JYX JYVÄSKYLÄN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

This is a self-archived version of an original article. This version may differ from the original in pagination and typographic details.

Author(s): Nuuttila, Olli-Pekka; Seipäjärvi, Santtu; Kyröläinen, Heikki; Nummela, Ari

Title: Reliability and Sensitivity of Nocturnal Heart Rate and Heart-Rate Variability in Monitoring Individual Responses to Training Load

Year: 2022

Version: Accepted version (Final draft)

Copyright: © 2022 Human Kinetics, Inc.

Rights: In Copyright

Rights url: http://rightsstatements.org/page/InC/1.0/?language=en

Please cite the original version:

Nuuttila, O.-P., Seipäjärvi, S., Kyröläinen, H., & Nummela, A. (2022). Reliability and Sensitivity of Nocturnal Heart Rate and Heart-Rate Variability in Monitoring Individual Responses to Training Load. International Journal of Sports Physiology and Performance, 17(8), 1296-1303. https://doi.org/10.1123/ijspp.2022-0145

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2022-0145
© 2022 Human Kinetics, Inc.
First Published Online: July 6, 2022

Human Kinetics
ORIGINAL INVESTIGATION

Reliability and Sensitivity of Nocturnal Heart Rate and Heart-Rate Variability in Monitoring Individual Responses to Training Load

Olli-Pekka Nuuttila,[1] Santtu Seipäjärvi,[2] Heikki Kyröläinen,[1] and Ari Nummela[3]
[1]Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland; [2]Department of Psychology, Center for Interdisciplinary Brain Research, University of Jyväskylä, Jyväskylä, Finland; [3]Finnish Institute of High Performance Sport KIHU, Jyväskylä, Finland

Purpose: To assess the reliability of nocturnal heart rate (HR) and HR variability (HRV) and to analyze the sensitivity of these markers to maximal endurance exercise. ***Methods:*** Recreational runners recorded nocturnal HR and HRV on nights after 2 identical low-intensity training sessions (n = 15) and on nights before and after a 3000-m running test (n = 23). Average HR, the natural logarithm of the root mean square of successive differences (LnRMSSD), and the natural logarithm of the high-frequency power (LnHF) were analyzed from a full night (FULL), a 4-hour (4H) segment starting 30 minutes after going to sleep, and morning value (MOR) based on the endpoint of the linear fit through all 5-minute averages during the night. Differences between the nights were analyzed with a general linear model, and intraclass correlation coefficient (ICC) was used for internight reliability assessments. ***Results:*** All indices were similar between the nights followed by low-intensity training sessions. A very high ICC ($P < .001$) was observed in all analysis segments with a range of .97 to .98 for HR, .92 to .97 for LnRMSSD, and .91 to .96 for LnHF. HR increased ($P < .001$), whereas LnRMSSD ($P < .01$) and LnHF ($P < .05$) decreased after the 3000-m test compared with previous night only in 4H and FULL. Increments in HR ($P < .01$) and decrements in LnRMSSD ($P < .05$) were greater in 4H compared with FULL and MOR. ***Conclusions:*** Nocturnal HR and HRV indices are highly reliable. Demanding maximal exercise increases HR and decreases HRV most systematically in 4H and FULL segments.

Keywords: endurance training, recovery, recovery monitoring, autonomic nervous system, parasympathetic nervous system

Heart rate (HR) and HR variability (HRV) either during exercise or at rest are commonly monitored in sport to estimate the current recovery and training status.[1] In terms of recovery, since HRV is a surrogate of cardiac parasympathetic nervous system activity,[2] it is a potential marker due to its responsiveness to different types of stressors.[3] Practical applications of HRV have been demonstrated in protocols that have fine-tuned endurance training based on fluctuations in HRV compared with normal individual values.[4]

Resting HRV recordings are optimally performed either immediately upon awakening or during sleep to minimize the effects of any possible external factors affecting functions of the autonomic nervous system.[1] Although sleep time could theoretically provide the most standardized period for the recording by minimizing external distractions,[1] morning/awake recordings have previously been utilized, for example, in all studies examining HRV-guided endurance training prescription.[4] Variation in autonomic nervous system function across different sleep stages,[1,5] as well as challenges in the data collection during the night,[1] have perhaps been the main reasons in favor of morning recordings. Also, it can be argued that measurements performed in the morning would better reflect the actual readiness to train on the following day, because sleep itself is a crucial contributor to the recovery process.[6] However, current technology provides validated and feasible opportunities to record HR and HRV through the night,[7–9] or even 24/7,[10] allowing broader deployment of nocturnal recordings in the monitoring process, if proven beneficial.

