Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Continuous Blood Pressure Monitoring using ECG and Finger Photoplethysmogram

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Abstract— **Pulse arrival time and the amplitude of the finger photoplethysmogram were used to track blood pressure continuously over 10-minute intervals. The measures were recorded with a holter-oximeter from a sample of 8 young, healthy human subjects in the supine and standing positions. Results indicate that, with individual calibration, systolic and diastolic blood pressure can be estimated with an average error of $\pm$6 and $\pm$4 mmHg respectively. Using pulse arrival time in combination with the amplitude of the finger photoplethysmogram gave better results than using any one alone, with PPG amplitude appearing to be more robust.**

I. Introduction

Recent studies have highlighted the clinical relevance of continuous blood pressure monitoring. Deviations from normal BP profiles have been associated with cardiovascular events [1], and ambulatory BP measurements have been found to better predict mortality than clinic measurements [2]. Currently approved ambulatory monitoring devices work mainly on the principles of auscultation and oscillometry, but they are still deemed cumbersome [3]. Modalities that are low-cost, more convenient and less intrusive will be useful in improving access to ambulatory blood pressure monitoring.

The objective of this study is therefore to evaluate the efficacy of cardiovascular measures in estimating and tracking both systolic (SBP) and diastolic blood pressure (DBP). These measures can be obtained relatively easily from the electrocardiogram (ECG) and pulse photoplethysmogram (PPG). A motivation is to be able to reliably track BP changes continuously using a holter-oximeter with minimal calibration.

II. Methods

8 young subjects (7 males, 1 female, aged 29$\pm$4 years, BMI 25$\pm$4 kg/m^2) with no known medical conditions volunteered for this study. Subjects performed three 10-minute maneuvers: paced breathing in the supine position (0.2 Hz), spontaneous breathing in the supine position, and spontaneous breathing in the standing position. Time was allowed ($\sim$5 minutes) between maneuvers for autonomic stabilization. Time of day and ambient temperature were not controlled for, although most recordings were made in the evening. An identical experiment was conducted on 4 of the subjects one month later.

This work was supported by Enterprise Ireland through project CFTD 2004 BRI 117.

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ECG and PPG were recorded using a holter-oximeter (NorthEast Monitoring, Inc, USA). Continuous BP was recorded using Portapres (Finapres Medical Systems BV, The Netherlands) via a 16-bit ADC (Cambridge Electronic Design, UK). Portapres values were verified to be within $\pm$5 mmHg of 2 readings obtained with a wrist BP monitor (Omron, Japan) before recording commenced. Recommended cuff sizes were chosen, a fixed cuff was used on the middle phalanx of the left middle finger, and Physiocal calibrations were activated. Portapres has also been shown to be stable in ambulatory recordings [4].

Four candidate measures, namely pulse arrival time (PAT), PPG amplitude, T-wave amplitude and heart rate were derived from the ECG and PPG. PAT was defined as the time interval between the R peak and the point with maximum gradient on the rising edge of the PPG. PPG amplitude was calculated as the foot to peak amplitude of the rising edge of the PPG. PAT has been shown to be inversely related to BP [5]; decreased arterial compliance during high arterial pressure causes a reduction in PAT, and vice versa. PPG amplitude is an indicator of the pulsatile changes in blood volume caused by arterial blood flow around the measurement site [6]. T-wave amplitude has been suggested as a sympathetic marker, while the baroreflex regulates heart rate inversely with respect to BP changes.

Multiple linear regression was used to quantify the relationships between BP and the candidate measures and to estimate BP. Non-significant regressors, outlying and influential data points were automatically identified and removed. BP was estimated using (1).

$$\begin{aligned} BP[i] &= b_0 + b_1 PPG[i] + b_2 PAT[i] \\ &\quad + b_3 PPG[i-1] + b_4 PAT[i-1] \end{aligned} \quad (1)$$

where i indicates beat-by-beat samples.

To provide comparison, BP was also estimated using PAT or PPG amplitude alone. Estimation error was defined as (estimated $-$ observed) measurements according to the European Society of Hypertension International Protocol [7]. Correlation between estimated and measured BP, bias and standard deviation of estimation error were used as performance measures. The performance of the scheme was also evaluated by averaging measured and estimated BP values into one-minute epochs.

