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A Novel Method for Assessing Arterial Stiffness by a Hydrostatic Approach

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Abstract—**Arterial stiffness is an important index for cardiovascular events. The objective of this study is to examine possible parameters related to arterial stiffness that can be estimated during simple arm movements. An experiment was conducted on 32 subjects divided into two groups, one with an age of 26±4 years old, and the other 61±9. The pulse transit time measured from electrocardiogram to finger photoplethysmogram (PPG) and the amplitude of PPG were calculated beat-to-beat for the subjects while they had their arms lowered. The results of the study showed that the ratio between percentage changes in PTT and finger height are significantly different for the two groups of subjects with different age and health conditions, indicating that parameters can be potentially extracted from this procedure to represent the difference in arterial stiffness of the two groups of subjects.**

Keywords—**Wearable devices, blood pressure, pulse transit time, hydrostatic calibration**

I. Introduction

Arterial stiffness has been broadly acknowledged as an important parameter associated with the risk of cardiovascular diseases such as stroke and coronary artery disease. Different methods have been investigated to obtain stiffness related indices. For examples the carotid-femoral pulse wave velocity (PWV) obtained from pressure transducers and heart sounds [1]-[8], amplitude ratios calculated from the second derivative photoplethysmogram (SDPTG) [3]-[11], brachial artery endothelial function test with ultrasound and blood pressure (BP) cuff [5], and some time intervals [7],[12]-[14] have been reported to relate with age or high BP. The SDPTG method advances other arterial stiffness index (ASI) as it simply takes use of the PPG waveform which can be easily measured from peripheral limb; however, the physiological meaning behind this parameter is still under investigations [3], [12]. Besides, since it is based on contour analysis of PPG, it may be subjected to factors that can affect the waveform of PPG and not the arterial properties, e.g. temperature, contact force and BP changes that are not related with vascular aging.

In this study we aim at testing a parameter obtained from an arm lowering process and its potential of being used as arterial stiffness index.

II. Methodology

We have previously proposed a model as shown in equation (1) based on the Bramwell-Hill equation and the volume-pressure relationship (V-P model) of artery to describe the changes of PTT under the effect of a varying hydrostatic component, e.g. during hand elevation movement [15]. In this study, we propose a novel parameter for quantifying arterial stiffness using this model.

$$PTT=\begin{cases}\dfrac{L\sqrt{\rho \mathrm{b}}}{\sqrt{1+\exp(\mathrm{bP_i})}} & ;\ \mathrm{h}=0\\[2ex] \dfrac{2L}{\sqrt{\rho \mathrm{b} g h}}\ln\left|\dfrac{\sqrt{\exp[\mathrm{b(P_i\text{-}P_h)}]+\exp(-bP_h)}-\sqrt{\exp(-bP_h)}}{\sqrt{\exp[\mathrm{b(P_i\text{-}P_h)}]+1}-1}\right| & ;\mathrm{h}\neq 0\end{cases},(1)$$

The study was performed on 32 subjects of age range from 22 to 83 yrs.. 14 of them are females. The subjects include those without known health problems, heart failure patients and subjects with other diseases. 21 subjects have not been diagnosed with any chronic diseases. All subjects were instructed about the study procedure and they all gave an explicit consent.

Subjects were asked to lie down on a slightly tilted table while their ECG, PPG measured on the left index finger, continuous BP (Finapres, Ohmeda, USA) and intermittent BP (Omron HEM-907) from right arm were recorded. The arm length of a subject, L, defined as the distance from shoulder (acromion) to the fingertip of index finger, was also measured.

Subjects were instructed to stretch out their left arms and slowly lower their arms from a vertically upward position to below the horizontal plane. The angle of elevation was monitored by an accelerometer worn on the subjects' left wrist.

From the recorded signal, PTTfin was defined as the pulse arrival time measured from the R-peak of ECG to the upstroke point of finger PPG pulse within the same heart cycle. HSr was defined as the slope of PTTfin changes vs.

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height during the arm elevation process by regression method. The student's t-Test was used to examine the difference and $p<0.05$ was regarded as statistically significant. Data were presented as mean±standard deviation (Mn±SD).

III. Results

Table I includes the pulse wave velocity which is calculated from dividing subject's arm length over his or her resting PTTfin, the arterial aging index (AI) which is obtained by locating the 5 points of flexion on SDPTG waveform (a, b, c, d and e) and calculating their amplitudes by (b-c-d-e)/a, the optimal model coefficient b calculated using measured BPs and PTTfins [15] and HSr which is calculated from as regression slope of PTTfin changes during the arm elevation process.

TABLE I
COMPARISON OF PARAMETERS FOR TWO SUBJECTS GROUPS IN THIS STUDY

	Control Group	Aged Group	P value
Number of Subjects	19	13	N/A
Age (yrs.)	26±4	61±9	<<0.05
Resting SBP:	120±14	134±18	<0.05
Resting DBP:	73±11	80±10	≈0.05
r (SBP, PTTfin)	-0.79±0. 13	-0.85±0. 16	>0.05
L/PTTfin (m/s)	5.1±1. 1	4.9±0. 7	>0.05
AI	-1.12±0. 41	-0.60±0. 53	<0.05
b ($mmHg^{-1}$)	0.05±0. 03	0.02±0. 02	<<0.05
HSr	0.004±0. 002	0.002±0. 001	<0.05