The reliability of the resting HR and HRV indices has mainly been examined via short daytime recordings.[11–13] In turn, day-to-day reliability of nocturnal recordings is poorly known. We found only 1 congress abstract which reported reproducibility of spectral HRV indices on nights after 2 identical low-intensity training (LIT) sessions.[14] A few studies have examined the within-week variation of HR and HRV during a typical training period,[9,15] or the within- and between-night reproducibility separately for different stages of sleep,[5] however, none of these have examined the similarity of the responses to standardized training load. Comparing the reliability of HRV responses from segments that could be collected via wearables, such as full night,[7,9] a 4-hour segment from the beginning of the night,[8,16] or the "outcome" value during the morning,[9] would therefore provide relevant information for the practitioners considering the most appropriate recording conditions.

In addition to the reliability of the monitoring marker, its sensitivity to detect meaningful positive and negative changes is another important aspect to evaluate.[1] Previously, HR and HRV responses to different types of exercises have been examined instantly,[17,18] during the following night,[15,16,19–21] and following certain measurement points up to 72 hours.[22] In acute responses, it has been observed that the intensity of the preceding exercise is the main contributor to the decrease in HRV,[17,18] and it has been suggested that full cardiac autonomic recovery may take up to 24 hours after low-intensity exercise and at least 48 hours after high-intensity exercise.[23] Somewhat surprisingly, such a clear conclusion could not be drawn from the previous studies examining nocturnal recordings. While some have found decreases in HRV on the following night after heavy and moderate exercises,[16,19] some others have found changes only in HR despite

Nuuttila (olli-pekka.s.nuuttila@jyu.fi) is corresponding author.

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

late-night training sessions.[15,20,21] Differences may relate to the multiple approaches utilized (slow-wave sleep, 4-h segment, and full night), as well as varying physiological demands of the training sessions. This study aimed to examine the reliability of nocturnal HRV recordings after standardized training load and sensitivity to maximal endurance exercise, which was expected to cause acute fatigue and impaired state of recovery. We hypothesized that the full-night segment would be the most reliable one, since it consists of the longest period of data; and that the 4H segment, being closest to the preceding stressor, would be affected more than other segments by the maximal exercise.

Methods

Subjects

Recreational male and female runners were recruited for a larger study project,[24] during which the current data collection was executed. Subjects whose full nocturnal HR and HRV data were available after the 2 first consecutive LIT sessions of the training period (n = 15) and/or the night before and after the second 3000-m test of the study (n = 23) were involved in the analysis. Characteristics of the subjects are presented in Table 1. The study protocol was approved by the ethics committee of the University of Jyväskylä and was performed in accordance with the principles of the Declaration of Helsinki.

Design

The study examined the reliability and sensitivity of nocturnal HR and HRV indices by comparing the results of 2 consecutive nights after (1) identical LIT sessions and (2) a rest day and a maximal 3000-m running test. Three different methods were used for the nocturnal HR and HRV analysis: full night (FULL),[9] 4-hour period starting 30 minutes after going to sleep (4H),[16] and morning value (MOR) from an endpoint of linear fit between 5-minute averages of full-night data.[9]

Methodology

LIT Session. The LIT sessions used in the current analysis were the first 2 identical training sessions of a 2-week training block. The sessions were supervised and performed outdoors, individually, at the same time of day. Average HR, distance covered (in kilometers), and rating of perceived exertion (0–10)[25] were analyzed from both sessions.

3000-m Running Test. The running test was performed on a 200-m indoor track. Before the test, a 15-minute low-intensity warm-up was executed. The test was run in small groups (maximum 7 persons) either in the afternoon (n = 12) or in the evening (n = 11), based on the preference of the individual. In the afternoon group, there was a gap of 7:54 (0:57) hours:minutes between the end of the test and bedtime, whereas in the evening group, the gap was 2:31 (0:52) hours:minutes. Time, average HR, and peak HR were analyzed from the test.

Table 1 Baseline Characteristics of the Subjects

	Low-intensity training (n = 15)	3000-m (n = 23)
Age, y	36 (7)	36 (7)
Height, cm	172 (11)	173 (10)
Body mass, kg	69 (13)	72 (13)
Training hours, h/wk	5.6 (2.3)	5.6 (1.5)
VO_2max, mL·kg^{-1}·min^{-1}	50 (6)	49 (7)

Abbreviations: LIT, low-intensity training; VO_2max, maximal oxygen uptake. Note: In the LIT group, there were 7 women and 8 men, and in the 3000-m group, 10 women and 13 men.

Nocturnal HRV Recordings. Nocturnal HR and HRV were recorded at home with the Firstbeat Bodyguard 2 device (Firstbeat Technologies LTD). Participants started recordings when going to bed and stopped upon awakening. Bedtime and waking up times were reported in the sleep diary. Recorded RR intervals were analyzed in Kubios HRV Premium Software (version 3.5.0, Biosignal Analysis and Medical Imaging Group, Department of Physics, University of Kuopio). Before performing analyses, automatic beat correction[26] was applied for the data. Average HR, the natural logarithm of the root mean square of the successive differences (LnRMSSD), and the natural logarithm of the high-frequency power (LnHF) were analyzed. The absolute power for LnHF was obtained with the fast Fourier transform method at the bandwidth of 0.15 to 0.40 Hz. Current HRV variables were chosen since: (1) They are suggested to reflect cardiac parasympathetic activity,[1] (2) they have been used in the guidance of endurance training,[4] and (3) they have been associated with endurance training adaptations.[27,28]

Subjective Recovery. Subjective readiness to train and sleep quality of the preceding night was estimated daily on a 0 to 10 visual analog scale. The questionnaire was adapted from a previous study.[29] The rationale behind subjective markers was to (1) confirm the similarity of the days in the reliability setting and (2) confirm possible negative changes in the recovery state followed by the 3000-m running test. Subjective estimations were missing from 1 participant after the 3000-m test, thus n = 22 in these analyses.

