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ORIGINAL ARTICLE

Pulse Transit Time and Finger to Finger ΔT Measurement in Reactive Hyperemia: A Comparative Study

Hassan Ali Hussein [1,*], Fezaa Shalal Neda [1], and Bassam T. Al Gailani [1]

[1] *Department of Physiology, College of Medicine, Mustansiriyah University, Baghdad, Iraq*

[*] *Corresponding author email: hassanmsc@uomustansiriyah.edu.iq*

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ABSTRACT

Background: Reactive hyperemia (RH) is a temporary increase in blood flow following ischemia and serves as a marker of vascular health by reflecting reductions in arterial stiffness. Pulse transit time (PTT) and finger-to-finger pulse arrival time difference ($f-f$ ΔT) are non-invasive techniques used to assess vascular stiffness. This study compares the effectiveness of PTT and $f-f$ ΔT in detecting vascular stiffness changes induced by RH.

Methods: Ten healthy male participants (mean age: 23.1 ± 5.0 years) were enrolled. PTT and $f-f$ ΔT were measured at baseline and at 1-minute intervals for 5 minutes following RH induction. RH was induced by occluding the left arm for 5 minutes.

Results: PTT increased significantly by 6% and 4% at 1 and 2 minutes post-occlusion release, respectively, compared to baseline (260.9 ± 19.1 ms). In contrast, $f-f$ ΔT showed larger relative increases of 362%, 200%, 133%, and 88% at 1, 2, 3, and 4 minutes, respectively, compared to baseline (5.1 ± 7.4 ms). While PTT exhibited only modest and short-lived changes, $f-f$ ΔT changes were more substantial and persisted longer.

Conclusion: The $f-f$ ΔT method demonstrated greater sensitivity in detecting RH-induced changes in vascular stiffness compared to PTT, with effects lasting up to 4 minutes. In contrast, PTT detected only transient changes, primarily within the first 2 minutes. These findings suggest that $f-f$ ΔT may offer a more sensitive approach for assessing vascular compliance during RH.

Key words: Pulse Transit Time; Finger-to-Finger Arrival Time Difference; Reactive Hyperemia.

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INTRODUCTION

Reactive hyperemia (RH) is the temporary increase in blood flow following a period of ischemia (restricted blood supply). It occurs due to vasodilation triggered by tissue hypoxia, the accumulation of vasodilator metabolites, and nitric oxide release from the endothelium, which collectively enhance blood flow upon blockage removal [1, 2].

RH serves as a non-invasive marker of vascular health, as it correlates with reduced arterial stiffness [3]. This reduction occurs because vasodilation decreases vascular resistance when perfusion pressure is restored. Arterial stiffness, defined as diminished elasticity and flexibility of arterial walls, elevates resistance to blood flow and increases cardiovascular risk. It results from structural and functional arterial changes, such as collagen deposition, elastin degradation, and endothelial dysfunction [4].

Arterial stiffness is linked to aging, hypertension, diabetes, and atherosclerosis [5]. Among non-invasive techniques for measuring arterial stiffness, pulse wave velocity (PWV) and augmentation index (AI) are the most widely employed methods [6]. These provide quantitative assessments of vascular stiffness to evaluate cardiovascular risk. PWV is calculated using the formula: $PWV = \frac{D}{PTT}$, where D is the distance between the heart and the pulse wave's arrival point, and PTT (pulse transit time) represents the time taken for the pulse wave to travel this distance [7]. A higher PTT indicates greater vascular compliance (lower stiffness). A pronounced decrease in arterial stiffness during RH reflects healthy vascular flexibility, whereas a blunted response suggests arterial rigidity or endothelial dysfunction. Thus, PTT may help assess changes in vascular smooth muscle tone induced by RH [8, 9].

A novel non-invasive technique measures the difference in pulse arrival time between the right and left fingers (f–f ΔT) to evaluate changes in PWV (or PTT) during RH. This method quantifies the time delay in pulse wave arrival between fingers to indirectly gauge arterial stiffness [10]. The developers of this technique validated it as a simple, effective alternative to conventional PWV/PTT measurements. f–f ΔT was able to detect attenuated pulse wave velocity responses during flow-mediated dilation (FMD) in patients with cardiovascular diseases, β-thalassemia/hemoglobin E, and individuals with lower mean arterial pressure compared to healthy volunteers [10].

This study aims to compare the validity and sensitivity of traditional vascular stiffness assessment methods (PWV or PTT) with those of the finger-to-finger pulse arrival time (f–f ΔT) following RH-induced changes in vascular stiffness.

