# Modeling the Effects of Radial Blood Pressure Change on Pulse Transit Time

Y.S.Yan and Y.T.Zhang*

*Abstract*—**Inconvenient individual calibration is a barrier for pulse transit time (PTT)-based approach to be used for noninvasive and cuffless blood pressure monitoring in wearable devices. In this paper, a linear model is proposed to describe effects of radial blood pressure (RBP) change on PTT during subject's hand elevation. It also provides a simple way to derive the desired calibration curve for each individual. The experimental results on 11 subjects show that most of the correlations (8 out of 11 for systolic RBP, and 7 out of 11 for diastolic RBP) are significantly (p<0.05) negative (R=-0.84 for SBP and R=0.82 for DBP), indicating that the method based on this model may be used to derive the calibration curve for noninvasive and cuffless BP measurement.**

*Index Terms*—**Blood pressure, hydrostatic pressure, pulse transit time, wearable medical device, mobile health**

## I. Introduction

Blood pressure (BP) is among the most vital signs for wide clinical applications. Wearable BP devices are very desirable particularly to the world's increasingly aging population, whose blood pressures have to be assessed regularly or monitored continuously. In order to make people feel comfortable and avoid any interference with their daily activities, wearable BP devices need to be noninvasive and cuffless.

Actually, a number of approaches for noninvasive and cuffless blood pressure measurement have been proposed in the past decades [1-4]. Pulse transit time (PTT) is commonly accepted as a candidate due to its good correlation with BP during steady state and dynamic exercise [5-8]. Nevertheless, as the relationship between BP and PTT is individual-dependent, it is very important to find a practical and convenient method to derive the calibration curve for each individual. In this paper, we aim to derive the calibration curve by modeling the effects of radial blood pressure (RBP) change on PTT during hand elevation.

## II. PTT-RBP Model

It is well known that the relationship between vascular volume (V) and transmural pressure ($P_{tm}$), which is defined as the difference of internal and external pressure, is commonly fitted as a sigmoid curve [9],

$$V = \frac{a}{1+\exp[-bP_{tm}]} = \frac{a}{1+\exp[-bP]}, \quad (1)$$

where a and b are fitting parameters. In this study, as external pressure equals to zero, the transmural pressure equals to the internal pressure.

The Bramwell–Hill equation describes how pulse wave velocity (PWV) relates to arterial distensibility [10]:

$$PWV = \sqrt{\frac{V\Delta P}{\rho \Delta V}}, \quad (2)$$

where $\Delta p$ and $\Delta V$ are the changes of blood pressure and volume, while ρ is the blood density.

Substituting Eq.1 to Eq.2 and re-arranging the equation with Taylor expansions, we obtain the relationship between PWV or PTT and $P_{tm}$:

$$PWV = \sqrt{\frac{\exp[bP]+1}{\rho b}} \approx \frac{1}{\sqrt{\rho b}} \frac{\sqrt{2}}{(1-\frac{bP}{4})} \equiv \frac{1}{cP - c/4}, \quad (3)$$

$$or, \quad PTT = L(cP - c/4)$$

where L is the distance the pulse travels (roughly equals to the arm length), and c is a constant determined by experiment data fitting. This equation indicates that one point calibration can roughly determine the relationship between PTT and Pressure.

Now, in order to make the Eq.3 consistent with previous experimental results [7-8], let's generalize it as follows:

$$PTT = L(cP + d), \quad (4)$$

where c and d are two independent values to be determined. Therefore, when the subjects elevate their hands, the PTT from heart to wrist can be obtained by integrating the travel time at different sites along the arm based on Eq.4:

$$PTT = L(\frac{P_R + P_0}{2}c + d) \quad (5)$$

where $P_R = P_0 - \rho gh$ represents the estimated RBP, and $\theta$ is the angle between the arm and horizon. Here, we assume the change of RBP at the wrist is only caused by hydrostatic pressure change. This derived equation suggests that RBP is linearly related to PTT, and the coefficients c and d could be achieved by curve fitting based on the PTT and RBP at different heights during hand elevation. Also, comparing Eq.4 with Eq.5, it is worth noting that the average value of RBP and aortic BP can be regarded as an equivalent pressure for PTT calculation.

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## III. Experiment And Results

### *A. Experiment protocol*

Eleven volunteers (7 males and 4 females, aged 20~30 yrs. old) participated in the experiment. They were asked to hold their right hand at specific heights (0cm, 15cm, 30cm, 45cm, and 60cm above the heart), and the Standard Lead I electrocardiogram (ECG) and photoplethysmogram (PPG) signals at the fingertip were recorded simultaneously for 60 seconds at a sampling rate of 1 kHz. Also, a wrist-type cuff-based device (National EW280, Japan) and an oscillometric BP meter (Omron HEM-907, Japan) were used to measure BP on the elevated hand and the reference arm respectively. Since the PPG signal at fingertip is much easier to detect, and the distance from wrist to finger is neglectable compared with the distance from heart to finger, the PTT from heart to wrist is estimated as the distance from the R peak of ECG to the foot of PPG at the fingertip in this study.

### *B. Results*

Fig.1 shows the measured RBP vs. the estimated RBP from the hydrostatic pressure during hand elevation. As shown in this figure, the estimated RBP (SBP and DBP) has a good correlation (R=0.91, $p<0.05$) with the measured RBP, although it has a bigger deviation at the lower end. This discrepancy is caused by elevated hand in higher position.

