Journal of Electrocardiology 63 (2020) 57–63

Contents lists available at ScienceDirect

Journal of Electrocardiology

journal homepage: www.jecgonline.com

An optimization study of the ultra-short period for HRV analysis at rest and post-exercise

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A R T I C L E I N F O

Article history:
Received 6 May 2020
revised 2 October 2020
accepted 8 October 2020
Available online xxxx

Keywords:
Ultra-short-term heart rate variability
Autonomic assessment
Post-exercise
Recovery

A B S T R A C T

Background: Ultra-short-term heart rate variability (HRV) analysis (< 5 min) has been extensively growing in the field of exercise performance for autonomic assessment. However, the validation of ultra-short-term HRV was unclear in the recovery period of exercise. This study aimed to elucidate the agreement between ultra-short-term HRV (0–30 s, 0–1 min, 0–2 min, 0–3 min, 0–4 min) and standard short-term HRV (5 min) and to explore the optimal recording duration under rest and post-exercise conditions.

Methods: 69 participants were recruited to perform physical exercise on a treadmill with an intensity of 6 km/h, 9 km/h and 12 km/h, independently. The standard deviation of RR-interval (SDNN) and root mean square of successive differences of RR-intervals (RMSSD) were calculated by using ultra-short periods and standard period at rest condition (Pre-E) and three post-exercise trials, i.e., Post-E1, Post-E2 and Post-E3, respectively. One-way ANOVA with repeated-measures and Cohen's d statistics were conducted, and Bland-Altman analysis and inter-class correlation coefficients (ICC) were used to assess the levels of agreement.

Results: For SDNN and RMSSD, the results of agreement analysis at rest condition were different from those at post-exercise. At Pre-E, SDNN and RMSSD were reliable for ultra-short-term HRV analysis at all ultra-short periods, i.e., 0–30 s, 0–1 min, 0–2 min, 0–3 min and 0–4 min, with most ICCs greater than 0.9 and Cohen's d showing trivial differences (Cohen's $d = 0.024$–0.117). However, at post-exercise, $SDNN_{0\text{–}30s}$, $SDNN_{0\text{-}1min}$, $RMSSD_{0\text{–}30s}$ and $RMSSD_{0\text{-}1min}$ showed significant differences with $SDNN_{5min}$ and $RMSSD_{5min}$, respectively ($p < 0.01$), and the ICCs was not perfect (< 0.9). HRV analysis with time duration longer than 2 min showed nearly perfect reliability in all post-exercise trials, with trivial differences (Cohen's $d = -0.003$–0.110) and perfect ICCs (ICCs = 0.916–0.998). Furthermore, the limits of the agreement became tighter as the period duration increased in Bland-Altman plots.

Conclusions: This study demonstrated that ultra-short-term HRV analysis was a good surrogate of standard HRV time-domain measures to reflect the autonomic regulation at rest and post-exercise. Specifically, ultra-short-term $HRV_{0\text{–}30s}$ or $HRV_{0\text{-}1min}$ was recommended at rest condition, whereas longer than 2 min recording period was reliable to obtain SDNN and RMSSD for the accuracy of HRV analysis.

Introduction

Heart rate variability (HRV) has been studied extensively across a variety of areas as it is thought to reflect the complex interaction between sympathetic and parasympathetic functions of the autonomic nervous system [1,2]. Extracted from the electrocardiographic (ECG) signals, HRV analysis is a non-invasive and reliable approach to distinguish some pathologies, i.e., psychiatric disorders [3], diabetes [4] and cardiac death [5–8]. Furthermore, HRV can be considered as a guideline for the evaluation of exercise adaptations to exercise intensity [9]. Traditionally, it has been recommended that at least 5-min stable periods for short-term HRV analysis are required in a quiet position for obtaining reliable HRV parameters, which is considered standard HRV [1].

Despite the apparent appeal of the standard HRV recording periods, more recently, ultra-short-term HRV analysis (< 5 mins) has been proposed to be a reliable alternative to evaluate automatic reaction [10–12]. Esco et al [12] determined that the ultra-short-term HRV parameters obtained from 1-min windows provided a strong correlation and performed well in the agreement with 5 min in collegiate athletes. Clinical studies [13,14] also found high correlations between 1 min HRV parameters and the criterion measure (5 mins) in diabetes mellitus patients, which indicated the utility of ultra-short-term HRV to track autonomic adaptations in clinical settings. In Munoz's experiment [15], time-domain HRV parameters including standard deviation of RR interval (SDNN) and root mean square of successive differences of RR-intervals

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https://doi.org/10.1016/j.jelectrocard.2020.10.002
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Table 1
Anthropometric and characteristics of the study participants.

