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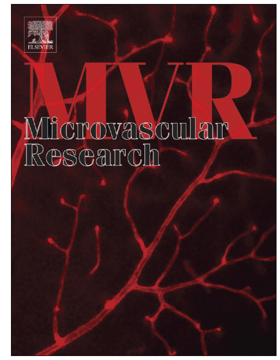

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Gaussian Modelling Characteristics Changes Derived from Finger Photoplethysmographic Pulses during Exercise and Recovery

Anran Wang[1], Lin Yang[1*], Weimin Wen[1], Song Zhang[1], Guanxiong Gu[1], Dingchang Zheng[2]

[1]College of Life Science and Bio-engineering, Beijing University of Technology, Beijing, 100124, China

[2]Health and Wellbeing Academy, Faculty of Medical Science, Anglia Ruskin University, Chelmsford, CM1 1SQ, UK

*Address correspondence to: Dr. Lin Yang, College of Life Science and Bio-engineering, Beijing University of Technology, 100 Pingluoyuan Chaoyang District, Beijing 100124, China. Phone: +86 10 6739 2010, Fax: +86 10 6739 2010, Email: yanglin@bjut.edu.cn

Abbreviations

AI, augmentation index; BMI, body mass index; DBP, diastolic blood pressure; H_1, the first peak amplitude; H_2, the second peak amplitude; H_3, the third peak amplitude; HR, Heart rate; min, minute; mins, minutes; N_1, the first peak time position; N_2, the second peak time position; N_3, the third peak time position; PPG, photoplethysmographic; RI, reflection index; $R_{1,2}$, the amplitude ratio between 1st and 2nd Gaussian wave; $R_{1,3}$, the amplitude ratio between 1st and 3rd Gaussian wave; SBP, systolic blood pressure; s.d., standard deviation; $T_{1,2}$, the peak time interval between 1st and 2nd Gaussian wave; $T_{1,3}$, the peak time interval between 1st and 3rd Gaussian wave; W_1, the first half-width; W_2, the second half-width; W_3, the third half-width

Highlights

We first use the Gaussian modelling approach to investigate the changes of finger PPG wave shape with exercise and during recovery.

We comprehensively quantify the changes of Gaussian modelling characteristics derived from finger PPG pulses with exercise and during recovery.

We provide evidence that the Gaussian modelling of arterial pulses can be potentially used to as a processing tool to identify waveform characteristics changes.

Abstract

Gaussian modelling method has been reported as a useful method to analyze arterial pulse waveform changes. This study aimed to provide scientific evidence on Gaussian modelling characteristics changes derived from the finger photoplethysmographic (PPG) pulses during exercise and recovery.

65 healthy subjects (18 female and 47 male) were recruited. Finger PPG pulses were digitally recorded with 5 different exercise loads (0, 50, 75, 100, 125W) as well as during each of 4 minute (min) recovery period. The PPG pulses were normalized in both width and amplitude for each recording, which were decomposed into three independent Gaussian waves with nine parameters determined, including the peak amplitude (H_1, H_2, H_3), peak time position (N_1, N_2, N_3) and half-width (W_1, W_2, W_3) from each Gaussian wave, and four extended parameters determined, including the peak time interval ($T_{1,2}$, $T_{1,3}$) and amplitude ratio ($R_{1,2}$, $R_{1,3}$) between 1st Gaussian wave and 2nd, 3rd Gaussian waves. These derived parameters were finally compared between different exercise loads and recovery phases.

With gradually increased exercise loads, the peak amplitude H_2, peak time position N_1, N_2, N_3, and half-width W_1, W_2 increased, peak amplitude H_3 decreased significantly (all $p<0.05$). The peak time interval $T_{1,2}$ and $T_{1,3}$ increased significantly from 10.6±1.2 and 36.0±4.4 at rest to 14.4±2.3 and 45.1±6.5 at 100W exercise load, respectively (both $p<0.05$). The amplitude ratio $R_{1,2}$ also increased from 1.07±0.2 at rest to 1.22±0.2 at 100W, and the amplitude ratio $R_{1,3}$ decreased from 1.10±0.3 at rest to 0.42±0.2 at 125W (all $p<0.05$). An opposite changing trend of these parameters was observed during recovery phases.

In conclusion, this study has quantitatively demonstrated significant changes of Gaussian modelling characteristics derived from finger PPG pulse with exercise and during recovery, providing scientific evidence for the physiological mechanism that exercise increases cardiac ejection and vasodilation, and reduces the total peripheral vascular resistance.

Keywords: Exercise load; Gaussian pulse decomposition; PPG; Pulse wave analysis.