Unit for BPs and BP ranges: mmHg

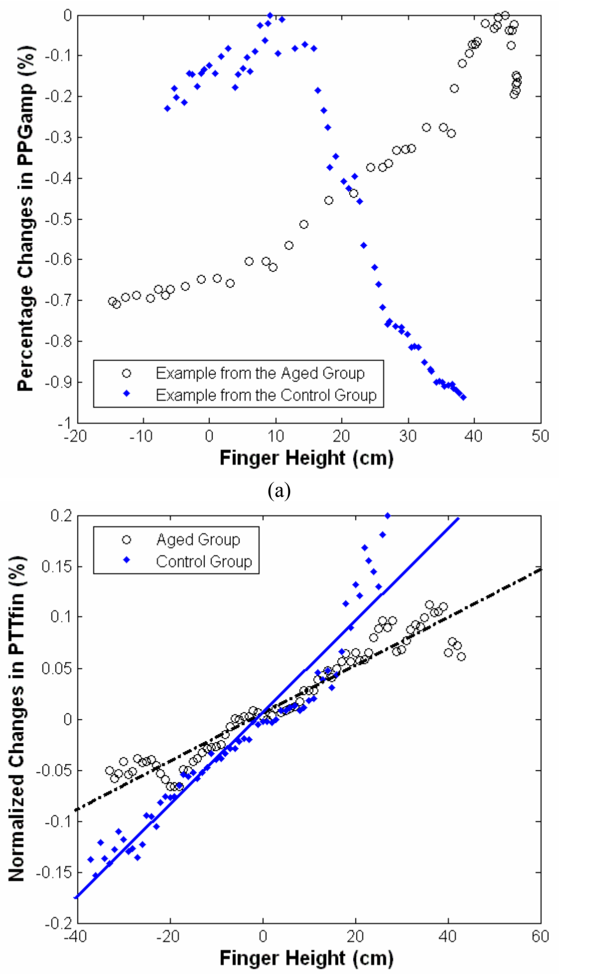

Fig. 1. (a) Percentage changes of PPG amplitude over height, and (b) normalized changes of PTTfin over height.

Fig. 1(a) gives typical examples of changes in the amplitude of PPG with height. The Y axis is normalized to the maximum amplitude observed during the process. Fig. 1(b) shows the mean percentage changes in PTTfin over height for all subjects after individually interpolating PTTfin from -40 cm to 45 cm.

Fig. 2 shows the simulation results of the percentage changes in PTT versus height based on the (1) under different BP at heart level (Pi) and elasticity of artery b.

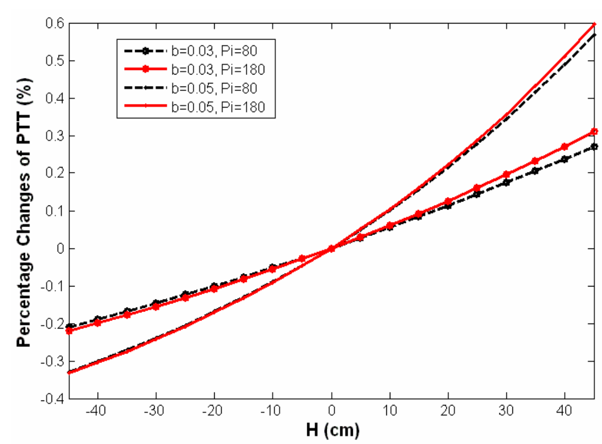

Fig. 2. Simulated* results of percentage changes in PTT over height.
* L=60 cm is used for simulation. Units: Pht0: mmHg, b: $mmHg^{-1}$

IV. Discussion and Conclusion

In a previous study, the relationship between peripheral BP and PTTfin as well as that between H and PTTfin have been discussed [15], [17]. In this study, our interest is to examine the changes in PTTfin and in the amplitude of PPG during a continuous arm elevation process for potential arterial stiffness related indices.

As shown in Fig. 1(a), when subject slowly lowered his/her arm, the amplitude of PPG gradually increased and then decreased after reaching a maximum, where transmural pressure (Ptr) is approximately zero. Corresponding height when Ptr approaches zero (Htr) is subject dependent and generally higher for subjects with higher BP. Htr is further used for identifying the appropriate height ranges for each individual, since the foot points on PPG when H higher than Htr is undesirably delayed due to the small digital BP.

The recorded data show that the curvature of PTTfin-H curve varies for different age groups as presented in Fig. 1(b). In [15], [17] it has been discussed that the coefficient b in (1) is originally derived from V-P model and is related to arterial stiffness. Different b values would result in different curvature of ΔPTT-H curves as given in Fig. 2. Noticed that in previous investigation, subjects with stiffer arterial wall properties are usually more advanced in age and/or with higher BP, it may be difficult to distinguish the effects of arterial stiffness and BP levels on those proposed indices. Therefore we vary b (stiffness of artery) and Pi (i.e. BP) separately in the simulation, and the results presented in Fig. 2 show that the curvature of ΔPTT-H curve is dominated by b and does not change significantly with Pi. HSr is a simple parameter that carries information of the curvature of the ΔPTT-H curve and could also be a potential indicator of arterial stiffness. The results of this experiment show that it is significantly different between the two groups of subjects with different age group as other arterial stiffness indices such b and AI (Table I).

To conclude, changes of PTTfin as well as the amplitude of PPG under the effects of a varying hydrostatic component is observed to be significantly different on two groups of subjects of different age and health conditions. Parameters can be potentially extracted from this procedure to represent the difference in arterial stiffness of the two groups of subjects.

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