Characteristics	$n = 69$ (male = 45)
Age (years)	22.9 ± 3.4
Height (cm)	172.1 ± 9.3
Body mass (kg)	72.4 ± 9.4
BMI (kg/m^2)	22.8 ± 2.6
HR $_{rest}$ (bpm)	74.8 ± 10.3
SBP $_{rest}$ (mmHg)	112.5 ± 10.9
DBP $_{rest}$ (mmHg)	69.5 ± 8.2

Data were calculated as means ± SD. BMI: body mass index; HR: heart rate; SBP: systolic blood pressure; DBP: diastolic blood pressure.

(RMSSD) were measured from ultra-short and standard recording periods under rest condition in 3387 adults. Munoz's study suggested a great performance of ultra-short period recording in obtaining accurate RMSSD and SDNN. In summary, ultra-short-term HRV analysis has been used in many fields and can represent an important method for the evaluation of autonomic modulation [16,17].

The shorter period of data for HRV analysis is better not only for providing time efficiency of data collection but also contributing to increasing the practicality of physiological monitoring applications. Considering the widespread promotion of treadmill exercise and the popularization of physiological monitoring equipment, it is essential to understand the physiological mechanism in exercise performance and the accuracy of ultra-short-term HRV as a surrogate of the criterion measures in physical activities. Hunt et al [18] revealed the feedback system of autonomic control by observing attenuation of HRV parameters with increasing intensity of treadmill exercise. Additionally, Shi et al [19] found the larger suppression of parasympathetic activity during the recovery period from higher intensity treadmill exercise. However, to our knowledge, these studies limited to focus on 5-min standard HRV analysis following physical exercise, the autonomic assessment response to exercise via ultra-short-term HRV analysis was necessary and important to investigate the fast recovery of cardiovascular modulation.

Therefore, the aim of the present study is to examine the relationship between ultra-short-term HRV and standard 5-min HRV under rest and post-exercise conditions. Moreover, the performance of ultra-short-term HRV has not been extensively validated during the recovery period. Accordingly, another aim is to explore the optimal period recording for obtaining reliable HRV parameters and provide evidence that the ultra-short-term HRV analysis is a valuable method for autonomic evaluation under rest and post-exercise conditions.

Materials and methods

Participants

Sixty-nine participants were approached to take part in the present study. The measurements of anthropometric and characteristics were illustrated in Table 1 regarding age, height, body mass, BMI, heart rate (HR), systolic blood pressure (SBP) and diastolic blood pressure (DBP) under rest condition. All participants in this study were physically healthy and none of them had a family history of cardiovascular disease and took medication. All participants were asked not to consume alcohol, coffee or any other drinks that could affect their physical performance 24 h prior to the study. All participants were asked to complete a consent form prior to the study, with approval from the ethics committee at University of Shanghai for Science and Technology, Shanghai, China. The study was conducted in accordance with the Declaration of Helsinki.

Experimental protocols

The experimental sessions were carried out in a separate room free from external distractions, with temperature controlled at 22–24 °C. Prior to the ECG data collection, participants were required to rest quietly in a seated position for 10 mins. Subsequently, ECG signals were recorded for 5 min periods before exercise as the baseline (Pre-E). Later, warming up for a 60 s period on a treadmill was for familiarization with the protocols and to ensure that ECG sensors were properly attached and the data could be recorded for each participant. Then, participants were asked to perform the treadmill exercise at three different intensity levels, i.e., 6 km/h (Post-E1), 9 km/h (Post-E2) and 12 km/h (Post-E3). ECG signals were collected for about 8 min immediately after the cessation of each exercise trial. Participants were required to remain stable and breathe naturally at a seated position to avoid the motion which could cause interference from ECG signals. Each exercise trial was performed for 3 mins, followed by a break of 30 min in-between trials. The procedure of experimental protocols was illuminated in Fig. 1.

Data acquisition and HRV measures

As a measure of the fluctuation of beat-to-beat differences, HRV was a recognized approach for estimating cardiac autonomic modulation [1]. In the present study, the ECG signals were acquired using the Powerlab/16sp system (Castle Hill AD Instrument, Australia, 2002). at 1 kHz with a pre-amplification and filtered by a 1 Hz high-pass filter and a 45 Hz low-pass filter [20]. Three electrodes were respectively placed on the right wrist, left wrist and right leg for each participant. The ECG signal was recorded. Data were visually inspected to identify the ectopic beats, which were automatically removed and replaced by linear interpolation of adjacent RR intervals. The normal-to-normal RR intervals corresponding to sinus rhythm were automatically downloaded and subsequently exported to Kubios HRV software for further analysis [21]. To eliminate the problem of time series nonstationarity immediately after the cessation of exercise, 0-3 min ECG signal was not quantified and only the last 5-min signal was analyzed at post-exercise trials.

