has been confirmed by many studies to provide better predictors of cardiovascular risk than those measured in conventional clinical settings [1]. Amongst BP measured at home at various times of the day, nighttime BP is found to better predict the 5-year risk of cardiovascular death than daytime BP and BP measured over a 24-hour period [2]. Nevertheless, existing home BP measurement technologies, e.g. the auscultative, oscillometric, tonometric or volume-clamp methods, required the use of an inflatable cuff in the measurement and therefore, are unsuitable to be used when the subject is asleep during nighttime.

In contrast, the estimation of BP based on pulse arrival time (PAT) is a promising way to measure continuous BP without an inflatable cuff. PAT is defined as the time interval between characteristic points on electrocardiogram (ECG) and a peripheral photoplethysmogram (PPG) during the same cardiac cycle. We have previously implemented this technology into wearable devices such that it can be used for the continuous measurement of BP in a home environment [4]. In this study, we intend to develop a novel system that allows the long-term and continuous monitoring of arterial BP at night. In particular, this is a contactless system in that it does not require the user to put on or get in contact with any sensors. The key advantages of the system are 1) BP can be monitored continuously without a cuff so that the user would not be disturbed whilst he is at sleep; 2) the contactless approach is more hygienic, and 3) most importantly, implementing the system on a sleeping bed makes it most convenient for nighttime monitoring, a time period where many cardiovascular events occurred without notice.

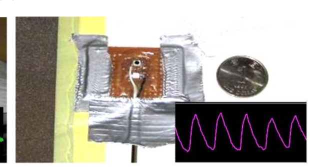
II. Design of the Contactless System

The contactless system was designed on a soft and flexible sleeping cushion (h-Cushion) that is to be placed in between the mattress and bed sheet. As shown in Fig. 1, e-textile electrodes and a pair of photo emitter and sensor were embedded on h-Cushion for capturing ECG and PPG by a contactless approach.

(a)



(b)



(c)

Fig. 1 Design of the contactless system: (a) appearance, (b) e-textile electrodes, and (c) LED and photodiode pair.

Manuscript received April 23, 2009. This work was supported in part by the Hong Kong Innovation and Technology Fund (ITF). The authors are grateful to Standard Telecommunication Ltd., Jetfly Technology Ltd., Golden Meditech Company Ltd., Bird International Ltd. and Bright Steps Corporation for their supports to the ITF projects.

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978-1-4244-3296-7/09/$25.00 ©2009 IEEE

The system was designed based on our earlier work on contactless and continuous ECG monitoring [3]. In this novel system, a PPG sensor board was carefully designed so that it is comfortable to be slept on while being able to maintain sufficient contacting pressure against the user for capturing the pulse from the back of the user. A pair of narrow-band infrared LED and photodiode was selected to reduce the interference of visible light from surrounding environment.

III. Methodology

In this study, systolic blood pressure (SBP) was estimated based on the bio-model-based cuffless method we developed for the h-Shirt [4], i.e.,

$$SBP = C_3 * \ln PAT + C_2 * \ln L + C_1 * ZX + C_0, \quad (1)$$

where C_3, C_2, C_1 and C_0 are constants for a group of subjects. ZX is the number of zero-crossings in the diastolic phase of the secondary derivative of PPG. PAT is defined as the time interval between the R peak of ECG and peak of the first derivative of PPG. L is the estimated arterial length from heart to the PPG sensor location. The coefficients C_0–C_3 were recalculated by a multivariate regression method for the data collected in the two experiments of this study.

A. Experiment I: Supine Study

Eleven healthy subjects, including 5 males and 6 females, aged 23-35 years, participated in this experiment. Each subject was asked to lie on the contactless system described in Section II for 6 minutes. For references, ECG and PPG were simultaneously collected by sensors that were clipped onto the fingertips and forearms of the subjects, i.e. by a contact approach. An automatic BP machine (OMRON, Model HEM-907, Japan) was used to measure reference BP on the left upper arm of the subject at the beginning of signal recording and every 2 minutes afterwards. Including a cuff reading taken after the 6-minute recording, a total of four cuff readings were measured from each subject.

From the above recording, 33 sets of data were extracted for each system. Each set of data consisted of the averaged PAT of a 1-minute recording and the averaged of the two cuff BPs measured before and after the recording. The distances from subject's shoulder to the PPG sensors were measured after data recording.

B. Experiment II: Sitting Study

Nine subjects of Experiment I participated in the second experiment, including 4 males and 5 females. The same protocol described in Experiment I was used except that in this experiment, 1) subjects were asked to sit on the chair instead of lying on the bed during signal recording and cuff BP measurements and 2) the h-Shirt described in [4] was used for signal recording instead of the novel contactless system proposed in this paper. A total of 27 datasets were collected.

IV. Results

A. Comparison of Contactless and Contact BP Estimation in Experiment I

Fig. 2 shows a typical segment of ECG and PPG recorded simultaneously by the contact and contactless systems. Fig. 3 shows a typical segment of the percentage variation in beat-to-beat PAT calculated from the contact and contactless systems.