Introduction

It has been widely accepted that arterial pulse waves could be used to evaluate cardiovascular function and hemodynamic characteristics in clinical research (Weber et al., 2012; Munakata, 2014) because the waveform characteristics are affected by cardiac function, arterial wall characteristic and peripheral resistance(Jeon et al., 2011; Saiki et al., 2014; Ben-Shlomo et al., 2014) . Recently, the changes of cardiovascular function during exercise and recovery have been studied in association with arterial pulse waveform characteristics changes (Edwards et al., 2004; Munir et al., 2008; Dischl et al., 2011; Gkaliagkousi et al., 2014). The majority of published studies mainly focused on pulse wave velocity (PWV) and pulse waveform shape analysis. Gkaliagkousi et al used PWV to assess arterial stiffness changes after acute exercise in normotensive subjects and untreated hypertensive patients (Gkaliagkousi et al., 2014). Dischl et al evaluated central and radial reflected waves in athletes during recovery from a maximal running test (Dischl et al., 2011). Munir et al investigated the effect of exercise on both PWV and arterial pulse pressure wave reflection (Munir et al., 2008), and observed that the time difference between the pulse foot point and the point of maximal diastolic augmentation was decreased during and immediately after exercise, which was then increased back to the baseline at later stages during recovery.

It is well accepted that arterial pulse mainly includes three elements: main wave, tidal wave and dicrotic wave (Wang et al., 2013). When the main wave transmits in the vascular network, it reaches several reflection sites causing wave reflection due to significant changes in arterial resistance and compliance. The first and second wave reflections are commonly known as the tidal and dicrotic waves. A small dip, called the dicrotic notch, is commonly observed between the first and second wave reflections (Baruch et al., 2011; Couceiro et al., 2015). The recorded arterial pulse waveform could be viewed as a linear addition of the main wave generated by left ventricular ejection and reflection waves at reflection sites. The techniques commonly used for arterial pulse wave characteristics analysis includes pulse area analysis and pulse characteristics frequency domain analysis (Song et al., 2004; Wang and Wang, 2009). However, it could be difficult for the traditional techniques to accurately and reliably analyze the completed pulse waveform and extract different pulse wave characteristics, especially for the pulses without obvious tidal or dicrotic points.

In order to overcome the challenges of arterial pulse feature identification, Gaussian modelling method has been developed recently (Rubins, 2008; Liu et al., 2013; Liu et al., 2014), which can decompose the arterial pulse waveform into different individual Gaussian waves, from which different characteristics could be derived. It has been confirmed by Liu et al that three positive Gaussian waves could be used to reliably decompose and model the arterial pulse waveform (Liu et al., 2013), where they compared the characteristics of Gaussian waves for the carotid and radial arterial waveforms between normal subjects and heart failure patients (Liu et al., 2014). Rubins's study also used Gaussian decomposed method on finger and ear photoplethysmographic (PPG) pulse wave and reported that the Gaussian peak amplitude ratio was closely related to the traditional reflection index (RI) and augmentation index (AI) (Rubins, 2008). It would be scientifically and clinically important to further explore the underlying physiological mechanisms of different Gaussian modelling characteristics, including the peak amplitude, peak time and half-width of the Gaussian waves, and their potential association with physiological changes of the heart and peripheral arteries. To the best of our knowledge, previous studies mainly focused on Gaussian modelling of arterial pulses recorded under resting conditions, this modelling technique has not been used to analyze the arterial pulse characteristic changes with exercise or during recovery.

This study aimed to comprehensively quantify the changes of Gaussian modelling characteristics derived from finger photoplethysmographic pulses during exercise and recovery.

Materials and Methods

Subjects

65 healthy subjects (18 female and 47 male) were enrolled from the Beijing University of Technology. None of them had any known cardiovascular diseases. The study has been fully approved by the local Ethics Committee of College of Life Science and Bio-engineering, Beijing University of Technology. The investigation conformed to the principles in the Declaration of Helsinki. All subjects gave written informed consent to participate in this study. The overall basic clinical information, including age, height, weight, BMI, HR, SBP and DBP, is shown in Table 1.

Table 1: Clinical variables from the subjects studied.

Variables	Male	Female	All
No.	47	18	65
Age, year	26±3	22±3	25±3
Height, cm	174±5	162±5	170±7
Weight, kg	67±7	51±6	62±9
BMI, kg/m^2	22±2	19±2	21±2
HR, beat/min	75±8	81±10	77±10
SBP, mmHg	112±10	107±10	111±10
DBP, mmHg	74±8	69±7	73±8

Note: BMI: Body mass index, HR: Heart rate, SBP: Systolic blood pressure, DBP: Diastolic blood pressure.

Experiment procedure to record arterial finger PPG pulses

The experiment was performed at a quiet clinical measurement room. Subjects were asked to sit quietly on a chair for 10 minutes (mins) before the baseline BP and HR were obtained using a validated electronic sphygmomanometer (HEM-7124 from Omron Corporation). An optical sensor was placed on the right middle finger for finger PPG pulse recording using a PowerLab data collection system (ADInstruments Pty Ltd., PowerLab 8/35, Bella Vista NSW 2153, Australia) at a sampling rate of 1000 Hz.