Time-domain HRV parameters including SDNN and RMSSD were measured. From each 5-min ECG recording period, SDNN and RMSSD

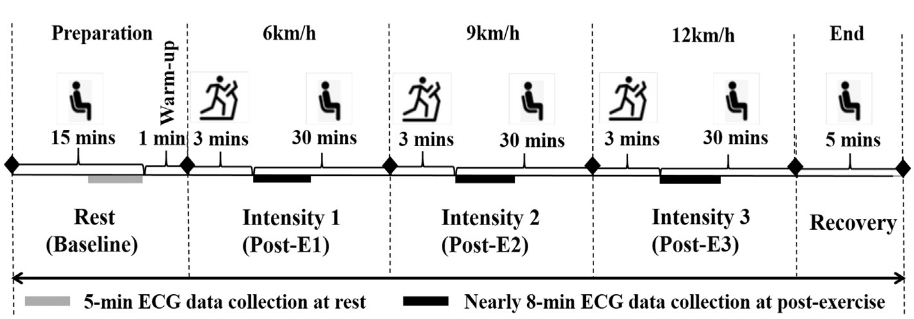

Fig. 1. The procedure of the experimental protocol.

Table 2
Comparison between HRV parameters calculated from ultra-short time duration (0–30s, 0-1 min, 0-2 min, 0-3 min, 0-4 min) and parameters calculated from 5 min duration at rest and post-exercise trials.

	0–30s	0-1 min	0-2 min	0-3 min	0-4 min	0-5 min
SDNN						
Pre-E	40.46 ± 15.75	41.10 ± 15.01	40.24 ± 14.44	40.04 ± 13.27	39.99 ± 12.63	39.51 ± 12.07
Post-E1	**35.06* ± 16.63**	**34.39* ± 16.57**	33.68 ± 15.15	33.38 ± 14.39	32.70 ± 13.26	32.14 ± 12.82
Post-E2	**29.99* ± 17.91**	**31.61* ± 15.44**	27.67 ± 13.53	26.46 ± 12.39	26.53 ± 12.77	26.76 ± 11.44
Post-E3	**32.57* ± 16.44**	**28.54* ± 15.46**	24.75 ± 14.79	26.97 ± 14.61	25.17 ± 14.31	25.45 ± 14.00
RMSSD						
Pre-E	36.00 ± 15.45	36.08 ± 14.79	35.42 ± 14.88	35.08 ± 12.97	34.94 ± 12.24	34.65 ± 11.87
Post-E1	30.86 ± 19.14	**29.83* ± 18.75**	31.67 ± 18.70	33.43 ± 17.69	32.73 ± 12.98	32.23 ± 16.58
Post-E2	**28.87* ± 18.90**	**28.81* ± 16.83**	26.71 ± 16.98	25.75 ± 16.54	25.87 ± 15.12	25.92 ± 14.96
Post-E3	**27.13* ± 19.44**	**26.34* ± 18.28**	24.33 ± 17.85	24.53 ± 18.45	24.66 ± 18.36	24.83 ± 18.34

Data were calculated as means ± SD. ANOVA with a post hoc Bonferroni test was applied. * $p < 0.01$.

were analyzed in the following periods: (1) 0–30 s; 0–1 min; 0–2 min; 0–3 min; 0–4 min (ultra-short-term HRV), and (2) 0–5 min (standard HRV).

Statistical analysis

Statistical analysis was conducted by using SPSS Statistics version 24.0 (SPSS, IBM, USA) and Microsoft Excel 2016 (Microsoft Corporation, UAS). All quantitative parameters were presented as mean ± standard deviation (SD). Shapiro-Wilk Normality Test was applied to evaluate the distribution of HRV parameters. Repeated one-way ANOVA with post hoc Bonferroni test was used to investigate the difference between ultra-short-term HRV and 5-min standard HRV. Cohen's d was calculated to determine the effect size of the mean difference, and the magnitudes of the ES were interpreted using the thresholds as following [22]: trivial (< 0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) or very large (> 2.0). In addition, the intraclass correlation coefficient (ICC) was applied to assess the agreement of HRV parameters between ultra-short-term HRV and standard HRV. Bland-Altman plots were used to identify the upper and lower limits of agreement of SDNN and RMSSD between ultra-short time and standard time analysis. All test results yielding p values <0.05 were considered statistically significant.

Results

As summarized in Table 2, the mean ± SD values of SDNN and RMSSD from ultra-short-term and standard HRV analysis were obtained at rest and three post-exercise trials. It was observed that SDNN and RMSSD values had a significantly decreased trend as exercise intensity increased. Meanwhile, the difference of SDNN and RMSSD between ultra-short time analysis and standard time analysis was compared by repeated one-way ANOVA with post hoc Bonferroni test in each trial. At Pre-E, no statistical difference for SDNN and RMSSD was found between any ultra-short period and the 5-min period, while the comparison of HRV analysis at post-exercise trials between different periods indicated that $SDNN_{0–30s}$ and $SDNN_{0\text{-}1min}$ showed significant differences with $SDNN_{5min}$. Likewise, $RMSSD_{0–30s}$ and $RMSSD_{0\text{-}1min}$ also showed significant difference with $RMSSD_{5min}$ at three post-exercise trials.