MATERIAL AND METHODS

Ten healthy male participants (mean age: 23.1 ± 5.0 years) were recruited for this study. All participants were free from medical illnesses and were not taking any medications. Prior to the experiment, they were instructed to fast for 2 hours, abstain from tea, coffee, and tobacco use, and avoid strenuous physical activity for 12 hours. Each participant received a full explanation of the study and gave verbal informed consent. The study procedures were approved by the department's ethics committee and adhered to the principles of the Declaration of Helsinki. The research was conducted in the Physiology Laboratory, Department of Physiology, College of Medicine, Mustansiriyah University, Baghdad, Iraq.

Systolic and diastolic blood pressure (SBP, DBP) and heart rate (HR) were recorded using an automated sphygmomanometer (Rossmax, Swiss GmbH). Repeated measurements of right brachial SBP, DBP, and HR were taken in a semi-supine position after a 10-minute rest period to ensure hemodynamic stability.

Lead II electrocardiogram (ECG) signals, acquired using three surface electrodes, and digital pulse wave (DPW) signals from the left and right middle fingertips, recorded via piezoelectric crystal mechanotransducers, were simultaneously recorded for five minutes. The PowerLab Data Acquisition System (Acquisition Unit 26T, AD Instruments Pty Ltd, New South Wales, Australia) was used to digitize the analog signals. Data were processed using LabChart Pro software, which enabled offline analysis of ECG and DPW signals. Pulse wave parameters were extracted using parameter-specific peak detection techniques. Both ECG and DPW signals were recorded at a sampling rate of 1 kHz.

Reactive hyperemia (RH) was induced using the following protocol:

i. A two-minute baseline recording of ECG and DPW signals.
ii. Five minutes of arterial occlusion by inflating a blood pressure cuff around the left arm to at least 50 mmHg above baseline SBP. This ensured complete arterial occlusion while minimizing discomfort and maintaining uniformity across participants. Occlusion was verified in real time by monitoring the disappearance of the DPW signal.
iii. Upon cuff deflation, the RH phase commenced, during which ECG and DPW signals were continuously recorded for an additional five minutes [11].

Pulse transit time (PTT) was calculated as the interval between the peak of the ECG R-wave and the first peak of the first-derivative DPW signal [12]. The time difference between pulse wave arrivals at the two middle fingers ($f-f$ ΔT) was measured both at rest and during RH. In this study, $f-f$ ΔT was determined using the peak of the first-derivative DPW signal to calculate the arrival time difference between the right and left middle fingertips (Figure 1). Beat-to-beat values and averages over 60–80 cardiac cycles were extracted for both the baseline and RH phases.

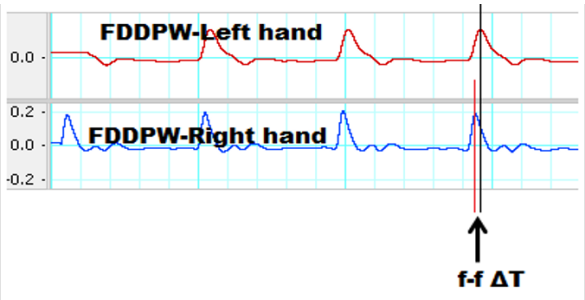

Figure 1. The time difference between pulses arriving at the middle fingers of each hand (f-f ΔT). FDDPW = First derivative of the digital pulse wave of left and right finger.

All data were reported as mean ± standard deviation (SD). Statistical comparisons were performed using both paired and unpaired Student's *t*-tests. A p-value < 0.05 was considered statistically significant. The paired *t*-test was used for within-group comparisons (e.g., pre- vs. post-occlusion).

RESULTS

The characteristics of the recruited volunteers in this study are shown in Table 1. Following arm occlusion release, PTT was significantly higher than baseline values at 1 and 2 minutes post-release, increasing by 6% and 4%, respectively (Figure 2), relative to baseline values (260.9 ± 19.1 ms).

Table 1. Characteristics of the participants recruited in the present study *No.* = 10.

Parameter	Mean ± SD
Age (years)	23.1 ± 5.0
Body mass index (kg/m^2)	29.0 ± 5.8
Systolic blood pressure (mmHg)	132.5 ± 7.0
Diastolic blood pressure (mmHg)	77.5 ± 9.5
Mean blood pressure (mmHg)	95.8 ± 7.4
Heart rate (beats/min)	74.9 ± 12.1

