Effect of Filtering on Pulse Wave Transit Time Measured by Photoplethysmography

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Abstract

The waveform of a photoplethysmography (PPG) signal depends on the measurement site and individual physiological conditions. Pulse transition time (PTT) is an important physiological parameter for blood pressure estimation. PTT can be derived from electrocardiogram (ECG) and PPG waveform features. Filtering can change PPG signal waveform and the timing of PPG feature points. We aim to quantitatively investigate the filtering-induced PTT changes at different measure sites in healthy subjects of different ages. The ECG, and fingertip and earlobe PPG signals were recorded simultaneously from 58 young (age<=50) and 40 old (age>50) healthy adults. The PPG signals were preprocessed and then filtered (low-pass, pass and stop bands: <3 Hz and >5 Hz). The PTT difference between the preprocessed and filtered PPG signals was calculated and analyzed using analysis of variance (ANOVA) and paired tests. The results show significant effect of age and measurement site on filtering-induced PTT difference and its relative difference (p<0.05 for all). We conclude that the physiological factor including measurement site and age should be considered in PTT-based blood pressure estimation methods.

1. Introduction

Photoplethysmography (PPG) signal reflects the volumetric changes in microcirculation. The AC component of a PPG signal reflects local pulse wave at microvascular level, which is also regulated by respiratory movements and neural activities. PPG signals can be easily measured at different body sites using wearable sensors. Therefore, PPG technology plays a key role in wearable healthcare monitoring [1].

Many physiological factors, including age, breathing pattern, and body site of measurement, can influence the waveform of a PPG signal. For example, PPG signals recorded from different body sites differ in signal quality and the timing of feature points in a cardiac cycle [e.g., 2-4]. With the change of vessel properties, age also has a significant influence on PPG waveform and the location of feature points. [2]. Hence, many physiological parameters can be derived from the waveform features of PPG signals. Pulse transit time (PTT), which refers the time for heart pulse wave to propagate through a length of the arterial tree, can be approximated as the interval between the R wave of electrocardiogram (ECG) and the end-of-diastolic valley of PPG signal in the same cardiac cycle [5]. PTT is negatively related to blood pressure, which provides theoretical basis of cuffless blood pressure measurement using wearable PPG sensors [6].

In many wearable applications, the original PPG signals are filtered before feature extraction. Filtering can change the waveform of PPG signals and the timing of feature points [7]. Especially, the finite impulse response (FIR) and infinite impulse response (IIR) [8] filters are widely applied in PPG signal processing [9]. However, the nonlinear phase response of the IIR filter can affect the PPG waveform, leading to inaccuracy in detecting the timing of PPG waveform feature points. There is a lack of quantitative evaluation of the effect of physiological factors on IIR filtering-induced PTT changes.

To address the research gap and provide a reference for PTT-based cuffless blood pressure estimation algorithms, this study aims to quantitatively investigate the effect of two important physiological factors (i.e., age and body measurement site) on the IIR filtering-induced PTT changes.

2. Methods

2.1. Subject and data collection

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Ninety-eight (48 males and 50 females, ages ranging from 20-71 years) healthy participants were recruited from staff, students and their relatives in Newcastle Hospitals and Newcastle University with written informed consent. No participants suffered cardiovascular disease before. The experimental procedures involving human subjects described in this work complied with the principles in the Declaration of Helsinki. The experiment began in a thermostatic room maintaining the temperature at 23 ± 1 ℃ . In order to stabilize the cardiovascular system, each subject rested in a supine posture on a couch for 5 minutes before signal recording. ECG and PPG signals from the right index fingertip and right earlobe were recorded simultaneously for 120 seconds at a sampling rate of 2500 Hz when all signals are clear and stable. During the whole experiment, the subjects kept normal breathing with arms located in parallel to the body without movement.

2.2. Signal preprocessing and filtering

The recorded data were imported to MATLAB (R2021b; The MathWorks Inc. Natick, USA) for signal processing. A bandpass filter (0.5-35Hz) was used to preprocess the ECG signal. The recorded raw PPG signals were preprocessed with a high-pass IIR filter (1 zero and 10 poles, passband: >0.5 Hz, stopband: <0.2 Hz) to remove the low-frequency and DC components (e.g., ‘baseline wander’). A low-pass IIR filter (1 zero and 16 poles, passband: <20 Hz, stopband: >30 Hz) was then used to remove the high-frequency noise which included the 50 Hz power line and electrophysiological noises. The preprocessed PPG signals were further filtered with a low-pass IIR filter (1 zero and 13 poles, passband: <3 Hz, stopband: >5 Hz) which was applied in our existing study [9].