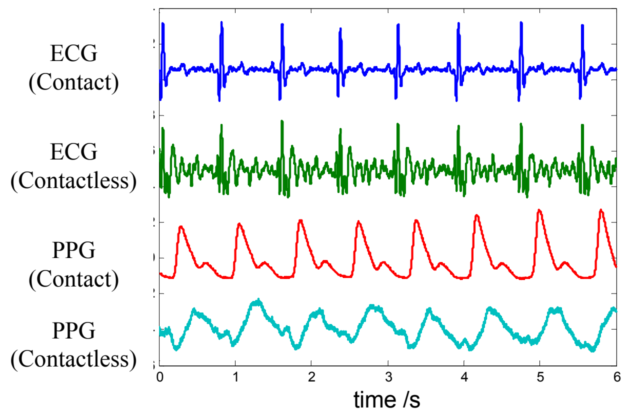

Fig. 2 A typical recording of the signals obtained by the contact and contactless systems

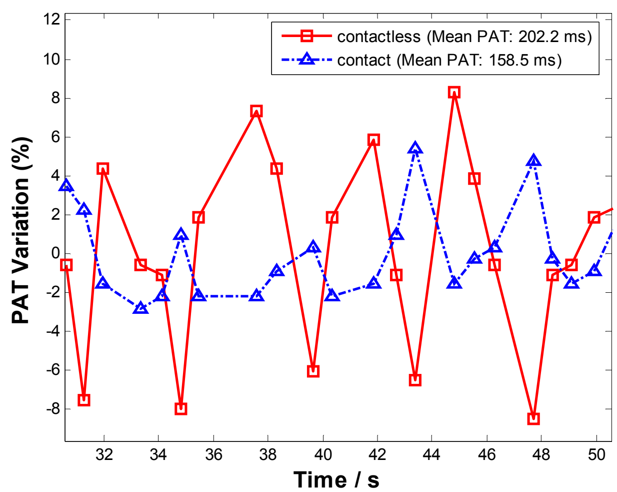

Fig. 3 Percentage variation of PAT from contact and contactless systems

SBP of the 11 subjects in Experiment I ranged from 86 mmHg to 117 mmHg with a standard deviation (SD) of 9.3 mmHg. Table I shows the regression results of the estimation of SBP by (1) for both the contactless and contact systems.

Table I Regression Results of SBP by (1) Using Signals from Contact and Contactless Systems

Signal Acquisition Method	Regression SD of SBP	P-value of variable coefficients			
		C_3 (PAT)	C_2 (L)	C_1 (ZX)	C_0
Contactless	7.1 mmHg	<0.05	<0.05	<0.05	0.091
Contact	7.4 mmHg	0.424	<0.05	0.568	<0.05

B. Comparison of Contact BP Estimation at Different Postures

For the 9 subjects who have participated in both experiments, their SBP were 101.3±9.8 mmHg and 111.6±13.4 mmHg when measured at supine and sitting postures respectively.

Using regression analysis on EQUATION(1), the SDs of differences between the estimated and reference BP were 7.9 mmHg and 5.5 mmHg for the supine and sitting postures respectively (see Table II). Fig. 4 compares the regression results at supine and sitting postures.

TABLE II REGRESSION RESULTS OF DIFFERENT POSTURES

Posture	Regression SD	Variation of Parameters		
		SBP	PAT	ZX
Supine	7.9 mmHg	101.3±9.8 mmHg	197±19 ms	5.1±0.6
Sitting	5.5 mmHg	111.6±13.4 mmHg	228±17 ms	4.4±0.6

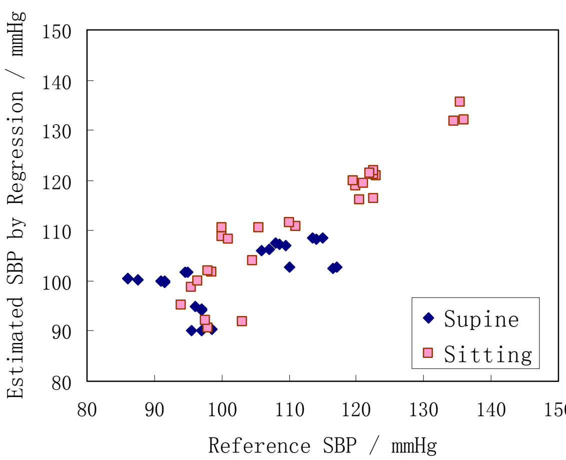

Fig. 4 Estimation of SBP by regression at different postures

V. DISCUSSION AND CONCLUSION

In this study, a novel contactless system for the cuffless measurement of arterial BP has been proposed and developed for the first time on a sleeping bed. The results of Experiment I showed that the quality of ECG and PPG obtained from the back of the subject by a cuffless approach are generally sufficient for estimating a robust PAT for the measurement of BP. Nevertheless, the beat-to-beat PAT measured by the two systems varied.

As showed in Fig. 3, variations of PAT calculated from the contactless and contact systems did not follow the same trend and sometimes even changed in the opposite direction. Since the two systems captured PPG from the back and finger of the subjects respectively, the variations in PAT of the two systems could be a result of the different physiological influence on the two measurement locations.

In a previous study, we have developed a cuffless SBP estimation and calibration method based on PAT, pulse transit distance and features of the second derivative of PPG and verified the method on over 20 subjects at a sitting posture [4]. The results of this study however showed that this method cannot be directly applied to estimate BP at the supine position.

PAT consists of pre-ejection period (PEP) and pulse transit time (PTT). According to Bramwell-Hill's model [5], PTT is negatively correlated with BP so that PTT should increase from sitting up to lying down when BP of the subject decreased. However, comparing the results of Experiment I and II, both PAT and BP decreased after the change of posture. One possible explanation of this phenomenon is that PEP variation with posture change should be accounted for and this kind of PEP variation is subject-specific [6]. Nevertheless, this could not fully explain the phenomenon. As shown in Table II and Fig. 4, the SD of differences between the reference BP and BP estimated by regression is considerably larger when measured at supine than at sitting, indicating new compensation factors must be considered. Further investigation should be conducted to understand the difference of BP estimation at different postures.

Nevertheless, a new method for cuffless BP monitoring has been proposed based on signals collected from a contactless system implemented on a sleeping bed. This technology is suitable for applying to nighttime monitoring of BP as it does not disturb the user's sleep.

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