The predictive ability within an individual was tested by validating regression coefficients obtained from the first

half of datasets (calibration segment) on the second half (validation segment). Also, the practical utility of this scheme was evaluated in two ways. The robustness of regression coefficients across postures was tested by cross-validating the coefficients in the supine and standing positions. The stability of regression coefficients was assessed by comparing coefficients from repeat experiments in the same subjects.

The relationship between BP and the candidate measures in a low-frequency band was investigated by low-pass filtering the data with a cut-off frequency of 0.02 cycles/beat. The goodness-of-fit of the linear regression model was evaluated by computing the power spectral density (PSD) estimates of the residual for each of the three positions. Statistical significance was assessed at the 5% level.

III. Results

Table I summarizes the performance of BP estimates obtained by regressing the BP data on the relevant measure/s. Using PAT and PPG amplitude in combination gave better BP estimates than using any one alone. Overall errors were 5.6 and 3.5 mmHg for SBP and DBP respectively. In the supine position, PPG amplitude was superior to PAT for both SBP and DBP. In the standing position, PAT performed better. Better estimates were obtained during paced breathing compared to spontaneous breathing.

Overall, higher correlations were found with SBP than DBP. Although errors appeared to be smaller for DBP, DBP had lower variability relative to SBP. In percentage terms, SBP errors were actually lower. T-wave amplitude and HR correlated only moderately with BP, and the direction of correlation was inconsistent. They were unreliable enough under the experimental conditions to be considered for BP estimation.

Fig. 1 gives a typical example of tracking performance. The estimated BP values were able to track trends in BP variation well, although they were not sensitive enough to track sharp short-term ($\sim$30 seconds) changes. By considering one-minute epochs, errors reduced by approximately half and correlation improved, especially for DBP. This suggest potential utility in clinical applications where lower temporal resolution is sufficient, such as ambulatory monitoring.

Within-subject validation performance is shown in Table II. Both SBP and DBP estimates were comparable to those obtained from the calibration segment, except for the presence of a slight bias, which was more significant for DBP. The minimum calibration segment required was found to be 3 minutes. The results suggest that with individual calibration, a combination of PAT and PPG amplitude can be used to estimate SBP and DBP reasonably on new data obtained from the same individual.

Separate calibration was required for the supine and standing positions, as although correlation was maintained, there was considerable bias and average error was large. The regression slope of PPG amplitude on SBP was highly stable in the supine position. Apart from that however, reproducibility of the calibration was rather low, indicating that intermittent recalibration is required.

TABLE II
WITHIN-SUBJECT VALIDATION PERFORMANCE (N=8)

Position	SBP			DBP		
	r	Bias (mmHg)	SD (mmHg)	r	Bias (mmHg)	SD (mmHg)
I	0.83	1.7	4.5	0.56	-0.1	2.7
II	0.70	-1.2	6.3	0.51	-0.8	3.7
III	0.74	-0.6	6.6	0.54	-2.5	4.3
Overall	0.76	-0.0	5.8	0.54	-1.1	3.6

Position I: Supine, paced breathing. II: Supine, spontaneous breathing. III: Standing, spontaneous breathing.

Considering only the low-frequency band, correlation between BP and PAT improved in the supine position, but not in the standing position. Between BP and PPG amplitude, correlation improved markedly in the standing position, with modest improvements in the supine position. The PSDs of the residuals were dominated by low frequency components, suggesting slow baseline drifts that could not be accounted for by the linear regression model.

IV. Discussion

With an overall correlation of 0.65 and 95% limits of agreement of $\pm$9.4 mmHg, this scheme compares moderately with similar techniques. On the one hand, Young et al. reported a pulse transit time-based device with bias of 0.37 mmHg and limits of agreement of -29.0 to 28.2 mmHg [8]. On the other hand, Chen et al. obtained SBP estimates that correlated highly (0.97$\pm$0.02) with invasive measurements [9].

There have been recent studies into the relationship between PAT and BP using similar equipment. In comparison, the correlation obtained in this study for SBP was lower while that for DBP was higher, including in the low-frequency band [10], [11]. This may support the view that PAT alone is not reliable enough for BP estimation.