Before the formal arterial pulse recording, subjects were asked to perform a trail exercise of 30s on the cycle ergometer (Monark Pty Ltd., Ergomedic 839 E, Sweden) to ensure the PPG sensor was comfortably placed and to ensure good quality of waveforms were obtained. During the formal PPG signal recording period, a baseline recording of finger PPG pulse waveform was firstly performed while the subject siting on the ergometer without any exercise load. Different exercise loads were then used, starting from 50W to a maximum load of 125W with a step of 25W. At each exercise load, the PPG pulse signals were recorded for 3 minute (min). The maximum load for 150W was instructed in the pilot experiments, but the majority of subjects, especially female subjects, were unable to complete the tasks. Therefore, a maximum load of 125 W was used in this formal study. After the maximum load, each subject was asked to stop doing exercise. 4 mins of finger PPG pulses were then continuously recorded.

Arterial finger PPG pulse segmentation and normalization

All the finger PPG pulses from the last minute's recording during each of the five exercise load phases were used for off-line signal processing. The PPG signal recorded during recovery was equally divided into 4 segments, making a total of 9 segments for each subject (5 from different exercise loads and 4 during recovery). For all the PPG pulses within a segment each segment of PPG pulse signal, the pulse waveform baseline drift was firstly removed. They were then normalized in both width (100 sampling points) and amplitude (0-1) from the foot of each pulse, and then averaged to obtain a single reference normalized pulse, which was used for subsequent analysis.

Gaussian modelling of finger PPG pulses

In this study, each normalized PPG pulse was decomposed into three positive Gaussian functions $f_i(n)$, as proposed by Liu et al.'s (Liu et al., 2013; Liu et al., 2014). The first Gaussian function $f_1(n)$ denotes the main wave, or the forward wave; the second Gaussian function $f_2(n)$ denotes the tidal wave and the third Gaussian function $f_3(n)$ denotes the dicrotic wave, or the backward wave. Each Gaussian function was defined as:

$$f_i(n) = H_i \times \exp\left(-\frac{2(n-N_i)^2}{W_i^2}\right) \qquad i = 1,2,3\,; n = 1,2,\ldots,100$$

where H_i means the peak amplitude, N_i means the peak time position and W_i means the half-width of each Gaussian wave, as shown in Figure 1.

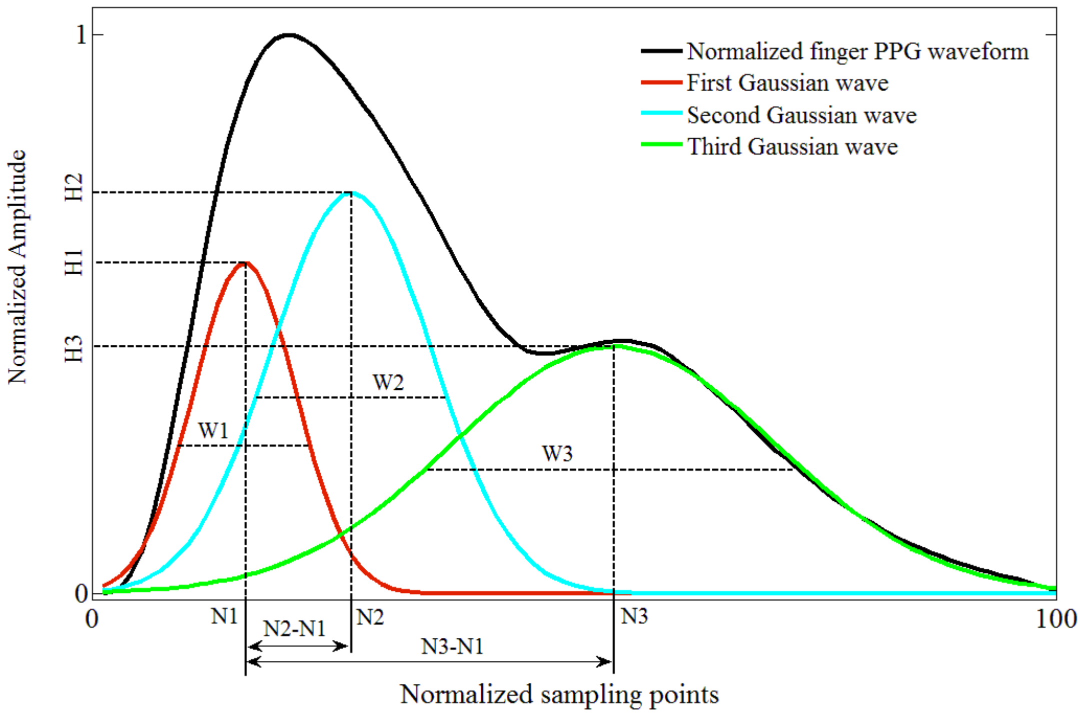

Figure 1: Demonstration of the Gaussian modelling of finger PPG waveform.