Statistical Analysis

All results are presented as mean (SD). The normality of the data was confirmed with the Shapiro–Wilk test, and the normality of the residuals was visually inspected via Q–Q plots. Differences in all measured variables between the first and second LIT sessions, between the nights before and after the 3000-m test, and between different analysis segments were assessed with a general linear model repeated measures. Time (first/second session or before/after 3000 m) and analysis segment (4H, FULL, and MOR) were used as within-subject factors. To compare the afternoon and evening subgroups in the HRV responses after 3000 m, the subgroup was used as a between-subject factor. In case of significant main effect or interaction (univariate tests, sphericity assumed) a Bonferroni post hoc test was used for within-group comparisons and simple contrasts for between-group comparisons. To examine the magnitude of observed changes, effect size (ES) was calculated as Cohen *d* (difference of the means divided by the pooled SD) for the HRV responses. The magnitude of changes was categorized as <0.2 trivial, 0.2 to 0.5 small, 0.5 to 0.8 moderate, and >0.8 large. Internight reliability after the LIT sessions was analyzed by intraclass correlation coefficient (ICC) and coefficient of variation (CV). Settings used in the ICC analyses were single-rating, absolute agreement, 2-way mixed model. Pearson correlation coefficient was used to analyze relationships between the change in nocturnal HR and HRV indices and estimated readiness to train

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

after the 3000-m test. Analyses were performed with Microsoft Excel (2016, Microsoft Corp) and IBM SPSS Statistics (version 26) programs.

Results

Responses to the 2 Consecutive LIT Sessions

Details of the training sessions, sleep characteristics, and subjective recovery of the following days are presented in Table 2. All HR and HRV indices were similar between the 2 consecutive nights after LIT (Table 3). No differences were found either between the absolute results obtained from 4H, FULL, or MOR. ICC values between the 2 nights with different indices and analysis segments are presented in Figure 1.

Table 2 Training Characteristics of the 2 Low-Intensity Sessions

	Session 1	Session 2	CV, %
Training			
Duration, h:min	1:24 (0:12)	1:24 (0:12)	1.5
Distance covered, km	13.4 (3.2)	13.7 (3.1)	3.1
Average HR, %/max	73.1 (4.7)	72.6 (5.3)	1.2
RPE (0–10)	2.7 (0.9)	2.9 (1.1)	16.0
Sleep			
Bed time, h:min	22:56 (0:56)	23:10 (0:50)	—
Sleep duration, h:min	7:55 (0:43)	8:05 (1:02)	9.0
Subjective recovery			
Sleep quality (0–10)	6.0 (1.7)	5.9 (2.7)	19.6
Readiness to train (0–10)	6.4 (1.6)	6.3 (2.0)	11.6

Abbreviations: CV, coefficient of variation; HR, heart rate; RPE, rating of perceived exertion. Note: Sleep characteristics are presented from the night following each session, and subjective recovery was estimated on the day following each session

Table 3 Nocturnal HR and HR-Variability Indices After the First (Night 1) and the Second (Night 2) Low-Intensity-Training Sessions of the Training Period

	Night 1	Night 2	CV, %
4H			
HR, bpm	50.2 (9.1)	49.7 (8.4)	3.3
LnRMSSD, ms	4.21 (0.48)	4.16 (0.46)	2.4
LnHF, ms^2	7.03 (0.86)	7.00 (0.90)	3.0
FULL			
HR, bpm	49.9 (8.7)	49.7 (8.5)	2.4
LnRMSSD, ms	4.22 (0.48)	4.22 (0.48)	2.1
LnHF, ms^2	7.05 (0.88)	7.01 (0.89)	2.4
MOR			
HR, bpm	49.3 (8.2)	50.3 (8.6)	3.0
LnRMSSD, ms	4.29 (0.49)	4.21 (0.47)	3.3
LnHF, ms^2	7.18 (0.89)	6.99 (0.85)	3.8

Abbreviations: bpm, beats per minute; CV, coefficient of variation; FULL, full night; HR, heart rate; LnHF, the natural logarithm of the high-frequency power; LnRMSSD, the natural logarithm of the root mean square of successive differences; MOR, morning segment; 4H, 4-hour segment.