An example of the relationship between PAT and SBP is given in Fig. 2. As shown, the assumption of a negative linear

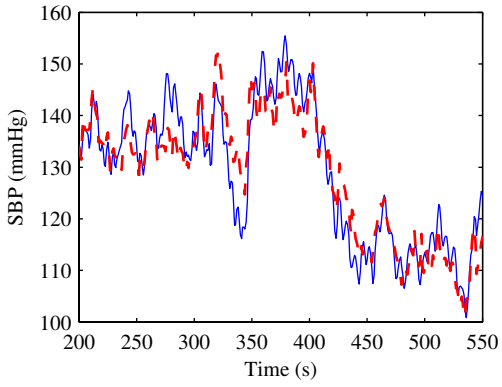

Fig. 1. Beat-by-beat SBP tracking in a single subject. (r=0.92, p<0.001, r^2=84%). Solid line: Measured SBP. Dotted line: Estimated SBP.

TABLE I

ESTIMATION PERFORMANCE (N=8)

	Correlation (Measured & Estimated BP)						SD (Estimation Error) (mmHg)					
	SBP			DBP			SBP			DBP		
Measure	PAT	PPG	PAT+ PPG	PAT	PPG	PAT+ PPG	PAT	PPG	PAT+ PPG	PAT	PPG	PAT+ PPG
I	0.36	0.66	0.81	0.42	0.51	0.61	7.0	5.6	4.5	2.8	2.7	2.5
II	0.43	0.70	0.79	0.36	0.48	0.55	8.2	6.4	5.5	4.1	3.7	3.5
III	0.64	0.34	0.75	0.39	0.31	0.54	8.0	9.8	6.8	4.9	5.4	4.5
Overall	0.48	0.58	0.78	0.39	0.44	0.57	7.7	7.2	5.6	4.2	3.9	3.5

Position I: Supine, paced breathing. II: Supine, spontaneous breathing. III: Standing, spontaneous breathing.

relationship, i.e. $BP{=}f(PAT)$ instead of an inverse relationship, i.e. $BP{=}f(1/PAT)$ as predicted by theory, was found to be more appropriate. Furthermore, correlations with BP were markedly stronger in the standing position. Standing is associated with vasoconstriction at the extremities and an increase in arterial tone, so it is speculated that a baseline arterial stiffness is required to observe a good correlation, by operating on a point on the compliance curve where there is a stronger relation between BP and PAT.

A negative linear relationship was found between PPG amplitude and BP, and it was useful for BP estimation, particularly in the supine position. The physiological basis of the relationship is thought to be due to the changes in compliance that results from changes in blood pressure. The lower average levels of PPG amplitude during standing is attributed to vasoconstriction, which causes a change in compliance arising from a reduction in arterial diameter. This marked difference in PPG amplitude also caused differences in the regression intercepts, resulting in the need for separate calibrations across postures. PPG amplitude was less effective in the standing position, which is speculated to be due to the effect of vasoconstriction at the finger restricting the dynamic range of amplitude variations.

Relative to PAT, PPG amplitude provided better correlations in all cases except for estimating SBP in the standing position. Furthermore, it was observed that PPG amplitude could reflect relatively fast-changing BP oscillations (in the order of a few beats) while PAT could not. This suggests that overall, PPG amplitude may be a more robust measure than PAT for BP estimation.

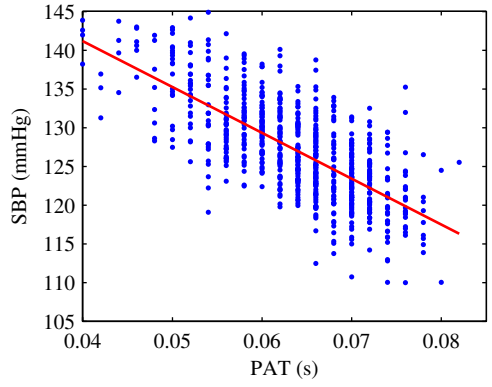

Fig. 2. Illustration of the relationship between PAT and SBP (r=-0.71, p<0.001, SBP=-592*PAT+165).

Although satisfactory estimates of beat by beat BP may be obtained with the proposed scheme, the error still exceeds the performance requirements for highly accurate blood pressure monitoring equipment [7]. Nevertheless, this work has demonstrated, with simple signal processing techniques, a baseline efficacy of using PAT and PPG amplitude to estimate short-term BP.

The possibility of using a more nonlinear model was evaluated. A simple neural network with a 4:2:1 topology was used to estimate SBP and DBP using current and one previous value of PAT and PPG amplitude. A cross-validation scheme was used, using data from all other subjects less the one in question to train the network. Bias fell considerably and SD of error was reduced, but overall the gains were incremental. While the neural network approach produced smaller errors, the estimates were coarser. The linear regression model actually produced tighter fits, albeit with greater bias.

