Novel Blood Pressure Estimation Method Using Single Photoplethysmography Feature

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***Abstract*—Continuous blood pressure (BP) monitoring has a significant meaning to the prevention and early diagnosis of cardiovascular disease. However, existing continuous BP monitoring approaches, especially cuff-less BP monitoring approaches, are all contraptions which complex and huge computation required. For example, for the most sophisticated cuff-less BP monitoring method using pulse transit time (PTT), the simultaneous record of photoplethysmography (PPG) signal and electrocardiography (ECG) are required, and various measurement of characteristic points are needed. These issues hindered widely application of cuff less BP measurement in the wearable devices. In this study, a novel BP estimation method using single PPG signal feature was proposed and its performance in BP estimation was also tested. The results showed that the new approach proposed in this study has a mean error -0.91 $\pm$ 3.84 mmHg for SBP estimation and -0.36 $\pm$ 3.36 mmHg for DBP estimation respectively. This approach performed better than the traditional PTT based BP estimation, which mean error for SBP estimation was -0.31$\pm$4.78 mmHg, and for DBP estimation was -0.18$\pm$4.32 mmHg. Further investigation revealed that this new BP estimation approach only required measurement of one characteristic point, reducing much computation when implementing. These results demonstrated that this new approach might be more suitable implemented in the wearable BP monitoring devices.**

I. Introduction

Cardiovascular diseases are becoming the leading causes of death in the world, nearly 17.3 million of people died from cardiovascular disease which accounting for 30% of global deaths every year according to the reports of World Health Organization. Blood pressure (BP), as a crucial vital sign, is considered as the most effective risk factor of the cardiovascular death. It has been proved that long term BP monitoring, especially continuous BP monitoring, has a significant meaning towards the prevention and early diagnostics of cardiovascular disease. Traditional continuous BP approaches includes finger-cuff methods, cuff-less BP estimation using pulse transit time (PTT), and images based cuff-less BP estimation, which principles are all based on the hemodynamics property. Comparing to cuff-based approaches, cuff-less continuous BP monitoring has received much attention due to its comfort and convenience.

PTT based BP estimation is the most sophisticated cuff-less continuous BP monitoring approach. However, due to the limitation of sensor technology, pulse transit time, the most important parameter in the PTT based approach, cannot be detected directly, thus an alternative parameter called pulse arrival time (PAT) was used as a alternative of PTT in BP estimation. But lots of problems were occurred due to this substitution. On the one hand, traditionally the pulse arrival time was measured from one characteristic point of electrocardiography (ECG) and one characteristic point of photoplethysmography (PPG) during one heart cycle, which means a simultaneous record of PPG and ECG is needed when application and various characteristic points needed to be detected for the feature calculation. On the other hand, it has also been reported that the ECG-PPG based pulse arrival time comprises the PTT and the pre-ejection period, which comprises the electromechanical delay time and isovolumic contraction period of the left ventricle, and this redundant period would strongly influence the accuracy of PTT based BP estimation [1, 2]. These issues are hindering the prevalence of PTT based BP estimation and an alternative method remove these effects need to be discovered.

Photoplethysmography, as a vital sign which could directly reflect the arterial properties, has been wildly researched in past years. Attempts have been made to estimate BP using PPG signal alone. A study conducted by Ding shown that the intensity ratio of PPG signal may directly reflect vascular diameter changes during one cardio cycle. Based on this, a new feature called PPG intensity ratio was proposed and its potential in BP estimation was also tested[3]. But only diastolic BP (DBP) was estimated using PPG intensity ratio in Ding's work, where PTT was also used in estimating systolic BP (SBP). Some BP estimating approaches using PPG signal alone were also reported, but these approaches mainly focused on machine learning or neural network methods in BP modeling, which were not the real physiological models [4, 5]. To our knowledge, there were no reports in estimating BP using PPG feature alone based on real physical model.

In this study, a novel BP estimation method based on single PPG feature - mean slope transit time (MSTT) was

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proposed and its performance was validated. This PPG feature MSTT had a strong correlation and well coherence with BP both in time domain and frequency domain. The new BP estimation approach also performed better than PTT based approach in BP estimating. Comparing to the traditional PTT based BP estimation method, this new approach only required single PPG signal and detecting one fiducial point, which may be more suitable in wearable continuous BP monitoring devices.