Responses to Maximal Endurance Exercise

Participants covered the 3000-m running test on an average time of 12:34 (1:26) minutes:seconds. The average and peak HR during the test was 94.5% (2.5%)/maximal HR and 99.4% (2.2%)/maximal HR, respectively. Bedtime was later after the 3000-m test ($P = .004$) (22:39 [0:59] vs 23:19 [1:05]), while sleep duration (8:06 [0:47] vs 7:41 [1:15] h:min) and subjective sleep quality (5.5 [2.0] vs 4.8 [2.5]) were similar between the nights. Readiness to train decreased after the 3000-m test (6.1 [1.9] vs 4.8 [2.0], $P = .019$).

In the total group of 4H, nocturnal HR increased (51.2 [8.8] beats per minute [bpm] vs 55.0 [7.9] bpm, $P < .001$, ES = 0.45), while decrements were found in LnRMSSD (4.19 [0.58] ms vs 4.02 [0.59] ms, $P < .001$, ES = −0.30) and LnHF (7.07 [1.05] ms^2 vs 6.78 [1.16] ms^2, $P = .002$, ES = −0.26). In the total group of FULL, similar changes were also observed in nocturnal HR (50.9 [8.3] bpm vs 54.1 [7.6] bpm, $P < .001$, ES = 0.40), LnRMSSD (4.23 [0.54] ms vs 4.10 [0.59] ms, $P = .002$, ES = −0.22), and LnHF (7.14 [1.00] ms^2 vs 6.94 [1.13] ms^2, $P = .014$, ES = −0.18). In the total group of MOR, nocturnal HR (51.1 [7.7] bpm vs 51.3 [7.5] bpm, ES = 0.01), LnRMSSD (4.25 [0.52] ms vs 4.21 [0.64] ms, ES = −0.04), and LnHF (7.16 [1.02] ms^2 vs 7.05 [1.23] ms^2, ES = −0.07) remained unchanged. In the subgroup analyses, no significant group × time or group × time × segment interactions were found. Individual relative changes are presented in Figure 2. Figure 3 illustrates 2 examples of nocturnal HR and LnRMSSD behavior on the night before and after the 3000-m test as 5-minute averages.

Associations Between Estimated Readiness to Train and Changes in Nocturnal HR and HRV

The readiness to train on the day after the 3000-m running test correlated significantly with the relative change of LnRMSSD in 4H and FULL (Figure 4). In addition, similar correlations were found in the relative change of LnHF in 4H ($r = .61$, $P = .002$) and FULL ($r = .59$, $P = .004$). In turn, no significant correlations were found between the estimated readiness to train and the relative change of LnRMSSD ($r = .35$, $P = .107$) or LnHF ($r = .36$, $P = .098$) in MOR, or the relative change in HR in any of the analysis segments.

Discussion

The main findings of the study were that all nocturnal HR and HRV indices were reliable in terms of high ICC and small CV between the nights. Furthermore, absolute values did not differ between analysis segments after LIT. Regarding the responses to maximal endurance exercise, the magnitude of changes was greatest in 4H and FULL, and these changes also aligned with the estimated readiness to train on the following day. While 4H and FULL may be superior segments to demonstrate the disturbance of cardiovascular homeostasis, further examinations are needed to clarify the proper interpretation of such responses in the context of day-to-day recovery monitoring.

To the best of our knowledge, the night to night reliability of nocturnal HR and HRV indices after identical training load has been reported only in 1 abstract, with quite similar results compared with the present study. In turn, several studies have assessed the test–retest reliability of short-term resting HR and HRV recordings while awake.[11–13] Nakamura et al[13] analyzed the reliability of resting LnRMSSD in a seated position, finding intraday