Gaussian modelling characteristic derived from three Gaussian waves

As shown in Figure 1, Gaussian modelling characteristics, including the peak amplitude (H_1, H_2, H_3), peak time position (N_1, N_2, N_3) and half-width (W_1, W_2, W_3), were derived from each of the three Gaussian curves. Four extended parameters were also determined, including the peak time interval ($T_{1,2}$, $T_{1,3}$) and amplitude ratio ($R_{1,2}$, $R_{1,3}$) between 1st Gaussian wave and 2nd, 3rd Gaussian waves, which were calculated as:

- $_{1,2} = N_2 - N_1$; $_{1,3} = N_3 - N_1$;
- $_{1,2} = \frac{H_2}{H_1}$; $_{1,3} = \frac{H_3}{H_1}$.

Data and statistical analysis

The mean ± s.d. of all the 13 parameters (3 peak amplitudes, 3 peak time positions, 3 half-width, 2 peak time intervals and 2 amplitude ratios) from the three modelled Gaussian waves were calculated across all the subjects, separately for different exercise loads and recovery phases. Post-hoc multiple comparison after one-way analysis of variance was then performed to compare the difference of these parameters with different exercise loads and recovery phases. A $P < 0.05$ was considered as significantly different.

Results

Changes of Gaussian peak, weight and width with exercise and during recovery

Figure 2 illustrates the Gaussian modelling of normalized finger PPG waveform recorded at 0W, 125W and the last min of recovery phases from one subject. With exercise load of 125 W, the second Gaussian wave amplitude increased, and the third Gaussian wave amplitude decreased. It was also observed that the peak time position of all the three Gaussian waves gradually moved to the right and the half-width of the first and second Gaussian waves increased at heavier exercise loads. During recovery, an opposite changing trend of these parameters was observed.

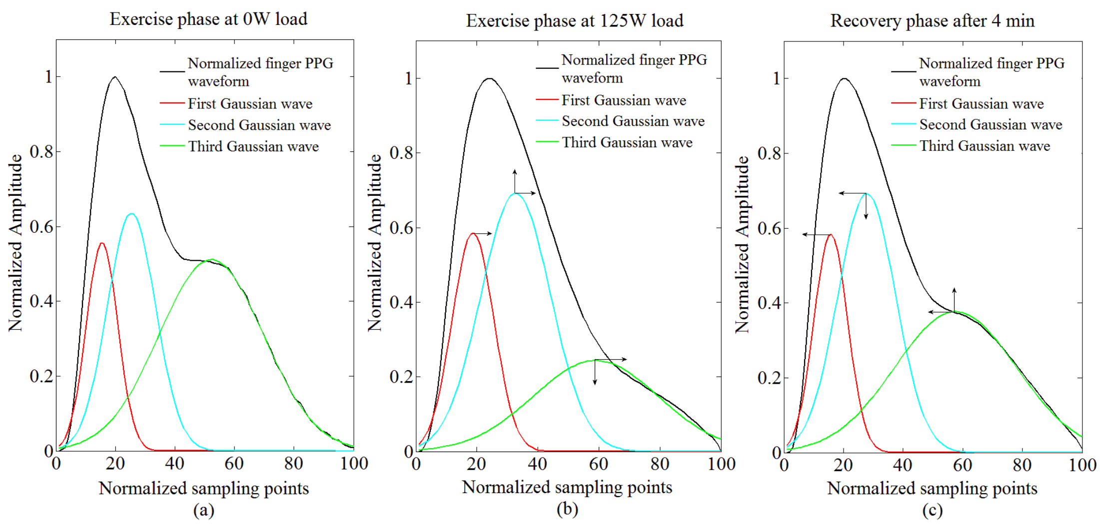

Figure 2: Illustration of Gaussian modelling of the arterial pulse waves recorded with 0W, 125W exercise loads and at the fourth min of recovery phase. These changes are shown with the arrows.

As shown in Figure 3, from the first Gaussian wave, the main Gaussian characteristics changes were observed with the peak time position N_1 and the half-width W_1. Both N_1 and W_1 increased significantly with exercise load (between baseline and maximum load; 14.0±1.3 vs 18.6±2.0 for N_1, 13.4±1.7 vs 18.6±2.3 for W_1). After 4 mins recovery, they decreased to 15.9±1.6 for N_1 and 16.0±1.8 for W_1. In comparison with baseline, both N_1 and W_1 changes with increased exercise loads and during recovery were significant (all $P<0.05$).