Table 3 provided the ICC values between ultra-short-term HRV and standard HRV at four trials. At Pre-E, most ICCs were nearly perfect in ultra-short-term HRV parameters, with ICCs greater than 0.9. At Post-E1, ICC between $RMSSD_{0–30s}$ and $RMSSD_{5min}$ showed moderate (ICC = 0.702), while others showed large to perfect in other comparisons (ICCs = 0.873–0.995). As the exercise intensity increased, i.e., Post-E2 and Post-E3, ICC values significantly decreased in $HRV_{0–30s}$ and $HRV_{0\text{-}1min}$. In three post-exercise trials, ICCs increased as the HRV measurement period increased, and $HRV_{0\text{-}2min}$ showed high values and nearly perfect reproducibility in all comparisons (ICCs >0.9). In addition, Cohen's d values were calculated to quantify the bias of SDNN and RMSSD analyzed by different recording periods, which were summarized in Table 4. Compared to $SDNN_{5min}$, $SDNN_{0–30s}$ and $SDNN_{0\text{-}1min}$ were found to have small ES at Post-E1 and Post-E2 (Cohen's d = 0.210–0.469). In other comparisons, the effect sizes were trivial (Cohen's d < 0.2).

Bland-Altman plots were used for agreement estimations between ultra-short-term HRV and standard HRV at rest and post-exercise. The bias and the limits of agreement (±1.96 SD) were indicated in the plot panels. The limits of agreement were observed decreased as the time windows increased, which were shown in Fig. 2-5.

Table 3
The intraclass correlation coefficient (ICC) between HRV parameters calculated from ultra-short time duration (0–30s, 0-1 min, 0-2 min, 0-3 min, 0-4 min) and parameters calculated from 5 min duration at rest and post-exercise trials.

	0–30s	0-1 min	0-2 min	0-3 min	0-4 min
SDNN					
Pre-E	**0.912***	0.895*	**0.940***	**0.967***	**0.991***
Post-E1	0.873*	**0.908***	**0.961***	**0.983***	**0.995***
Post-E2	0.709*	0.839*	**0.924***	**0.980***	**0.994***
Post-E3	0.633*	0.704*	**0.916***	**0.974***	**0.995***
RMSSD					
Pre-E	0.838*	**0.904***	**0.933***	**0.966***	**0.993***
Post-E1	0.702*	**0.933***	**0.975***	**0.991***	**0.995***
Post-E2	0.632*	0.817*	**0.983***	**0.989***	**0.997***
Post-E3	0.462	0.691	**0.985***	**0.991***	**0.998***

Note: ICC was used for analyzing the concordance between ultra-short periods (0–30s, 0–1 min, 0–2 min, 0–3 min, 0–4 min) and standard time (5 min). ICC values lower than 0.4 were considered small, values between 0.4 and 0.75 were considered moderate, values between 0.75 and 0.9 were considered large, values greater than 0.9 were consider perfect.
* *p < 0.05 values showed statistical significance.*

Table 4
The Cohen's d values for quantification of the bias of SDNN and RMSSD calculated from different time duration at rest and post-exercise trials.

	0–30s	0-1 min	0-2 min	0-3 min	0-4 min
SDNN					
Pre-E	0.068	0.117	0.055	0.042	0.039
Post-E1	0.198	0.153	0.110	0.091	0.043
Post-E2	**0.220**	**0.361**	0.073	0.025	−0.019
Post-E3	**0.469**	**0.210**	−0.049	0.106	−0.020
RMSSD					
Pre-E	0.099	0.107	0.058	0.035	0.024
Post-E1	−0.077	−0.136	−0.032	0.070	0.034
Post-E2	0.174	0.182	0.049	−0.011	−0.003
Post-E3	0.122	−0.028	0.027	−0.016	−0.009

Discussion

In order to investigate the applicability of shorter ECG recordings (< 5 min) for daily HRV monitoring, ultra-short-term HRV and standard 5-min short-term HRV were compared in a group of healthy participants under rest and post-exercise conditions. In this study, significant differences were found between $HRV_{0\text{–}30s}$, $HRV_{0\text{-}1min}$ and HRV_{5min} under different conditions.