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

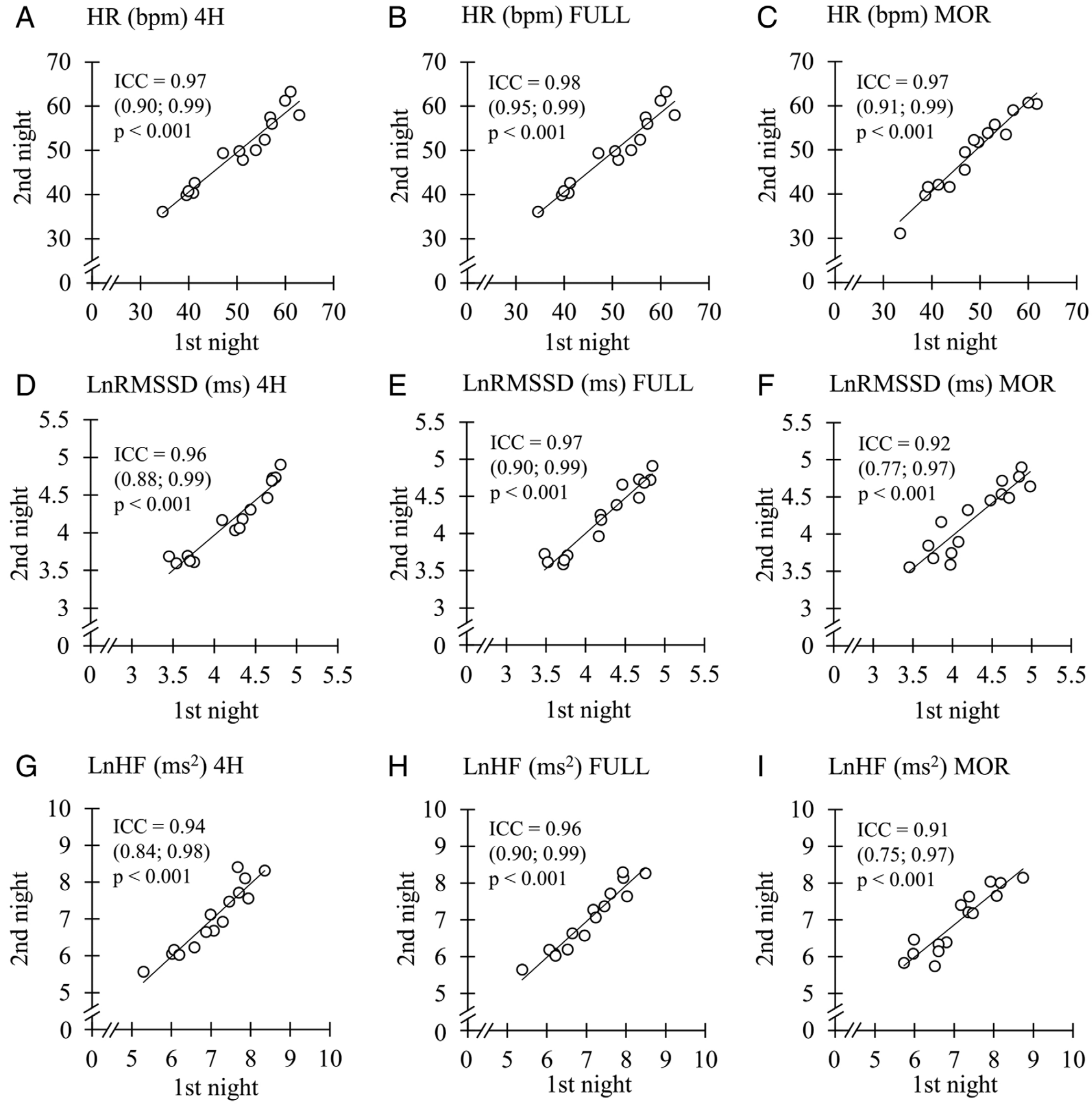

Figure 1 — ICC values (and 95% CIs) between the first and second nights after low-intensity training in different indices and analysis segments. bpm indicates beats per minute; FULL, full night; HR, heart rate; ICC, intraclass correlation coefficient; LnHF, the natural logarithm of the high-frequency power; LnRMSSD, the natural logarithm of the root mean square of successive differences; MOR, morning segment; 4H, 4-hour segment.

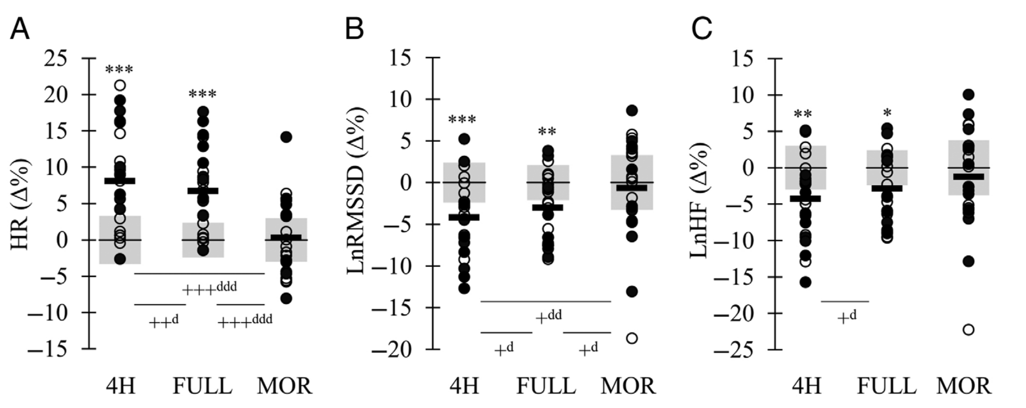

Figure 2 — Relative changes from the night after a rest day to the night after 3000-m test in HR, LnRMSSD, and LnHF. The gray area illustrates the typical error (±CV) from the variable and analysis method in question, applied from Table 3. Black dots are individuals from the evening subgroup, transparent dots are individuals from the afternoon subgroup, and black rectangles refer to the mean of the group. CV indicates coefficient of variation; ES, effect size; FULL, full night; HR, heart rate; LnHF, the natural logarithm of the high-frequency power; LnRMSSD, the natural logarithm of the root mean square of successive differences; MOR, morning segment; 4H, 4-hour segment. $^{*}P < .05$, $^{**}P < .01$, $^{***}P < .001$ compared with rest day. $^{+}P < .05$, $^{++}P < .01$, $^{+++}P < .001$ difference between analysis method. ^{d}ES = 0.2 to 0.5; ^{dd}ES = 0.5 to 0.8; ^{ddd}ES > 0.8.