From the second Gaussian wave, the peak amplitude H_2, peak time position N_2 and half-width W_2 all increased significantly with increasing exercise loads (between baseline and maximum load; 0.59±0.10 vs 0.69±0.07 for H_2, 24.6±2.1 vs 32.2±3.5 for N_2, 23.4±2.9 vs 31.1±3.8 for W_2). After 4 mins recovery, they decreased to 0.69±0.09 for H_2, 28.1±2.5 for N_2 and 27.4±2.9 for W_2. In comparison with baseline values, all the changes of H_1, N_1 and W_1 with increased exercise loads and during recovery were significant (all $P<0.05$).

From the third Gaussian wave, the peak amplitude H_3 decreased significantly during exercise from 0.60±0.13 at rest to 0.39±0.11 and 0.29±0.15 at 50W and 125W, and then increased to 0.38±0.11 at 4 mins recovery phase. The peak time position N_3 increased significantly during exercise from 50.0±4.8 at rest to 61.1±9.7 at 125W, and then decreased to 59.4±6.5 at 4 mins recovery phase. All these changes were significant (all $P<0.05$). But there were no significant differences in the half-width W_3 with exercise loads and during recovery phase except at 50W and 75W load phases.

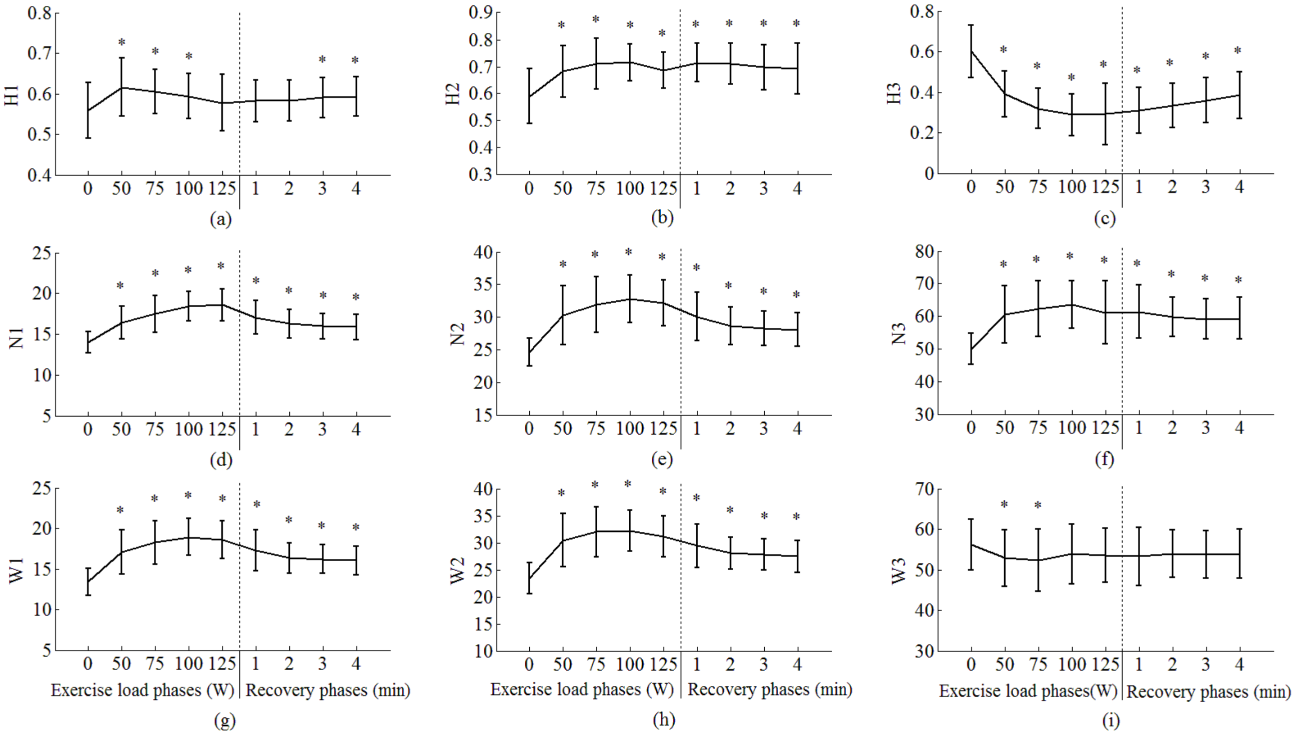

Figure 3: Gaussian characteristic parameters (mean ± s.d.) at different exercise loads and during recovery from the 65 subjects studied. H_i (i=1, 2, 3) is the peak amplitude, N_i is the peak time position and W_i is the half-width of each Gaussian wave; *: $P<0.05$: significantly different in comparison with that from 0W exercise load (baseline).

