Pulse Transit Time and Arterial Blood Pressure at Different Vertical Wrist Positions

Yinbo Liu and Y.T. Zhang

***Abstract*—Pulse transit time (PTT), which is inversely proportional to pulse wave velocity (PWV), can be used to measure blood pressure (BP) changes continuously. It is well known that during traditional BP measurements, the limb needs to be positioned at the height of heart level to eliminate the effect of hydrostatic pressure, however, little is known about the estimated BP from the PTT based approach when the limb height varies. The objective of this study is to examine PTT and peripheral arterial BP changes at discrete vertical wrist positions above heart level (*h*). Eleven subjects aged from 20 to 53 were recruited. The results showed that the PTT increased with *h* and became significant longer ($p<0.05$) at *h* = 30 cm compared with that at heart level. On the other hand, the brachial mean arterial pressure (MAP) from the stable arm remained almost constant, while the radial MAP from the moving arm gradually reduced with increasing *h*. Moreover, the correlation coefficient between PTT and radial BP was significantly high ($p<0.05$) on most subjects during the hand elevating process ($r=-0.91\pm0.13$, $r=-0.84\pm0.15$ and $r=-0.88\pm0.14$ for systolic BP, diastolic BP and MAP respectively). The results indicate the potential use of the PTT based approach to monitor peripheral BP noninvasively while allowing the limb maintaining at different positions from heart level.**

I. Introduction

An increase in transmural blood pressure (P_{tm}) makes the arterial wall stiffer and therefore results in an increased pulse wave velocity (PWV) and a deduction in pulse transit time (PTT) [1]. P_{tm} is defined as the pressure difference between internal arterial blood pressure (BP) and external pressure. When a limb, e.g. the arm, is held to a particular vertical wrist position relative to heart level, the hydrostatic pressure varies [2] and results in continuous changes in the P_{tm} and therefore the PWV along the limb artery. Thus PTT which takes the pressure pulse to transfer from aorta to peripheral arteries would be expected to vary with different vertical wrist positions. Gundersen reported a reduction of the digital systolic blood pressure (SBP) greater than the hydrostatic pressure change during hand elevation [3]. Foo *et al.* reported a significant increase in PTT calculated from finger photoplethysmogram (PPG) when the test arm was vertically raised [4]. However, little is known about the changes in PTT and its correlation with corresponding peripheral BP during the process of hand elevation. The objective of this study is to quantitatively examine the PTT changes as well as the correlation coefficients between PTT and radial BP at discrete vertical wrist positions above heart level.

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II. Experiment

A. Pre-experiment Test

For each subject BP was simultaneously measured from left upper arm and right wrist for three times at rest status using automatic BP devices (Omron HEM-907 and National EW280, respectively). The difference between the mean BP readings from the two devices was considered as bias, and was removed from the radial BP readings obtained later during the arm elevating session for each individual.

Two reflective photoplethysmograph sensors (EVERLIGHT, PT11-21C-L41-TR8 and IR11-21C) named PPG-1 and PPG-2 having the same circuit design, were made with different configurations. PPG-1 was located inside a ring sensor with an adjustable contact force, which was measured by a force sensor (MSIsensors FC21). PPG-2 was located inside a light band. These two sensors were fixed around the right index and ring fingertips respectively during the whole experiment.

B. Experiment Protocol

Eleven healthy volunteers aged from 20 to 53 including 4 females were recruited in the experiment. Subjects were seated upright and their right arms were kept constantly at the heart level during the whole experiment. They were requested to stretch out their right (test) arm unbent to different vertical wrist positions above heart level (*h*) without support. The *h* was set to be 0, 15, 30, 45 and 60 cm in a randomized sequence, where the test arm was held for 15s for electrocardiogram (ECG) and PPG recordings.

After this procedure, subjects were instructed to stretch the test arm to the five wrist positions again. BPs from the test wrist and the stable arm were simultaneously measured using the mentioned automatic devices, while their arms were maintained at each *h*. One minute was allowed in between each two BP measurements.

PTT was measured as the time interval from the peak of the ECG R wave to the upstroke of the PPG pulse in the same cardiac circle. Data were presented as mean ± standard deviation. The paired student's *t*-Test was used to examine the difference and $p<0.05$ was regarded as statistically significant.

III. Results

For all the subjects, the mean arterial blood pressure (MAP) was calculated from $MAP = DBP + (SBP - DBP)/3$. One trial of PTT at h = 45 cm, two trials of PTT and one set of radial BP at h = 60 cm were absent due to the device errors.

As shown in Fig.1, the radial MAP from the test arm reduced, while PTT values from PPG-1 and PPG-2, named PTT-1 and PTT-2, increased with the ascending h. The radial MAP calculated by $MAP_0 - \rho gh$ was illustrated in Fig.1(a) as a dashed line. The contact force between PPG-1 and the test index fingertip (F_{ext}) was normalized by that at h = 0 cm for each subject and shown in Fig.1(c).

Moreover, as presented in Table I, the heart pressure denoted by the brachial MAP remained stable, while the changes in the measured radial MAP were somewhat less than ρgh at each h. On the other hand, the normalized PTT-2 changes showed that PTT values at $h \geqslant 30$ cm were significantly different from those at heart level ($p<0.05$).