II. METHODS

A. Mean Slope Transit Time (MSTT) Derivation

Pulse wave transmission in the artery was influence by many issues like the artery diameter, the arterial stiffness, it is expected that the transmission of blood wave may varied cyclically with the inner blood pressure changed during the respiration activity. As the pulse wave transmission varied with the heart cycle, the final plethysmographic waveform we observed in practice is the association of a series of pulse waveform from many heart cycles. A recent study reported by Addison discussed this aggregation of internal pulse in pulse wave [6]. By observing the pulse wave components change during the respiration cycle, Paul reported that the gradient of the upslope of the initial pulse wave component varied directly with transit time, which may be a potential alternative of PTT in hemodynamic researches. This upslope was not influenced by the heart rate effects and ejection period, which means it would provide a more accurate alternative than other parameters. In this case, Paul proposed a novel PPG factor named slope transit time (STT) as the proxy alternative of PTT, this factor is computed from the single fiducial point of upslope of PPG, the detail illustration of slope transit time was shown in Fig.1 [6].But there are still many limitations in implementing STT, as the STT was computed from the single point of PPG signal, its stability may be strongly influenced by signal quality.

In this study, we proposed a novel factor called mean slope time (MSTT) as a proxy alternative of PTT, the MSTT referenced the slope transit time but improving its stability by implementing new factors. In previous work, STT was defined as a function below:

$$\mathrm{STT} = \mathrm{A}/\mathrm{m} \quad (1)$$

Where m is the max-slope of upslope of PPG, and A is a constant arbitrary amplitude related to the amplitude of PPG signal. To enhance its anti-noise ability, in this study, we defined parameter MSTT as

$$\mathrm{MSTT} = \mathrm{f}(\mathrm{A}/m_1) \quad (2)$$

m_1 is the mean slope of a constant periods of PPG includes the max-slope point of upslope. f is a function for MSTT computation. A is the constant related to the amplitude of PPG.

B. Experiments

Ten health subjects were involved in this study. There were five males and five females with average age of 24.8$\pm$1.7 years. All subjects were nonsmokers and with no cardiovascular disease history. Subjects were asked to sit for 5 minutes rest before test. Reference continuous BP were measure by the non-invasive continuous BP measurement (FMS, FINAPRE MEDICAL SYSTEM, NETHERLAND), the standard I lead ECG and finger PPG were recorded simultaneously with the sampling rate 250HZ (MP150, BIOPAC, USA). All tests were performed when the subjects were seated and all physiological signals were recorded for five minutes. This test was approved by the University Ethic Community and all participates were gave their info consent.

c. Blood Pressure Estimation

Continuous MSTT was computed from the PPG signal using the function as (2) shown above. PAT was also calculated as the time interval from R-peak of ECG to the peak of PPG. Spectrum domain analysis was applied on MSTT, PAT, continuous SBP and DBP to investigate the neural modulation of these parameters. In order to validate the potential of MSTT to estimate BP, a sophisticated transit time based BP estimation algorithm was also applied on MSTT and PAT, and their performances were evaluated. For the PAT, the estimation algorithm was

SBP =

$$a_1 * \ln\frac{PAT0}{PAT} + b_1 * PP_0 * \frac{PAT0}{PAT} + \frac{2}{3} * PP0 + MBP_0 + c_1 \quad (3)$$

DBP =

$$a_2 * \ln\frac{\mathrm{PAT0}}{\mathrm{PAT}} + \mathrm{b}_2 * PP_0 * \frac{\mathrm{PAT0}}{\mathrm{PAT}} - \frac{1}{3} * \mathrm{PP0} + MBP_0 + \mathrm{c}_2 \quad (4)$$

Where PAT_0, MBP_0, PP_0 are the calibration value of PAT, mean blood pressure (MBP), and pulse pressure (PP) respectively. $\mathrm{a}_1, \mathrm{b}_1, \mathrm{c}_1$ and $\mathrm{a}_2, \mathrm{b}_2, \mathrm{c}_2$ are the corresponding function coefficients.

MSTT was a proxy alternative of PAT in BP estimation, so for the parameter MSTT, the BP estimation algorithm was

SBP =

$$a_3 * \ln\frac{MSTT0}{MSTT} + b_3 * PP_0 * \frac{MSTT0}{MSTT} + \frac{2}{3} * PP0 + MBP_0 + c_3 \quad (5)$$

DBP =

$$a_4 * ln\frac{MSTT0}{MSTT} + b_4 * PP_0 * \frac{MSTT0}{MSTT} - \frac{1}{3} * PP0 + MBP_0 + c_4 \quad (6)$$

Where MSTT_0 is the calibration value of MSTT, a_3, b_3, c_3 and a_4, b_4, c_4 are the corresponding function coefficients.