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

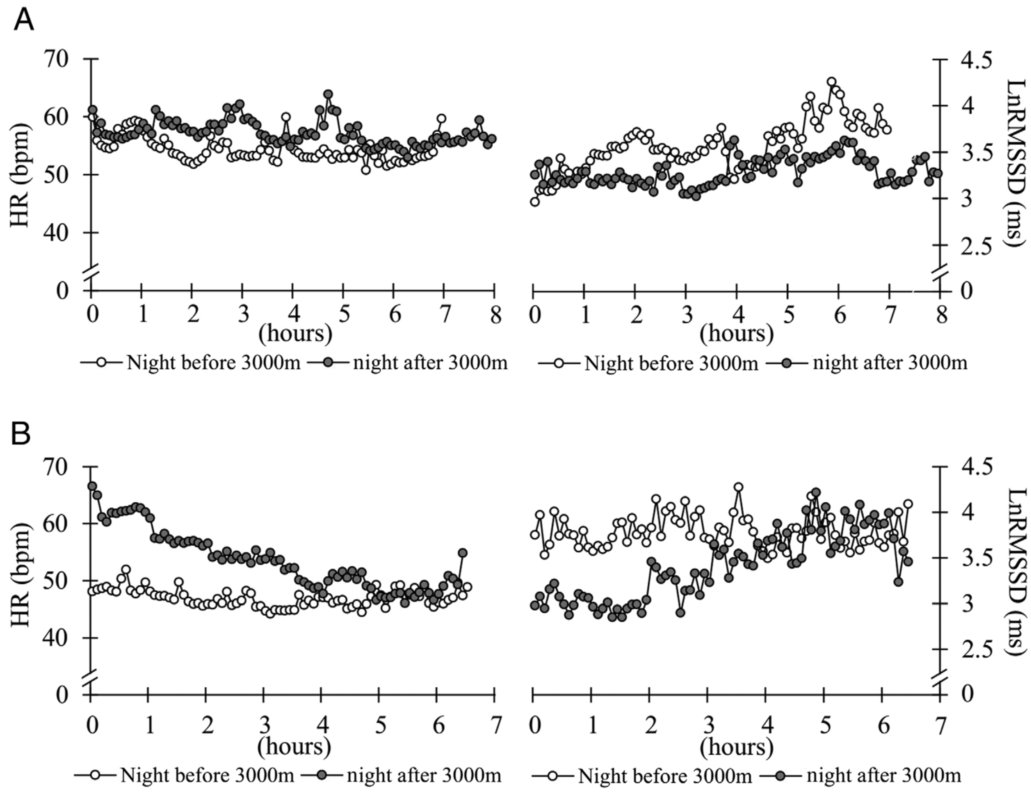

Figure 3 — Example within-night trends in HR and LnRMSSD illustrated by (A) an individual having increased HR and decreased LnRMSSD through the whole night after a 3000-m test and (B) an individual having significant recovery in HR and LnRMSSD after a 3000-m test leading to similar values between nights in the morning. bpm indicates beats per minute; HR, heart rate; LnRMSSD, the natural logarithm of the root mean square of successive differences.

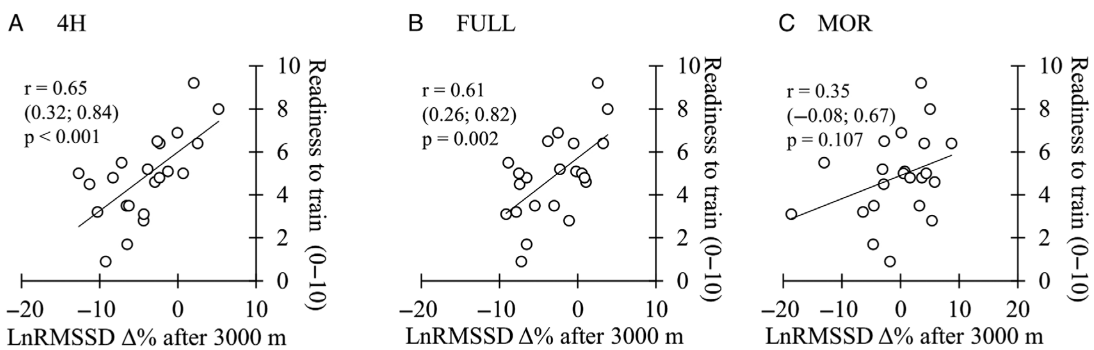

Figure 4 — Correlations (and 95% CIs) between the relative change in nocturnal LnRMSSD after the 3000-m test and estimated readiness to train on the following day. FULL, full night; LnRMSSD, the natural logarithm of the root mean square of successive differences; MOR, morning segment; 4H, 4-hour segment.