At Pre-E, no significant differences were found between $HRV_{0\text{–}30s}$, $HRV_{0\text{-}1min}$ ($SDNN_{30s}$, $SDNN_{1min}$, $RMSSD_{30s}$ and $RMSSD_{1min}$) and HRV_{5min} ($SDNN_{5min}$ and $RMSSD_{5min}$) with trivial effect size, and most ICCs were considered nearly perfect with values larger than 0.9, suggesting that ultra-short-term HRV analysis with 0–30 s or 0–1 min periods had good levels of agreement with standard HRV. The results under rest condition were consistent with some previous studies [10,15], which indicated that HRV obtained from shorter periods (< 1 min) had good agreement with that obtained from 5-min periods [23]. At post-exercise, significant differences were found between $HRV_{0\text{–}30s}$, $HRV_{0\text{-}1min}$ and HRV_{5min}. Moreover, the effect size showed slightly less accurate results compared with that under rest condition, and most ICCs decreased lower than 0.9. The concordance was not observed between $HRV_{0\text{–}30s}$, $HRV_{0\text{-}1min}$ and $HRV_{0\text{-}5min}$ regarding post-exercise trials, which confirmed the requirement of longer time duration for applicability of ultra-short-term HRV after aerobic exercise. When the recording periods were longer than 2 mins, the results showed really good agreements with standard HRV at post-exercise trials. In addition, Bland-Altman analysis reinforced the main results with acceptable levels of agreement and small bias. Specificlly, SDNN and RMSSD calculated with 30-s or 1-min time windows under rest condition, and those calculated with 2-min windows at post-exercise were good surrogates of HRV parameters calculated with 5-min windows.

Physiologically, it was reasonable to explain that vagal withdrawal was remained after exercise, which meant vagal influence on HR was stable in the initial early recovery period [5,24]. Meanwhile, it may also result from the increased error of unstable RR-interval data at post-exercise. Due to the results, 30 s duration for daily HRV monitoring under rest condition could provide acceptable reliability, while longer duration (2 mins) was recommended after some physical activities. RMSSD was believed to mark vagal modulation [1] and SDNN was influenced by both sympathetic and parasympathetic nerve activities [25]. Based on the present findings, the enhancement of parasympathetic activity and sympathetic withdrawal could be concluded during the recovery period of exercise by using ultra-short-term HRV analysis, which was in agreement with previous studies [24,26]. The results provided reliable information that ultra-short-term HRV could also monitor the autonomic alteration at post-exercise as a useful tool. It was worth noting that HRV frequency-domain parameters were not analyzed in this study since the ultra-short periods (< 1 min) was not sufficient to achieve the power spectrum analysis.

Furthermore, we observed the decreased SDNN and RMSSD while exercise intensity increased, which was in accordance with some investigations [27–29]. In the present study, we focused on investigating the optimal period for ultra-short-term HRV analysis under rest and post-exercise conditions instead of explaining the physiological reaction to different exercise intensity. Accordingly, Bland-Altman plot analysis at post-exercise was intended to verify the universal applicability of ultra-short time recording for HRV analysis by integrating all data together from three post-exercise trials. The results confirmed that the limits of agreement were tighter as the time segment increased. A possible interpretation of the high dependence of SDNN and RMSSD on recording length was that SDNN reflected the total power of HRV frequency components and RMSSD was a reflection of high-frequency HRV components [15,30]. In summary, our findings highlighted the use of ultra-short-term HRV as a surrogate of standard HRV, and there were different optimal ultra-short periods at rest and post-exercise.

The statistical approaches in the present study pertaining to the accuracy of ultra-short-term HRV focused on ICC values, Cohen's *d* statistics and Bland-Altman plots. It was necessary to point out that Pearson correlation coefficients could be used to measure the strength of linear association, but the results were not showed in the paper since there