Changes of Gaussian peak time interval with exercise and during recovery

As shown in Figure 4, the peak time interval $T_{1,2}$ increased significantly with exercise from 10.6±1.2 at rest to 14.4±2.3 at 100W, and then decreased to 12.2±1.4 at 4 min recovery phase. Correspondingly, the peak time interval $T_{1,3}$ increased from 36.0±4.4 at rest to 45.1±6.5 at 100W, and then decreased to 43.5±5.8 at 4 mins recovery phase. All $T_{1,2}$ and $T_{1,3}$ changes were significant at different loads and during recovery in comparison with the baseline (all $P<0.05$).

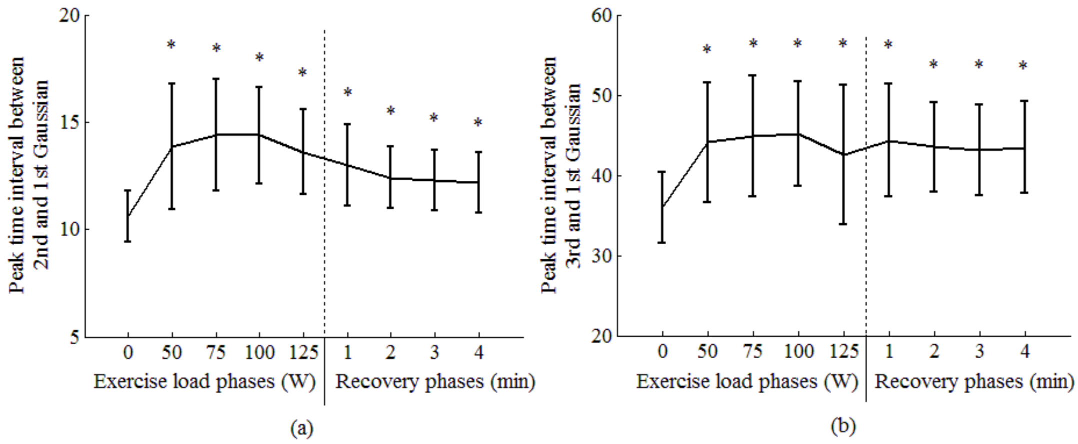

Figure 4 Gaussian wave peak time interval (mean ± s.d.) with different exercise loads and during recovery from the 65 subjects studied. *: P<0.05: significantly different in comparison with the 0W exercise load.

Changes of Gaussian amplitude ratio with exercise and during recovery

As shown in Figure 5, the amplitude ratio $R_{1,2}$ increased significantly during exercise from 1.07±0.2 at rest to 1.22±0.2 at 100W, and then decreased to 1.18±0.22 at 4 mins recovery phase. The amplitude ratio $R_{1,3}$ decreased from 1.10±0.3 at rest to 0.42±0.2 at 125W, and then increased to 0.66±0.22 at 4 mins recovery phase. All $R_{1,2}$ and $R_{1,3}$ changes were also significant at different loads and during recovery in comparison with the baseline (all P<0.05, except at 50 W for $R_{1,2}$).

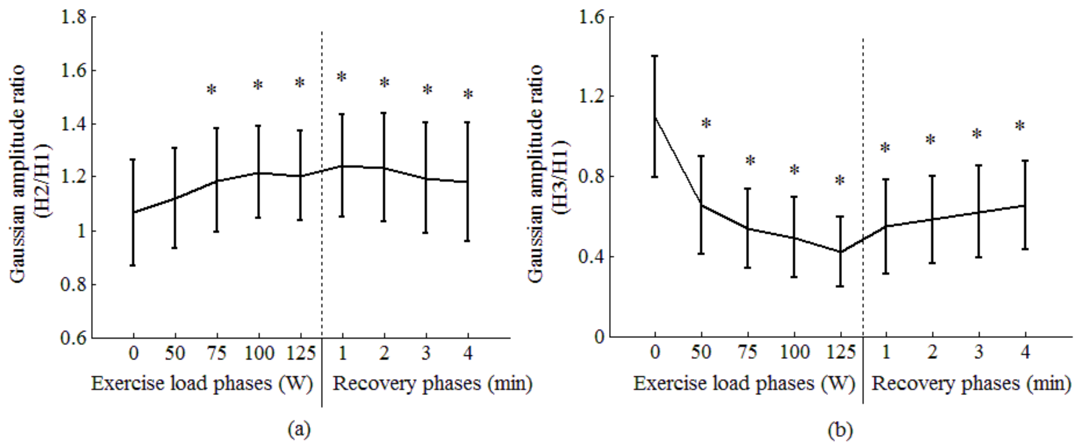

Figure 5 Gaussian wave amplitude ratio of (mean ± s.d.) with different exercise loads and during recovery from the 65 subjects studied. *: P<0.05: significantly different in comparison with the 0W exercise load.

Discussion and conclusion

In this study, arterial PPG pulses characteristics derived from three Gaussian modelling waves have been quantified and compared between different exercise loads and recovery phases. To the best of our knowledge, it is the first comprehensive study to use the Gaussian modelling approach to investigate the changes of finger PPG wave shape and its characteristic parameters with exercise and during recovery.