III. RESULTS

A. Waveform in Time Domain

Parameter MSTT, PAT was computed from the simultaneously recorded ECG and PPG. Fig.2 (a) and 2 (b)

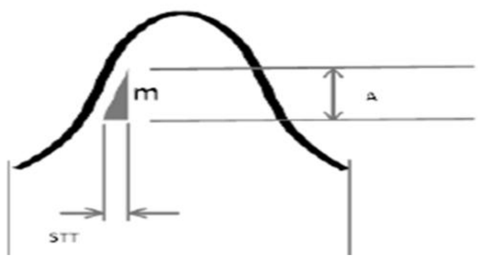

Fig.1 Schematic of STT Measurement, m is max-slope of the upslope of PPG, A is the constant arbitrary amplitude

showed the continuous SBP and the corresponding DBP waveform of one subject. Beat to beat PAT and MSTT corresponding to the continuous BP wave shown in Fig.2 (c) and Fig.2 (d). It can be easily observed that, the parameter MSTT had a similar variation with the continuous BP, where the variation of PAT was less similar with continuous BP. The waveform of PAT was less stable than MSTT where many high frequency noises were involved. The MSTT was also in phase with PAT, which was in accordance with the results that the gradient of upslope of PPG may be a proxy alternative of PAT[6]. The coherence between MSTT and PAT also demonstrated that the MSTT may be a proxy alternative of transit time.

B. Spectrum Analysis

Spectrum analysis was also performed in this study. The power spectral density (PSD) of SBP, DBP, PAT and MSTT were analyzed, which was shown in Fig.3. It is obvious that the spectral peak of SBP was at around 0.25 HZ, which was at the high frequency (HF, 0.15-0.40HZ) domain. The spectral peak of DBP was at low frequency (LF, 0.04-0.15HZ) domain, which was at around 0.08HZ. The results that the spectral peak of SBP was at HF where the spectral of DBP was at LF were in accordance with previous studies [7]. For the PAT, there was a spectral peak at HF which was about 0.22HZ, which was quite similar with the peak of SBP. For the parameter MSTT, two spectral peaks were observed in its PSD figures, where one peak was at LF and the other peak was at HF respectively.

C. Blood Pressure Estimation Performance

In order to validate the MSTT's potential for continuous BP estimation, a transit time based BP estimation algorithm was also applied on both PAT and MSTT. BP estimation algorithm were shown in (3), (4), (5) and (6), model coefficients in these function were the derived using the least square method. Estimation results were shown in Tab.1. For the traditional PAT based BP estimation, the error for SBP estimation was -0.31$\pm$4.78 mmHg, where the error for DBP estimation was -0.18$\pm$4.32 mmHg. However, for the new approach proposed in this study, the error for MSTT based SBP estimation is -0.91$\pm$3.84 mmHg, and -0.36$\pm$3.36 mmHg for DBP estimation. The MSTT based approach had a better performance than traditional PAT based approach as the whole, though its mean little larger than traditional one. Fig.4 showed one of SBP estimation results, the blue, red and green curve was the reference SBP, PAT estimated SBP and MSTT estimated SBP respectively. The variation of MSTT based approach is much similar to the variation of reference continuous BP than PAT based estimation, the overall performance of MSTT based estimation was also better than PAT based one.

IV. DISCUSSION

Cuff-less BP estimation has been extensively researched for its feasibility in continuous and non-invasive BP monitoring. Many approaches have been proposed and the most sophisticated one is PTT based BP estimation. But this approach hasn't been widely applied in wearable health devices because of many issues besides accuracy. In this study, MSTT, a new factor extracted from PPG signal was proposed as a proxy alternative of pulse transit time, and its and its potential of estimating BP was also validated. The

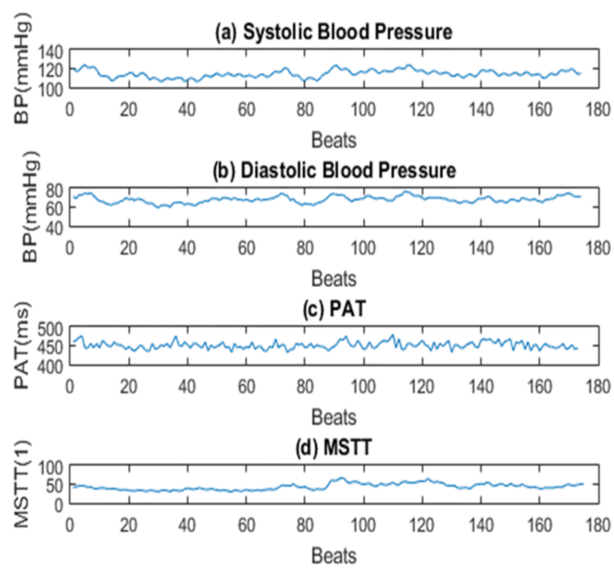

Fig.2 Continuous waveform of (a) SBP, (b) DBP, (c) corresponding PAT, (d) corresponding MSTT