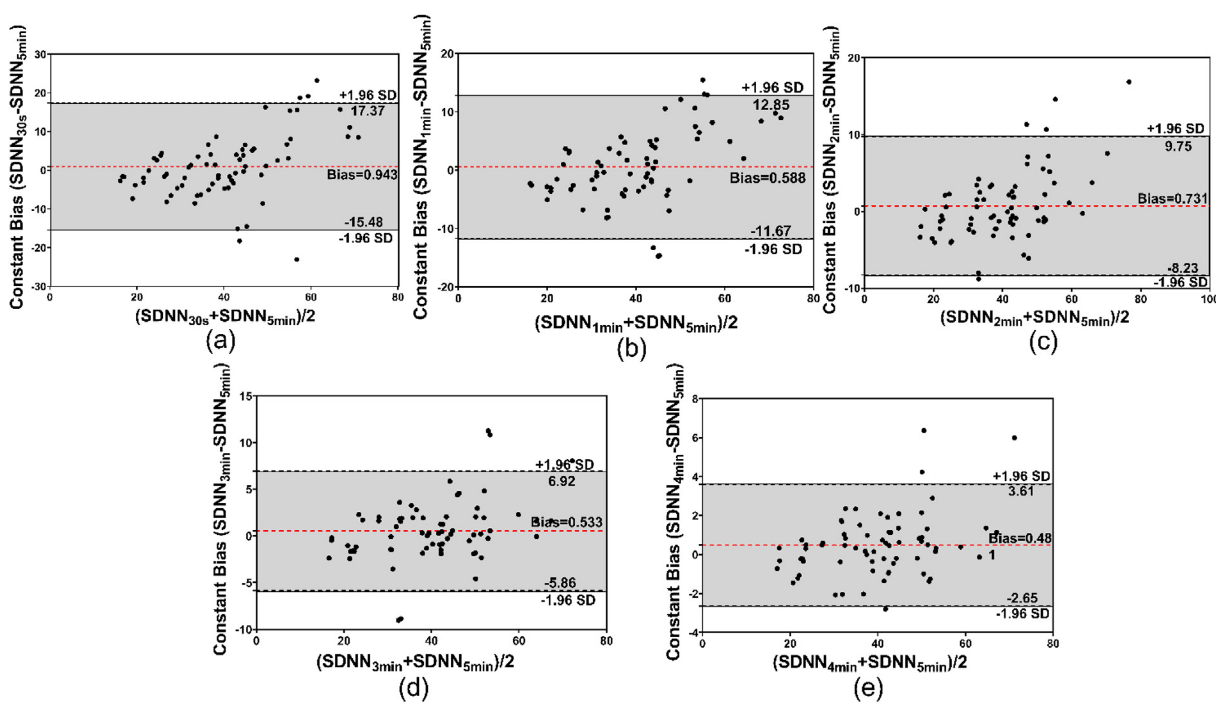

Fig. 2. The Bland-Altman plots of differences with ultra-short periods against the reference standard time analysis for SDNN at rest condition. (a), (b), (c), (d) and (e) represented 0–30 s, 0–1 min, 0–2 min, 0–3 min and 0–4 min, respectively. The red middle line indicated bias, while the two dashed lines indicated upper and lower limits of agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

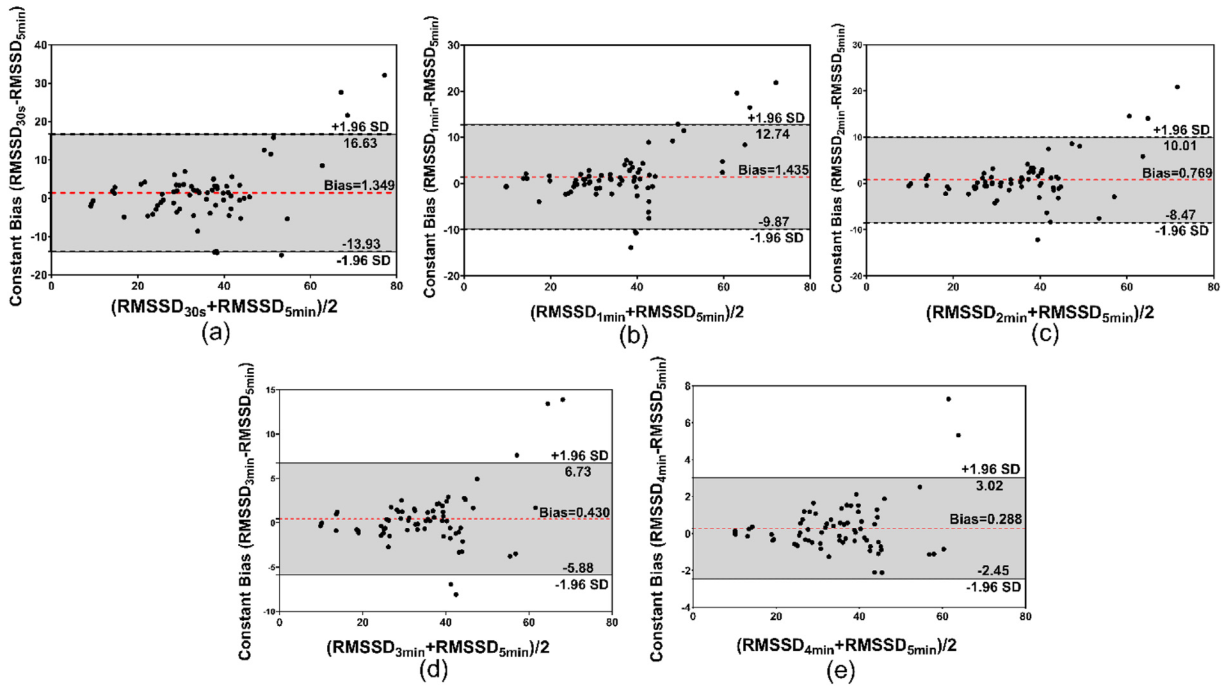

Fig. 3. The Bland-Altman plots of differences with ultra-short periods against the reference standard time analysis for RMSSD at rest condition. (a), (b), (c), (d) and (e) represented 0–30 s, 0–1 min, 0–2 min, 0–3 min and 0–4 min, respectively. The red middle line indicated bias, while the two dashed lines indicated upper and lower limits of agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