(recordings separated by 10 min) and interday (3 consecutive mornings) ICC being .96 and .90, respectively. In turn, Cipryan and Litschmannova[12] reported ICC values of .96 and .93 for mean RR and LnHF in intraday comparison (separated by 6-min standing) and .76 and .78 in interday comparison (separated on average by 9 d), respectively. Costa et al[15] measured LnRMSSD on 6 consecutive nights of alternating training and rest days. ICC for hour-by-hour-derived results varied between .89 and .95, while for slow-wave sleep episodes it was .95. All segments that were applied in the current study induced comparable or slightly higher ICC values (.96–.98 for HR and .91–.96 for HRV), indicating good reliability. Although HRV may vary across different sleep stages,[1,5] it seems that averaging the results for a longer period would smooth the possible within-night differences in the sleep characteristics. Previously, it has been suggested that analyzing HRV during slow-wave sleep would be the best alternative in terms of standardization and reproducibility.[1,5] However, the timing of such segments would, in some cases have a significant effect on the outcome of interpretation, as illustrated in Figure 3. In addition, one may question whether the accuracy of current wearables is sufficient to distinguish sleep stages accurately when applying methods to field use.[30]

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

The HRV results are typically interpreted with respect to the "smallest worthwhile change," which illustrates a fraction of typical variation (eg, 0.5–1 × SD) within an individual.[1] This type of approach has also been used in studies that have utilized HRV-guided training.[4] Therefore, the typical error or the day-to-day variation of a marker is relevant by affecting the "noise" and the ability to detect meaningful changes. Previously, Nakamura et al[13] and Al Haddad et al[11] have reported interday CV of 7.7% and 12.3% for daytime LnRMSSD, respectively. Mishica et al[9] reported both morning and nocturnal results in the same group of subjects, and they found within-week CV of 4.1% and 5.2% for nocturnal and morning HR, respectively. In turn, CV for nocturnal and morning RMSSD was 9.5% and 19.4%. While Mishica et al[9] used the ballistocardiography method for nocturnal recordings, Costa et al[15] applied the same devices that were used in the current setting. They reported 6-night CV for LnRMSSD varying between 4.2% and 5.6% in hour-by-hour method and being 6.1% for slow-wave sleep episodes. In the present study, very low between-night CV (2.4%–3.3% for HR and 2.1–3.8 for HRV) was observed in all segments, which supports the previous findings of lower variation in nocturnal recordings compared with those reported from morning recordings in general. As an advantage, the lower day-to-day variation could potentially facilitate faster reactions to possible changes in a recovery state.

The responsiveness of the marker is another important aspect to consider when evaluating monitoring tools since it defines the "signal" of signal-to-noise ratio.[1] Although Buchheit[1] has previously analyzed the signal as an increase in HRV with concurrent improvement in performance, the reverse response and impaired recovery state would also be important to detect in terms of monitoring. A certain challenge in this regard is there is no unequivocal reference value for the "recovery state" against which responses could be compared. In the current setting, it was expected that the maximal 3000-m test would induce acute fatigue and a significant disturbance of cardiovascular homeostasis in recreational runners. Despite the fact that this was confirmed "only" by estimated readiness to train, the marker has been useful in the prediction of functional overreaching,[29] and has also been associated with the acute changes in performance followed by high-intensity interval training block.[24] When evaluating current responses, changes of HR and HRV were greatest in magnitude in 4H and FULL segments, and the averages exceeded the typical error. Previously, the responses to endurance exercises in nocturnal recordings have been somewhat contradictory, as some have found greater increases in HR and decrements in HRV[16,19] compared with the present study, while others have found changes only in HR[15,20,21]despite late-time exercise. At least partly, these contradictions may relate to multiple analysis methods applied (slow-wave sleep, 4H, and FULL), which was illustrated also in the current study by small to moderate differences between all analysis segments and the lack of change in MOR segment. These findings may also demonstrate that, as opposed to HR, actually quite a demanding (maximal) session is required to induce such a significant disturbance in cardiovascular homeostasis that would lead to systematic change in nocturnal HRV. Previously, Stanley et al[23] have suggested that cardiac autonomic recovery may take up to 24 hours after low-intensity exercise and at least 48 hours after high-intensity exercise. In recent studies that have examined resting HRV in the daytime after different types of either running[17] or rowing sessions,[22] no group-level differences have been found in any type of low-, moderate-, or high-intensity sessions 24 hours afterward. It seems that, although autonomic recovery may take up to 48 hours, such a long period is not required for all individuals. As an example, a few individuals showed increased HRV in 4H and FULL align with the high estimated readiness to train after the test (Figure 4), illustrating rapid autonomic nervous system recovery. Large interindividual variation in the HRV recovery kinetics illustrates the differences in the internal responses despite similar external load and the usefulness of HRV assessments in the individual recovery monitoring.