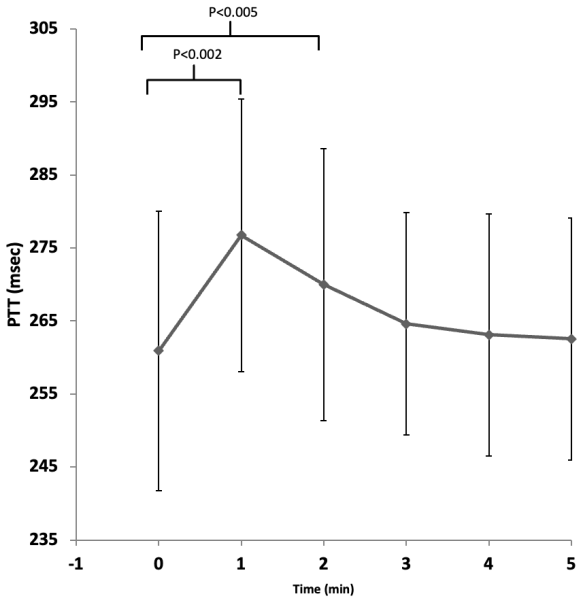

Figure 2. Pulse transit time (PTT) following the arm post-occlusion release (i.e., during RH). *N* = 10. Time "0" represents baseline values.

Time differences in pulse arrival between the middle fingers of both hands (f-f ΔT) were used to assess vascular stiffness. Pulse arrival times at the right middle finger were subtracted from those at the left middle finger, yielding predominantly positive values. This design resulted in negative f-f ΔT values in only 2 of 10 subjects. To address this limitation, results were expressed as percentage changes after excluding these two subjects' data.

At 1, 2, 3, and 4 minutes post-arm occlusion release, f-f ΔT increased significantly by 362%, 200%, 133%, and 88%, respectively, compared to baseline values (5.1 ± 7.4 ms). These results demonstrate that vascular stiffness changes persisted for up to 4 minutes post-release (Figure 3).

To compare the two techniques, PTT and f-f ΔT changes were expressed as percentages (Figure 4). The percentage increases in PTT relative to baseline (100%) at 1, 2, and 3 minutes post-release were 104% ($p < 0.009$), 102% ($p < 0.06$), and 101% (NS), respectively. During the same intervals, f-f ΔT increased to 281% ($p < 0.005$), 178% ($p < 0.03$), and 139% ($p < 0.03$), respectively.

In conclusion, f-f ΔT effectively captured vascular stiffness changes following arm occlusion release, with significant changes persisting for up to 4 minutes. The PTT method detected transient changes lasting only up to 2 minutes. The f-f ΔT method reflected changes on the order of hundreds of percent, whereas the PTT method detected smaller changes (a few percent).

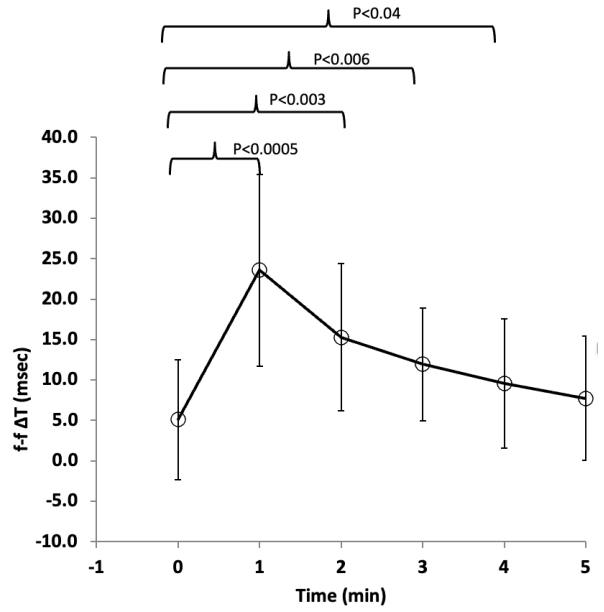

Figure 3. The time difference between pulses arriving at the middle fingers of each hand (f-f ΔT) following the arm post-occlusion release (i.e., during RH). $N = 10$. Time "0" represents baseline values.

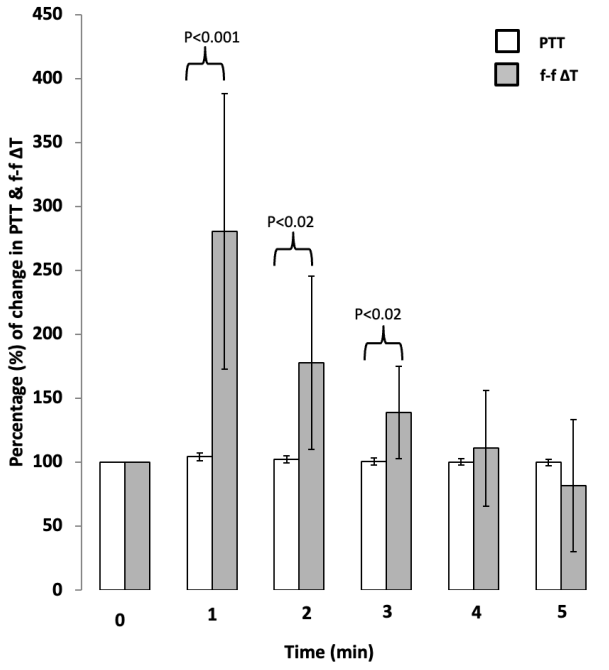

Figure 4. Percentage of change in pulse transit time (PTT) and the time differences between pulses arriving at the middle fingers of each hand (f-f ΔT) during reactive hyperemia following release of arm occlusion. Time "0" represents baseline value (100%).