Pilot efforts have been made to extend this study to overnight sleep recordings from young, healthy subjects. ECG and finger PPG were recorded using Biopac (Biopac Systems, Inc, USA), and continuous BP using Portapres. For Portapres, the same precautions described were applied. In addition, 30-minute switching intervals were used. Baseline shifts between cuffs were remedied before recording commenced. The heart level reference was placed on the chest to account for changes in sleeping position.

Regression coefficients were determined at 20-minute intervals, using 20 Portapres BP values from the beginning and end of the 20-minute segment. This was motivated by considering the typical operation of an ambulatory blood pressure monitor, which typically makes a measurement every 20-30 minutes over a 10-15 beat period. The coefficients were then used to estimate BP within the segment. Two recordings have been made to date, and initial results were encouraging. Both SBP and DBP estimates were reasonably correlated and had relatively low errors (SBP: r=0.59$\pm$0.16; Bias=0.7$\pm$3.4 mmHg; SD=5.9$\pm$1.3 mmHg) (DBP: r=0.59$\pm$0.18; Bias=0.3$\pm$1.7 mmHg; SD=3.6$\pm$0.8 mmHg).

Fig. 3 shows an example of SBP and DBP tracking across

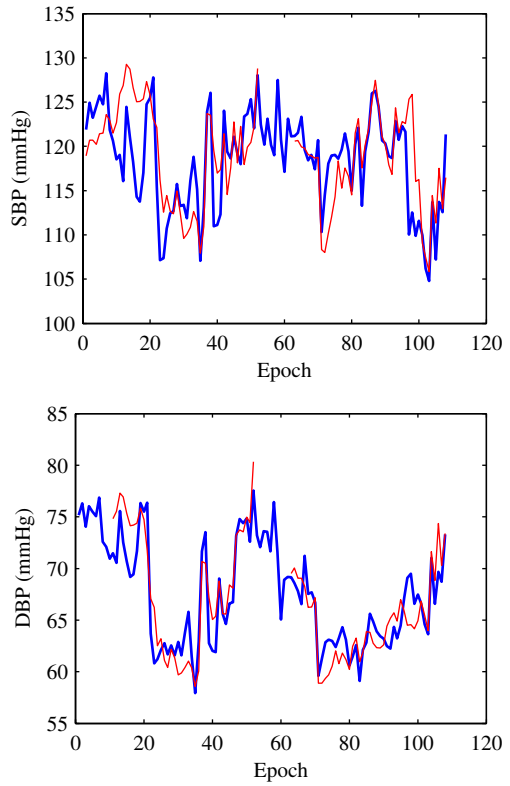

Fig. 3. Overnight SBP and DBP tracking in a single subject. Thick lines: Measured BP. Thin lines: Estimated BP. Gaps in estimated BP were due to unsuccessful calibration.

the night, with the estimates averaged over 2-minute, non-overlapping epochs. (SBP: r=0.65, Bias=0.6 mmHg, SD=4.6 mmHg). (DBP: r=0.89, Bias=0.2 mmHg, SD=2.5 mmHg). This suggests that with intermittent re-calibration and at the expense of some temporal resolution due to averaging, this scheme may be extended to overnight BP estimation.

Further work will be required to fully evaluate this possibility. In particular, the impact of changes in peripheral arterial tone, which may occur either spontaneously or as a result of sympathetic activation within the night [12], needs to be further established. Also, the ability to pin-point the need for re-calibration more precisely is necessary to improve the practical utility of this scheme. One possible approach is to detect changes in PPG pulse shape, which is characteristic of vasoconstriction.

To further assess the utility of BP estimates obtained using this scheme, the efficacy of using estimated SBP to measure the baroreflex effectiveness index (BEI) was evaluated. BEI measures the proportion of SBP ramps that successfully triggers a reflex change in RR interval, and in hypertensive patients with chronic renal failure it was found to be markedly reduced [13]. Estimated BEI values were comparable to those obtained using measured SBP in the supine position, while in the standing position they tend to be underestimated.

This study focused on estimating SBP and DBP over mean arterial pressure (MAP), as it has been shown that the prognostic significance of ambulatory SBP, DBP and their derivative, pulse pressure, were generally higher than MAP [14]. Nevertheless, this scheme can be extended to estimate MAP. In fact, MAP estimation performance was between that for SBP and DBP, as MAP is a linear combination of SBP and DBP.

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