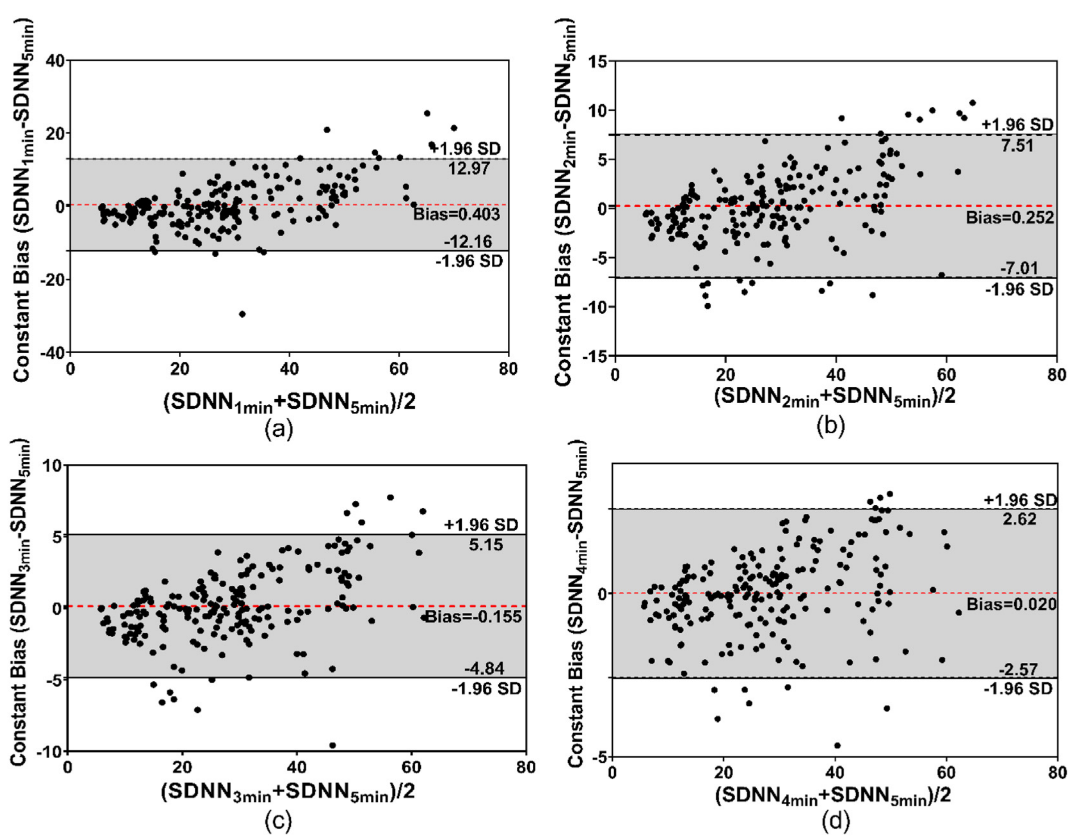

Fig. 4. The Bland-Altman plots of differences with ultra-short periods against the reference standard time analysis for SDNN at post-exercise. (a), (b), (c) and (d) represented 0–1 min, 0–2 min, 0–3 min and 0–4 min, respectively. The red middle line indicated bias, while the two dashed lines indicated upper and lower limits of agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