2.3. Definition of PTT

PTT is usually defined as the time between the R-peak of the ECG and a reference point on systolic PPG signal segment. The reference point can be derived from different PPG features (e.g., end-of-diastolic valley, systolic peak, etc.), which leads to different PTT values [6]. Considering the inaccuracy of systolic peak location caused by filtering-induced waveform distortion, especially on earlobe PPG signal which has flat systolic peak, we used the end-of-diastolic valley to calculate the PTT, as shown in Fig1.

2.4. Extraction of feature points

On ECG signals, the R wave peak was detected as the maximal value in a cardiac cycle using the Pan Tompkins method [10]. On preprocessed and filtered PPG signals, the end-of-diastolic valley points were extracted as the minimal values in a cardiac cycle. The details of the valley detection algorithm were based on the calculation of first order difference of PPG signals. Considering the high sampling frequency (2500 Hz), the error caused by the approximation is very limited ($<4\times10^{-4}$ s for the timing of any feature point). The details can be found in our published work [9]. Considering the noisy PPG signals in some cardiac cycles, only the valleys within 50-500 ms after the ECG R-peak (i.e., $50\ \text{ms} \leqslant \text{PTT} \leqslant 500$ ms) were selected for analysis. For each PPG signal, the PTT was calculated as the mean value of PTTs of the selected cardiac cycles.

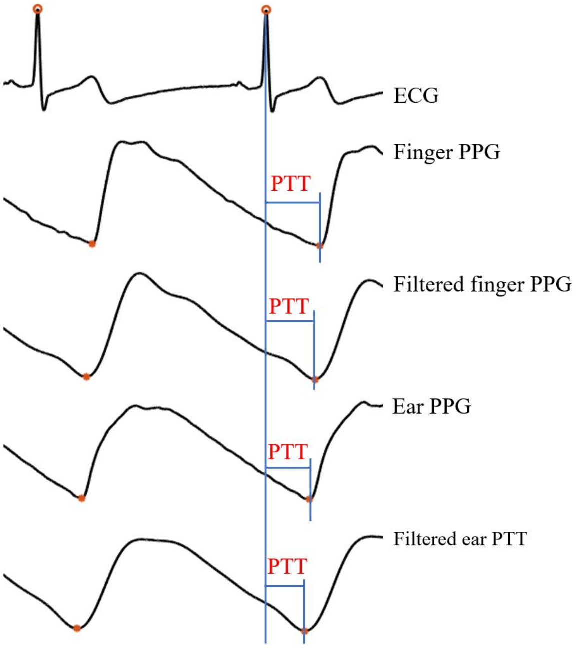

Figure 1. Calculation of pulse transit time (PTT) using synchronously recorded ECG and PPG signals at different body sites.

2.5. Definition of PTT

The data of all subjects were separated in two age groups: age $\leqslant 50$ and age > 50, with 58 and 40 subjects respectively. For each subject, the filtering-induced PTT difference was calculated between the PTT values derived from filtered and preprocessed PPG signals. The relative PTT difference was calculated as:

$$RD_{PTT}=(PTT_{filtered}-PTT_{preprocessed})/PTT_{preprocessed} \quad .(1)$$

Statistical analysis was performed using SPSS (Version 24.0, IBM Corp) and R programming language (R Core Team, 2021). Kolmogorov-Smirnov test (data size>50) or Shapiro–Wilk test (data size<=50) was performed to investigate the normality of data distribution. For normally distributed data (defined as p>0.05 in Kolmogorov-Smirnov or Shapiro–Wilk test), the

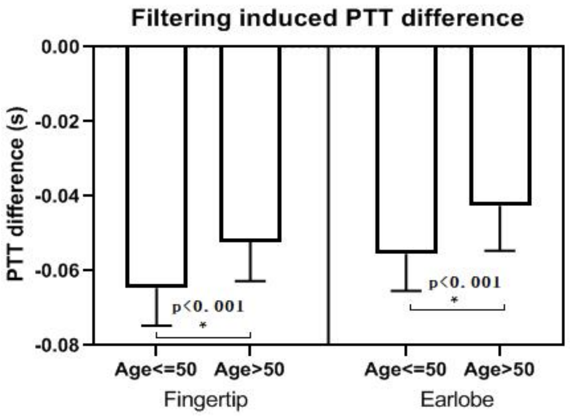

Figure 2. Filtering induced PTT difference at fingertip and earlobe.