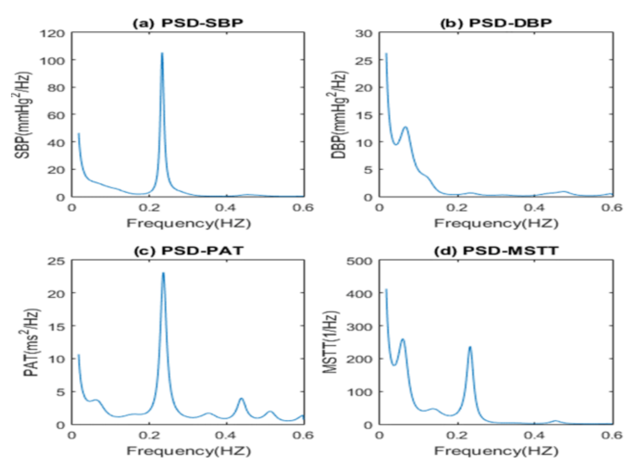

Fig.3 PSD of (a) SBP, (b) DBP, (c) PAT, (d) MSTT

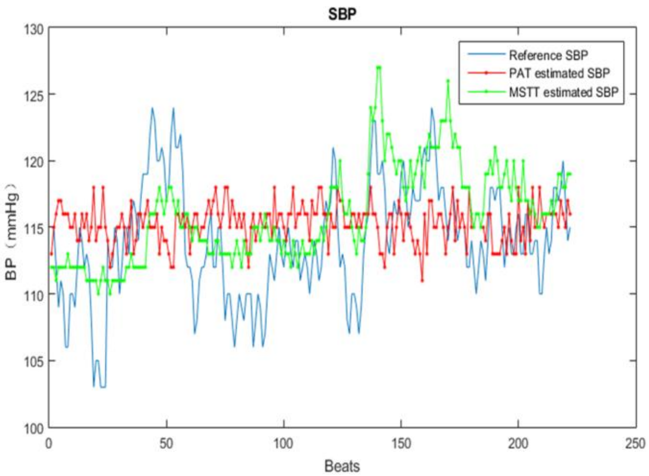

Fig.4 Reference continuous SBP (blue), PAT based estimated SBP (red) and MSTT based estimated SBP (green)

TABLE I. BP ESTIMATION RESULTS

APPROACHES	ERROR (mmHg)	
	Mean Error	*Standard Deviation*
PAT-SBP	-0.31	4.78
PAT-DBP	-0.18	4.32
MSTT-SBP	-0.91	3.84
MSTT-DBP	-0.36	3.36

results showed that MSTT had a strong correlation with BP and its performance in BP estimation was better than traditional pulse transit time one.

It has been long recognized that BP pressure was modulated by spontaneous fluctuation such as respiration activity in HF by spontaneous fluctuation such as respiration activity in HF range, and vasomotion activities in LF range, thus many issues may lead to the poor accuracy of traditional PTT based BP estimation. For example, by analyzing the spectral components of PTT, BP, previous study conducted by Ma reported that PTT was only able to reflect BP changes in HF range, which means PTT may be more suitable to estimating SBP rather than the DBP [8]. Also, due to the limitation of sensor technology, PTT cannot be detected directly where the most common alternative was pulse arrival time which comprise both PTT and ejection period. These issues may cause the dilemma today. In this study, we found that MSTT were associated with both spontaneous activities and vasomotion activities according to its PSD which was shown in Fig.3 (d). This phenomenon may indicate that the modulation of MSTT was similar to the BP modulation. The estimation results shown in Tab.1 also demonstrated the fact that MSTT performed better in BP estimation. These results showed that MSTT might be a potential factor in BP estimation using PPG alone. This new parameter MSTT, which only required one fiducial point, could be potentially widely applied on the wearable cuff-less BP monitoring system.

But there are still some limitations in this study. The BP estimation model used for MSTT was just a modification of PAT based model, it may not be the most suitable model for MSTT. In future study, we may further investigate this parameter and search for a more accurate BP estimation model for BP estimation in hypertension patients.

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