It is traditionally accepted that the arterial pulse waveform contains both forward and backward components (Torjesen et al., 2014). The first Gaussian wave denotes the forward wave in associated with left ventricle ejection (Couceiro et al., 2015). During exercise, the body requires more blood to transport oxygen, so the ejection ability of heart strengthens and endovascular blood filling increases, resulting in the wider half-width of first Gaussian wave (W_1) and the longer peak time position (N_1).

The second and third Gaussian waves represent the backward component, denoting the tidal wave and dicrotic wave, respectively (Couceiro et al., 2015). The second Gaussian wave could be associated with reflected wave, and the third Gaussian wave with the second rise in early diastole after the notch in association with aortic valve closure (Avolio et al., 1983). During exercise, an increased demand of oxygen and other nutrients for muscle leads to increased muscle metabolism, generating a large number of vasodilation substances to cause the muscle vasodilation and the decrease of muscle vascular resistance (Tschakovsky and Sheriff, 2004). When the peripheral resistance is low, arterial pulse waveform characteristics shows a narrow and high main wave, un-noticeable tidal wave and highlighted dicrotic wave, meanwhile the PWV is decreased (Kingwell et al., 1997). Therefore, the reduced reflection wave velocity leads to the backward of tidal wave (N_2) and dicrotic wave (N_3) with increased exercise loads. Published studies have also indicated that dicrotic notch and dicrotic wave would lift up with the augment of peripheral resistance (Munir et al., 2008; Allen and Murray, 2003), leading to depressed H_3 with exercise loads. But the reduction of late systolic augmentation in radial pressure pulse wave reported by Munir et al was inconsistent with the results found in our study, where H_2 was increased (Munir et al., 2008). This could be caused by the potentially different underlying mechanism between arterial PPG pulses and radial pressure pulses.

Kingwell et al found that PWV in the aortofemoral and leg region were both reduced after exercise (Kingwell et al., 1997). Sugawara et al exerted 5 min low-intensity single leg and reported that femoral and ankle arterial PWV of the exercised leg was significantly reduced and its arterial stiffness was obviously improved after exercise (Sugawara et al., 2003). The arterial PWV would decrease with exercise. The underlying physiological mechanism could be that exercise increases the cardiac output, which leads to accelerated whole body blood flow, and vasodilation reduces the total peripheral vascular resistance, leading to increased arterial compliance. The increased peak time interval $T_{1,2}$ and $T_{1,3}$ with exercise from our study can be interpreted in the same way.

This study also investigated the changes of Gaussian wave amplitude ratio with exercise. From their definitions, it can be seen that the amplitude ratio $R_{1,2}$ is associated with the augmentation index (AI), and the amplitude ratio $R_{1,3}$ is associated with the reflection index (RI) (Couceiro et al., 2015). Rubins's study compared RI evaluated by the Gaussian fitting method and reference method (RI_G vs RI_{Ref}) and concluded a good correlation between them (Rubins, 2008). AI and RI reflect the enhancement effect from reflected waves to forward wave. Since AI and RI measure peripheral resistance, it is expected that peripheral resistance in the subjects with compliant arteries is lower, leading to lower AI and RI in those subjects (JM Padilla, 2006; Kohara et al., 2004). Our results regarding the decreased $R_{1,3}$ with exercise was consistent with those from Munir et al and Dischl et al, where a relative reduction of diastolic RI was reported with exercise (Munir et al., 2008; Dischl et al., 2011) . Contrarily, they reported the reduction of late systolic AI, which was different with our results where the increasing trend of $R_{1,2}$ was observed here. This could be explained by the different analysis methods used. Furthermore, the correlation between amplitude ratio $R_{1,2}$ and physiological parameters changes during exercise needs comprehensive investigation in future studies.

During recovery period, all the Gaussian modelling parameters gradually recovered towards unloading level. However, it has been observed that, at the end of 4 mins recovery, not all the waveform characterize studied here returned to the baseline level, and the speed of recovery was different for different parameters. This suggested that a comprehensive investigation of the parameters changes over a long period should be conducted in the future.

In conclusion, this study quantitatively demonstrated significant changes of Gaussian modelling characteristics derived from finger PPG during exercise and recovery, providing better understanding of the physiological changes during exercise and recovery and also providing evidence that the Gaussian modelling of arterial pulses can be potentially used to as a processing tool to identify waveform characteristics changes in association with different physiological changes.

Author's contribution

Anran Wang, Lin Yang and Song Zhang coordinated the study. Weimin Wen and Anran Wang prepared the samples. Anran Wang, Lin Yang, Weimin Wen and Song Zhang performed the exercise experiments. Guanxiong Gu and Dingchang Zheng performed pulse waveform decomposition program. Anran Wang, Lin Yang and Dingchang Zheng performed pulse waveform characteristics data analysis. All authors discussed the results and contributed to preparing the manuscript.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Weber, T., et al., 2012. Wave reflections, assessed with a novel method for pulse wave separation, are associated with end-organ damage and clinical outcomes. Hypertension. 60, 534-+.