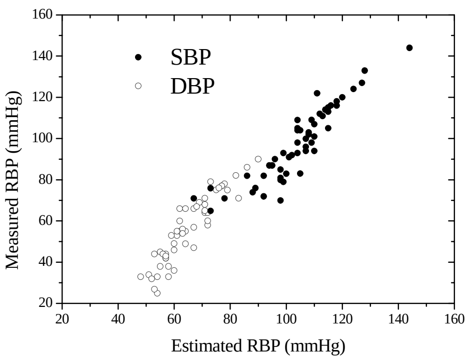


Fig.1. The plot of the measured RBP vs. estimated RBP by hydrostatic pressure during hand elevation

Fig.2 gives the PTT and systolic RBP during hand elevation of one typical subject. It is clear that for this subject PTT has significant ($p<0.05$) negative correlation (R= -0.98) with systolic RBP. The coefficients L*c and L*d of the calibration curve are calculated as -0.48 and 195 by curve fitting.

Furthermore, Table I shows the intra-subject correlation of PTT with systolic and diastolic RBP for all the tested subjects. All of the correlations of PTT with RBP are negative (-0.84±0.22 for systolic RBP, -0.80±0.20 for diastolic RBP). And most of the correlations (8 out of 11 for systolic RBP, and 7 out of 11 for diastolic RBP) are significant ($p<0.05$). This result verifies our proposed model (Eq.5) that radial BP is linearly correlated with PTT during the subject's hand elevation. Most importantly, it can be used to obtain the calibration curve (Eq.4) with the determined coefficients L*c and L*d by curve fitting based on this model.

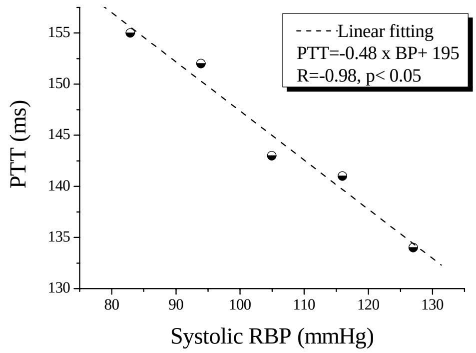


Fig.2.The plot of PTT vs. Systolic RBP during hand elevation of one typical subject from the heart level: the correlation coefficient between PTT and FBP is -0.98 (p<0.05).

TABLE I. Correlation coefficients between PTT and measured systolic RBP (SRBP)

| | PTT vs. systolic RBP | PTT vs. diastolic RBP |
|---|---|---|
| R (mean ± sd) | -0.84 ± 0.22 | -0.80 ± 0.20 |
| Negative* | 11(8) | 11(7) |
| Positive* | 0(0) | 0(0) |

* Number of subjects with positive or negative correlations: number in parenthesis indicates number of subjects with significant correlation ($p<0.05$)

## IV. Discussion

Our previous studies [8] have shown that there was an average decrease of about 40ms in PTT caused by aortic blood pressure elevation of about 20mmHg for 15 subjects immediately after exercise. Actually, the average slope of PTT-RBP curve for the tested subjects in this study is about 0.5. It indicates that the derived PTT-RBP curve in this study can be used for BP estimation immediately after exercise.

Nevertheless, it should be beared in mind that to obtain an accurate calibration curve using the proposed approach has to satisfy the following assumptions: 1) the aortic blood pressure should not change significantly during hand elevation; and 2) the RBP change at the wrist is caused by hydrostatic pressure change alone.

## V. Conclusion

In summary, a model for PTT changes with hand elevation was proposed and verified by experiments. By its ability to easily extract the slope and intercept of the calibration curve, it has a potential application for the noninvasive and cuffless BP measurement in wearable devices.

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## REFERENCES

[1] A. Steptoe, H. Smulyan and B. Gribbin, “Pulse wave velocity and blood pressure change: calibration and applications”, Psychophysiology”, vol.13, pp.488-493, 1976

[2] L. A. Geddes, M. H. Voelz, C. F. Babbs, J. D. Bourland and W. A. Tacker, “Pulse transmit time as an indicator of arterial blood pressure”, psychophysiology, vol.18, pp.71-74,1981

[3] A. A. Awad, M. A. Ghobashy, R. G. Stout, D. G. Silverman and K. Shelly, “Blood pressure determination using the pulse oximeter waveform”, 2001
Available: http://www.gasnet.org/interface/12.1.2.abstract

[4] Y.S.Yan and Y.T.Zhang, “Noninvasive Estimation of Blood Pressure Using Photoplethysmographic Signals in the Period Domain”, in Proc. of 27th Annu. Int. Conf. of IEEE Engineering in Medicine and Biology Society, 2005

[5] A. Steptoe, Pulse wave velocity and blood pressure changes: calibration and applications, Psychophysiology, vol. 13, no. 5, pp. 488-493, 1976.

[6] G. V. Marie, C. R. Lo, J. Van Jones, and D.W. Johnston, The relationship between arterial blood pressure and pulse transit time during dynamic and static exercise, Psychophysiology, vol. 21, pp. 521-527, 1984.

[7] C.C.Y. Poon and Y.T. Zhang, “Cuff-less and noninvasive measurements of arterial blood pressure by pulse transit time”, in Proc. of 27th Annu. Int. Conf. of IEEE Engineering in Medicine and Biology Society, 2005

[8] Y.M. Wong and Y.T. Zhang, “The effects of exercises on the relationship between pulse transit time and arterial blood pressure”, in Proc. of 27th Annu. Int. Conf. of IEEE Engineering in Medicine and Biology Society, 2005

[9] P. Shaltis, A. Reisner and H. Asada, “A hydrostatic pressure approach to cuffless blood pressure monitoring,” in Proc. of 26th Annu. Int. Conf. of IEEE Engineering in Medicine and Biology Society, 2004.

[10] W.W. Nichols and M.F. O’Rourke. McDonald's blood flow in arteries: theoretical, experimental and clinical principles. Oxford University Press, 1998.