Levene's test was performed to investigate the homogeneity of variance (defined as p>0.05). If the hypothesis of homogeneity of variance was satisfied, the analysis of variance (ANOVA) was performed to investigate if there are significant effects of age and measurement site on PTT difference or its relative difference, otherwise the Scheirer–Ray–Hare test was performed as a substitute. For each measurement site, Student's t test (for data of normal distribution) or Mann-Whitney U test (if normal distribution is violated) was performed between two age groups. Statistical significant was defined as *p* value less than 0.05.

3. Results

IIR filtering caused the shorting of PTT in both age groups (i.e., young and old) and measurement sites (i.e., fingertip and earlobe). The results showed significant effects of measurement site and age on filtering-induced PTT difference and its relative difference.

3.1. Filtering-induced PTT difference

For filtering-induced PTT difference, normal distribution was observed in both finger and ear data (p=0.52 and p=0.08, respectively). The overall distribution satisfied homogeneity of variance (p=0.82), therefore ANOVA was performed. Both measurement site and age showed significant effects on filtering-induced PTT difference (p<0.001 for both), without any significant interaction (p=0.87). To summarize, the amplitude of IIR filtering-induced shortening of PTT was significantly larger in the young group and the fingertip PPG signals.

3.2. Filtering-induced PTT relative difference

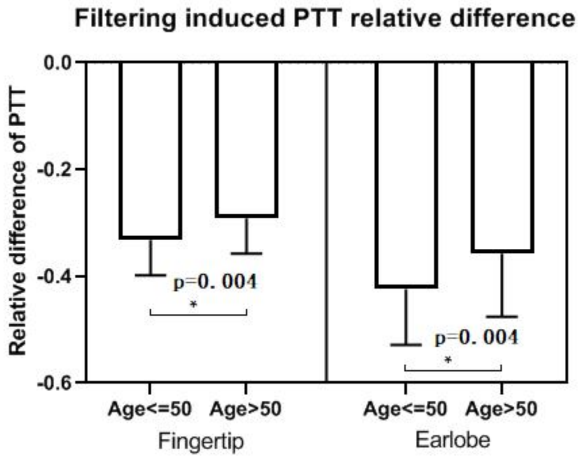

Figure 3. Filtering induced PTT relative difference at fingertip and earlobe.

For filtering-induced PTT relative difference, normal distribution was satisfied by the ear data (p=0.40) but violated by the finger data (p=0.015). The overall distribution did not satisfy homogeneity of variance (p<0.001), therefore the Scheirer–Ray–Hare test was performed. Both measurement site and age showed significant effect on filtering-induced PTT difference (p<0.001 for both), without any significant interaction (p=0.63). To summarize, the IIR filtering-induced relative change of PTT was significantly larger in the data from the young group and the earlobe PPG signals.

3.3. Difference between two age groups

Figure 2 shows the filtering-induced PTT difference in different age groups. All the data in each subgroup satisfied normal distribution (p>0.05 for all in Shapiro Wilk test). At each measurement site, the data satisfied homogeneity of variance (p=0.99 and p=0.54 in Levene's test for finger and ear respectively). Therefore, t test was performed. The young group has a significantly larger (lower negative values) filtering-induced PTT difference than the old group (p<0.001 for both, Fig. 2).

Figure 3 shows the filtering-induced PTT difference in different age groups. All the data in each subgroup satisfied normal distribution (p>0.05 for all in Shapiro Wilk test). At each measurement site, the data satisfied homogeneity of variance (p=0.97 and p=0.43 in Levene's test for finger and ear respectively). Therefore, t test was performed. The young group has a significantly larger (lower negative values) filtering-induced PTT difference than the old group (p=0.004 for both, Fig. 3).

4. Discussion and conclusion

This work aimed to find out the effects of physiological factors, i.e., age and measurement site, on the change of PTT induced by IIR filtering. We found out that PTTs were shortened in both fingertips and ears after filtering and there were statistically significant effects of age and measurement site on the filtering-induced PTT changes. Vascular stiffness increases with age, which has a significant effect on PPG signal waveform. No previous quantitative studies on the study filled this gap. The results indicated that care need to be taken in the calculation of PPG-derived PTT when applying IIR filtering on the PPG signals at earlobe where the PTT is shorter, especially in young subjects.

At present, the filter parameters of many commercial wearable PPG sensors are unrevealed. In published works, the filtering parameters are not uniform and narrow frequency bands were widely used (e.g., 0.5-4 Hz [11], 0.5-4 Hz [12], and 0.8-4 Hz [13]). 0.5-10 Hz was suggested for estimation of heart rate from PPG signals [6]. To achieve accurate estimation of blood pressure, considering the narrow frequency range, the filtering-induced PPG waveform deformation and resultant changes of PTT deserve further investigation. Liu et al. proved that measurement site had significant impacts on the time shift in feature points between prefiltered and filtered PPG signals [8]. The influence of filtering on the signal feature points measured at different sites is different, so the variations of PTTs we get from different measurement sites are also different. Our results highlight the necessity of physiological parameters in filter design and provide preliminary quantitative considerations for filter parameter settings of wearable PPG signal sensors.