[2] Munakata, M., 2014. Brachial-ankle pulse wave velocity in the measurement of arterial stiffness: recent evidence and clinical applications. Curr. Hypertens. Rev. 10, 49-57.

[3] Jeon, Y. J., et al., 2011. A clinical study of the pulse wave characteristics at the three pulse diagnosis positions of chon, gwan and cheok. Evid-Based. Compl. Alt: eCAM. 2011, 904056-904056.

[4] Saiki, H., et al., 2014. Cerebral circulation in patients with fontan circulation: assessment by carotid arterial wave intensity and stiffness. Ann. Thorac. Surg. 97, 1394-1399.

[5] Ben-Shlomo, Y., et al., 2014. Aortic pulse wave velocity improves cardiovascular event prediction an individual participant meta-analysis of prospective observational data from 17,635 subjects. J. Am. Coll. Cardiol. 63, 636-646.

[6] Edwards, D. G., et al., 2004. Effect of exercise training on central aortic pressure wave reflection in coronary artery disease. Am. J. Hypertens. 17, 540-543.

[7] Munir, S., et al., 2008. Exercise reduces arterial pressure augmentation through vasodilation of muscular arteries in humans. Am. J. Physiol-Heart. C. 294, H1645-H1650.

[8] Dischl, B., et al., 2011. Enhanced diastolic reflections on arterial pressure pulse during exercise recovery. Scand. J. Med. Sci. Spor. 21, E325-E333.

[9] Gkaliagkousi, E., et al., 2014. Exercise-induced pulse wave velocity changes in untreated patients with essential hypertension: the effect of an angiotensin receptor antagonist. J. Clin. Hypertens. 16, 482-487.

[10] Wang, L., et al., 2013. Multi-Gaussian fitting for pulse waveform using Weighted Least Squares and multi-criteria decision making method. Comput. Biol. Med. 43, 1661-1672.

[11] Baruch, M. C., et al., 2011. Pulse decomposition analysis of the digital arterial pulse during hemorrhage simulation. Nonlinear. Biomedical. Physics. 5, 1-1.

[12] Couceiro, R., et al., 2015. Assessment of cardiovascular function from multi-gaussian fitting of a finger photoplethysmogram. Physiol. Meas. 36, 1801-1825.

[13] Song, J., et al., 2004. Predicting pregnancy-induced hypertension with dynamic hemodynamics. Eur. J. Obstet. Gynecol. Reprod. Biol. 117, 162-168.

[14] Wang, C., Wang F., 2009. Improved algorithm of pulse wave threshold denoising based on lifting wavelet transform. 2009 3rd International Conference on Bioinformatics and Biomedical Engineering. 1-4.

[15] Rubins, U., 2008. Finger and ear photoplethysmogram waveform analysis by fitting withGaussians. Med. Biol. Eng. Comput. 46, 1271–1276.

[16] Liu, C., et al., 2013. Modeling carotid and radial artery pulse pressure waveforms by curve fitting with gaussian functions. Biomed. Signal. Proces. 8, 449-454.

[17] Liu, C., et al., 2014. Gaussian fitting for carotid and radial artery pressure waveforms: comparison between normal subjects and heart failure patients. Bio-Med. Mater. Eng. 24, 271-277.

[18] Torjesen, A. A., et al., 2014. Forward and backward wave morphology and central pressure augmentation in men and women in the Framingham heart study. Hypertension. 64, 259-+.

[19] Avolio, A. P., et al., 1983. Effects of aging on changing arterial compliance and left ventricular load in a northern Chinese urban community. Circulation. 68, 50-58.

[20] Tschakovsky, M. E., Sheriff, D. D., 2004. Immediate exercise hyperemia: contributions of the muscle pump vs. rapid vasodilation. J. Appl. Physiol. 97:739-747.

[21] Kingwell, B. A., et al., 1997. Arterial compliance increases after moderate-intensity cycling. Amer. J. Physiol. 273, H2186-H2191.

[22] Allen, J., Murray, A., 2003. Age-Related changes in the characteristics of the photoplethysmographic pulse shape at various body sites. Physiol. Meas. 24, 297-307.

[23] Sugawara, J., et al., 2003. The effects of low-intensity single-leg exercise on regional arterial stiffness. Jpn. J. Physiol. 53, 239-241.

[24] Padilla, J. M., et al., 2006. Assessment of relationships between blood pressure, pulse wave velocity and digital volume pulse. Computers in Cardiology. IEEE. 893-896.

[25] Kohara, K., et al., 2004. Radial augmentation index: A simple and easy-obtainable parameter for vascular aging. Am. J. Hypertens. 17, 48A-48A.