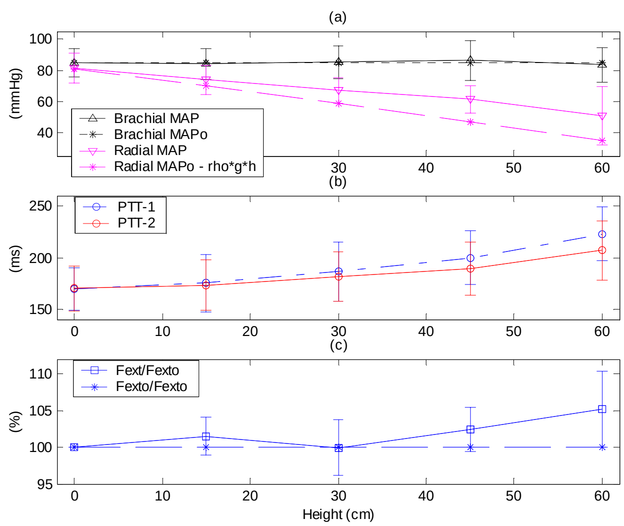

Fig. 1. The mean values (mean ± SD) of (a). Measured brachial and radial MAP, (b). PTT from two PPG sensors, and (c). Normalized F_{ext} for all the individuals at different vertical wrist positions.

It was indicated in Table II that for most subjects, both PTT-2 and the radial BP were almost linearly correlated with h; During the hand elevation process, PTT-2 and radial BP were significantly correlated ($p<0.05$) for each individual. PTT-1 followed a similar trend as PTT-2, which was shown in Fig.2.

TABLE I
PERCENTAGE CHANGES OF PTT-2, DIFFERENCE BETWEEN MEASURED RADIAL MAP CHANGE AND ρgh , AND BRACHIAL MAP CHANGES FROM HEART LEVEL AT DIFFERENT WRIST POSITIONS

Height (cm)	$\Delta\frac{\text{PTT-2}}{\text{PTT-2}_0}$ (%)	Δ Radial MAP - ρ gh (mmHg)	Δ Brachial MAP (mmHg)
0	0	-0.8±1.3	0
15	1.7±4.5	-4.0±5.3	-0.7±3.5
30	6.6±3.5 *	-8.2±5.0 *	0.3±3.8
45	11.2±5.0 *	-14.4±4.0 *	1.5±5.1
60	21.8±10.3 *	-15.9±7.9 *	-1.5±3.6

* $p<0.05$
$\rho = 1.05 \times 10^3$ kg/m^3, g = 9.8 m/s^2, h = Height/100 m,
1 mmHg = 133.3 Pa.

TABLE II
AVERAGED CORRELATION COEFFICIENTS BETWEEN HEIGHT AND PTT-2, HEIGHT AND BP, AND BETWEEN PTT AND BP OF ALL THE SUBJECTS

r	HEIGHT	PTT-2
PTT-2	0.94 ± 0.10^{1}	N/A
Radial MAP	-0.97 ± 0.02^{0}	-0.88 ± 0.14^{3}
Radial SBP	-0.96 ± 0.04^{1}	-0.91 ± 0.13^{2}
Radial DBP	-0.95 ± 0.03^{1}	-0.84 ± 0.15^{4}

The superscript represents the number of subjects with $p>0.05$.

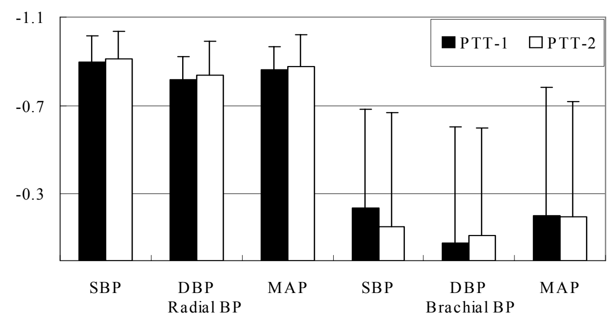

Fig. 2. Averaged individual correlation coefficients between PTT and radial BP as well as between PTT and brachial BP of all the subjects.

IV. Discussions

In the present study, it is demonstrated that the MAP at heart level kept roughly constant, while the radial MAP gradually reduced with a raising wrist position. Similar phenomena were also found in other studies [3], [5]. The somewhat less reduced radial MAP compared with theoretical hydrostatic pressure change during limb elevation was reported by previous work in popliteal arterial pressure [6]. This might be attributed to several factors such as the transfer of kinetic energy that was ignored in our current calculations, the autoregulation mechanism in skeletal muscle, and the holding of the arm without any support while measuring the BP.

On the other hand, PTT progressively increased with the rising h and was significantly longer from h = 30 cm than that at heart level. The effects of position on PTT were consistent with previous work in [4]. The high correlation coefficient between PTT and radial MAP could be expected if PWV is considered to be approximately inversely related to the arterial MAP as supported by previous experiment study [8]. At a certain *h*, the reducing internal MAP along the transfer arteries would result in continuous decreases in PWV, and PTT would therefore be proportional to the peripheral MAP when h varies, which was elaborated in our other work [7].

Another interesting phenomenon is that, with an ascending *h*, the differences between PTT-1 and PTT-2, i.e. PTT_{diff} in an increasing manner was illustrated in Fig.1(b). At the same time, a raising trend of normalized F_{ext} could also be observed as shown in Fig.1 (c). The PTT_{diff} at the same *h* might be attributed to the unequal contact force that applied on the test index and ring fingertips, since it was reported that an increase of digital P_{tm} would result in a prolonged PTT [9]. This is also supported by the occurrence of the increasing trend of PTT_{diff} and F_{ext} observed with larger *h* in this study.

V. Conclusion

The increased PTT and decreased radial BP with the rising *h*, as well as high correlation coefficients between the two were observed during the hand elevation process indicates the potential of using the PTT-based approach to continuously monitor peripheral BP, while allowing the concerned limb positioned at different levels from the heart. This would be helpful for clinical applications such as hand surgeries and studies of reactive hyperemia.

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