However, there are some limitations. The sample size was small in this pilot study. Also, we only included the healthy subjects, without considering the effect of pathological changes on PPG signal waveform. There are several definitions of PTT using different PPG features points as the reference of pulse arrival. We only studied the PTT defined in terms of end-of-diastolic valley. With high-frequency components excluded, filtering can decrease the slope of systolic uprising segment, which may move the locations of systolic peak and end-of-diastolic valley in different amplitudes and directions. In future studies, filtering-induced PTT changes derived from different PPG feature points can be comprehensively investigated. More subjects especially those with cardiovascular diseases can be included to verify our results and further explore the effect of pathological changes on PTT value. In conclusion, the results in this work showed that the filtering-induced PTT difference was significantly different between PPG signals at fingertip and earlobe, and between different age groups. The physiological factor including measurement site and age should be considered in PTT-based blood pressure estimation using wearable sensors.

References

[1] J. Allen, “Photoplethysmography and its application in clinical physiological measurement,” *Physiological measurement*, vol. 28, no. 3, p. R1, Feb. 2007.

[2] J. Allen, and A. Murray, “Age-related changes in the characteristics of the photoplethysmographic pulse shape at various body sites,” *Physiological measurement*, vol. 24, no. 2, p. 297, Mar. 2003.

[3] Y. Maeda, M. Sekine, T. Tamura, T. Suzuki, and K.I. Kameyama, “Position dependency in photoplethysmographic sensor-comparison of adjoining PPG signals in light sources and measurement sites,” *Journal of Life Support Engineering*, vol. 23, no. 3, pp. 124–129, May. 2011.

[4] V. Hartmann, H. Liu, F. Chen, Q. Qiu, S. Hughes, and D. Zheng, “Quantitative comparison of photoplethysmographic waveform characteristics: effect of measurement site,” *Frontiers in physiology,* vol. 10, p. 198, Mar. 2019.

[5] M.H. van Velzen, A.J. Loeve, S.P. Niehof, and E.J. Mik, “Increasing accuracy of pulse transit time measurements by automated elimination of distorted photoplethysmography waves,” *Medical and biological engineering and computing*, vol. 55, no. 11, pp. 1989–2000, Mar. 2017.

[6] R. Mukkamala, J.O. Hahn, O.T. Inan, L.K. Mestha, C.S. Kim, H. Töreyin, and S. Kyal, “Toward ubiquitous blood pressure monitoring via pulse transit time: theory and practice,” *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 8, pp. 1879-1901, Aug. 2015.

[7] J. Allen and A. Murray, "Effects of filtering on multisite photoplethysmography pulse waveform characteristics," *Computers in Cardiology*, pp. 485-488, Sep. 2004.

[8] H. Liu, J. Allen, S.G. Khalid, F. Chen, and D. Zheng, “Filtering-induced time shifts in photoplethysmography pulse features measured at different body sites: the importance of filter definition and standardization,” *Physiological Measurement*, vol. 42, 074001, Jul. 2021.

[9] C. Park, H. Shin, and B. Lee, “Blockwise PPG enhancement based on time-variant zero-phase harmonic notch filtering,” *Sensors*, vol. 17, no. 4, p. 860, Apr. 2017.

[10] L. Sathyapriya, L. Murali and T. Manigandan, “Analysis and detection R-peak detection using modified Pan-Tompkins algorithm,” in *2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies*, pp. 483–487, May. 2014.

[11] L. Wang, B. P. Lo and G. -Z. Yang, “Multichannel reflective PPG earpiece sensor with passive motion cancellation,” in *IEEE Transactions on Biomedical Circuits and Systems*, vol. 1, no. 4, pp. 235-241, Dec. 2007.

[12] S. Vogel, M. HÜlsbusch, T. Hennig, V. Blazek and S. Leonhardt, “In-ear vital signs monitoring using a novel microoptic reflective sensor,” in *IEEE Transactions on Information Technology in Biomedicine*, vol. 13, no. 6, pp. 882-889, Nov. 2009.

[13] M. Z. Poh, K. Kim, A. Goessling, N. Swenson and R. Picard, “Cardiovascular monitoring using earphones and a mobile device,” in *IEEE Pervasive Computing*, vol. 11, no. 4, pp. 18-26, Oct.-Dec. 2012

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