DISCUSSION

Pulse transit time (PTT) and finger-to-finger pulse arrival time difference (f-f ΔT) are two techniques used to evaluate vascular stiffness and hemodynamic changes during reactive hyperemia (RH). Both methods assess the transient reduction in arterial stiffness caused by increased blood flow and shear stress, which induces nitric oxide (NO)-mediated vasodilation.

PTT measures the time taken for a pulse wave to travel between two arterial sites. During RH, PTT typically shows a transient increase, peaking approximately 59 seconds after cuff deflation and returning to baseline within 2–3 minutes [13]. This trend aligns with studies by [9, 14, 15], which confirm that the reduction in arterial stiffness during RH is flow-dependent. These studies demonstrate that restricting blood flow abolishes the PTT increase and emphasize the role of shear stress in this process. The accompanying decrease in pulse wave velocity (PWV) further supports NO-mediated endothelial function as a key regulator of vascular compliance. Compared to PTT, the f-f ΔT technique is more sensitive in detecting subtle changes in vascular stiffness during RH. Study by [10] indicates that f-f ΔT exhibits a significantly higher percentage change in vascular stiffness than PTT or brachial-femoral PWV. However, a limitation of f-f ΔT is its baseline variability, where values can sometimes be zero or negative. In the present study, negative f-f ΔT values were recorded in 2 of 10 subjects, likely due to anatomical differences between the right and left vascular pathways. The left subclavian and brachial arteries emerge directly from the aorta, while the right subclavian artery, which is shorter due to its proximal origin, branches off from the brachiocephalic trunk [16, 17], leading to variations in pulse wave arrival times.

The f-f ΔT response showed a significant increase in the first 2 minutes post-occlusion, followed by a gradual return to baseline. However, after upper-arm occlusion, f-f ΔT remained elevated for up to 4 minutes, likely due to increased metabolite accumulation and sustained sympathetic activation [18–21]. Both PTT and f-f ΔT provide valuable insights into vascular responses during RH. While f-f ΔT offers greater sensitivity in detecting subtle changes in arterial compliance, its application requires careful consideration of baseline variability and anatomical differences. Study by [15] highlights the correlation between PWV and arterial elastic modulus, suggesting that RH-induced changes in vascular stiffness are influenced by both structural and functional properties of the arterial wall. The findings of this study imply that the f-f ΔT method for measuring vascular stiffness (and consequently endothelial function) during RH is straightforward and sensitive, making it a promising candidate for widely accessible screening tools.

This study has several limitations. First, the sample size was relatively small, which may affect the generalizability of the findings. Second, inter-individual anatom-

ical differences—particularly in vascular branching patterns—introduced variability in f-f ΔT measurements. Third, the study was limited to healthy volunteers; thus, the performance of both techniques in clinical populations with established cardiovascular disease remains to be determined. Finally, external factors such as sensor placement, hand temperature, or ambient noise could influence pulse detection accuracy and should be standardized in future protocols.

CONCLUSION

Pulse transit time (PTT) remains a well-established method for assessing transient arterial stiffness changes, whereas finger-to-finger pulse arrival time difference (f-f ΔT) shows promise for detecting subtle variations in vascular compliance. Future research should refine these methodologies to enhance their clinical utility in evaluating endothelial function and cardiovascular health.

Further work is required to address unresolved questions in subjects at high cardiovascular risk.

ETHICAL DECLARATIONS

- **Ethics Approval and Consent to Participate**

  All subjects gave informed consent for inclusion before participating in the study. The study was approved by Mustansiriyah University, College of Medicine (Document No. 1661, dated February 25, 2025).

- **Consent for Publication**

  Non.

- **Availability of Data and Material**

  The datasets are available from the corresponding author upon reasonable request.

- **Competing Interests**

  The authors declare that there is no conflict of interest.

- **Funding**

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- **Use of Generative Artificial Intelligence**

  The authors declare that ChatGPT, a generative AI-based tool developed by OpenAI, was used by the author solely to enhance clarity and grammatical accuracy during the final editing phase. It was not used for content generation, data analysis, or interpretation.

- **Authors' Contributions**

  All authors contributed significantly, directly, and intellectually to the work and consented to its publication.

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