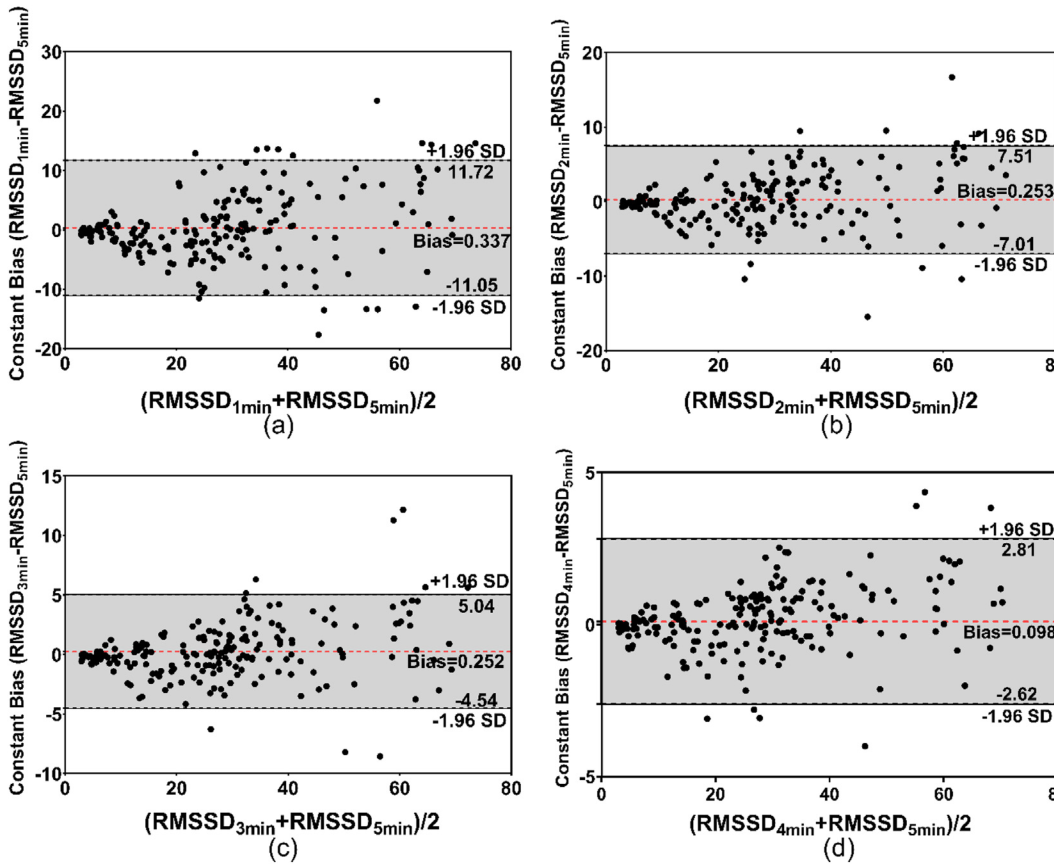

Fig. 5. The Bland-Altman plots of differences with ultra-short periods against the reference standard time analysis for RMSSD at post-exercise. (a), (b), (c) and (d) represented 0–1 min, 0–2 min, 0–3 min and 0–4 min, respectively. The red middle line indicated bias, while the two dashed lines indicated upper and lower limits of agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

was no difference in reliability of SDNN and RMSSD in all trials, with all r values higher than 0.9. Therefore, the reliability of ultra-short-term HRV analysis was reinforced by ICCs, Cohen's *d* and Bland-Altman plots.

The autonomic modulation of heart rate at post-exercise was very important to evaluate cardiovascular health [31]. It was believed that extreme alterations in cardiovascular autonomic response to dramatical exercise could contribute to the increased risk of cardiac death [5,6,32]. Therefore, a healthier and more appropriate way of exercise was necessary for our daily life. Furthermore, with the popularity of wearable devices which monitored autonomic modulation reflected via HRV parameters, short monitoring duration would improve the convenience of HRV assessment and make it more practical in physical exercise. Also, the development of the wearable devices would benefit from the shortened HRV monitoring duration. A prompt monitor of cardiovascular response to exercise could provide guidance to adjust the exercise program. In this circumstance, ultra-short-term HRV was studied and the results yielded an important finding that 30 s or 1 min of periods were sufficient to obtain acceptable SDNN and RMSSD at rest, while at least 2 min were necessary at post-exercise, i.e., good levels of agreement and small bias, as well as trivial to small effect size and nearly perfect ICCs.

The main limitations in the current study included: (a): autonomic nervous modulation was not measured directly, whether the the agreement of HRV parameters in different time windows reflected the autonomic regulation at rest and post-exercise needed further research; (b): some non-ANS factors may influence the HRV analysis results in this study; (c): future research should be performed with larger populations including different age groups, professional athletes and various clinical samples, so that the results could extrapolated to other groups, or to subjects with cardiovascular diseases.

Conclusion

To sum up, the ultra-short time recording for HRV analysis was a good surrogate of standard 5 min to evaluate autonomic activities. Specifically, these findings suggested that 30 s or 1 min recording periods for daily HRV measures under rest condition was acceptable. Moreover, at least 2 min ultra-short periods should be considered for HRV analysis at post-exercise. We supported the utility of ultra-short-term HRV to evaluate autonomic response at rest and post-exercise. This study was expected to contribute to the development of HRV monitoring applications in daily life.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Liang Wu: Conceptualization, Formal analysis, Investigation, Methodology, Software, Validation, Writing - original draft. **Ping Shi:** Conceptualization, Investigation, Resources, Validation, Writing - review & editing. **Honngliu Yu:** Funding acquisition, Project administration, Validation. **Yang Liu:** Resources, Supervision, Writing - review & editing.

Acknowledgments

We would like to express our gratitude to the volunteers who participated and generously contributed their time.

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