When considering the optimal period for HRV recording, there currently exists no clear consensus. While resting HRV is thought to reflect the internal response to stressors[3] and the current state of cardiovascular homeostasis,[23] the capability to capture these aspects reliably from day-to-day is perhaps the most important factor to speculate on. It could be argued that the morning recording, being further away from the previous stressors and closer to the following, would provide more relevant information regarding the current state of homeostasis. Furthermore, it can be speculated that nocturnal recordings would rather reflect the physiological and psychological load of the previous day than the actual state of recovery and readiness to perform on the following day. The dilemma is illustrated in Figure 3 where individual B would have a dramatically different conclusion of the recovery state depending on, whether HRV was assessed from 4H, FULL, or MOR segment. On the other hand, one may argue that since the preceding stressors (eg, training load) are closer, abnormal changes in the response within an individual would be more clear during the night. Although sleep is an essential period of recovery,[6] there is currently no clear evidence, whether decreased HRV through the night, or at the beginning of sleep could have some negative acute or cumulative effects on factors related to training adaptation, recovery, and performance—especially in the case HRV returns to baseline by the end of the sleep. Recently, it was found that nocturnal and morning HRV are significantly correlated,[9] and it is quite likely that in long-term averages (eg, 7 d), responses in both conditions would be quite similar. Thus, until proven otherwise, the best period to record HRV is probably the most feasible one that would allow frequent high-quality monitoring for an individual.

Practical Applications

The results of the current study demonstrate the good reliability of nocturnal recordings in resting HR and HRV monitoring. In the current setting, 4H and FULL were affected the most by the maximal exercise, and these HRV responses were also best aligned with the estimated readiness to train on the following day. As a limitation, a high number of possible subjects were excluded from the analysis due to the lack of full-night data. Another limitation relates to the insufficient number of subjects to analyze sexes separately. Although sex may not significantly affect absolute HRV values,[3] whether the menstrual cycle phase could influence the HRV responses to different types of stressors would be relevant to examine. While results of the current study may encourage the applicability of nocturnal recordings, further studies are needed to better understand the physiological significance of HRV during different times of day, and its consequences to long-term recovery and training adaptations.

Conclusions

Nocturnal HR and HRV indices analyzed with any of the current methods were reliable and had a low typical error. The magnitude of responses to the preceding training load is likely to be smaller in

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

FULL, and especially in MOR, compared with 4H. This likely illustrates both greater sensitivity to detect disturbances in cardiovascular homeostasis, and the presence of an acutely ongoing recovery process, which may not be similarly relevant in the day-to-day monitoring context if the individual is able to recover after the restorative effect of sleep.

Acknowledgments

The authors would like to thank all research assistants helping in the data collection and the subjects who participated in the study. In addition, the authors also thank Mirjaliisa Vuorikoski for reviewing the language. HR monitors were received from Firstbeat Analytics, and the research project was partially funded by grants from the Foundation of Sports Institute and The Finnish Sports Research Foundation

References

1. Buchheit M. Monitoring training status with HR measures: do all roads lead to rome? *Front Physiol*. 2014;27(5):73. PubMed ID: 24578692 doi: 10.3389/fphys.2014.00073
2. Martinmäki K, Rusko H, Kooistra L, Kettunen J, Saalasti S. Intraindividual validation of heart rate variability indexes to measure vagal effects on hearts. *Am J Physiol Heart Circ Physiol*. 2006; 290(2):H640–H647. doi:10.1152/ajpheart.00054.2005
3. Altini M, Plews D. What is behind changes in resting heart rate and heart rate variability? A large-scale analysis of longitudinal measurements acquired in free-living. *Sensors*. 2021;21(23):7932. PubMed ID: 34883936 doi:10.3390/s21237932
4. Düking P, Zinner C, Trabelsi K, et al. Monitoring and adapting endurance training on the basis of heart rate variability monitored by wearable technologies: a systematic review with meta-analysis. *J Sci Med Sport*. 2021;24(11):1180–1192. PubMed ID: 34489178 doi:10.1016/j.jsams.2021.04.012
5. Herzig D, Eser P, Omlin X, Riener R, Wilhelm M, Achermann P. Reproducibility of heart rate variability is parameter and sleep stage dependent. *Front Physiol*. 2018;8:1100. PubMed ID: 29367845 doi:10.3389/fphys.2017.01100
6. Halson SL. Sleep in elite athletes and nutritional interventions to enhance sleep. *Sports Med*. 2014;44(suppl 1):13–23. PubMed ID: 24791913 doi:10.1007/s40279-014-0147-0
7. Cao R, Azimi I, Sarhaddi F, et al. Accuracy assessment of oura ring nocturnal heart rate and heart rate variability in comparison with electrocardiography in time and frequency domains: comprehensive analysis. *J Med Internet Res*. 2022;24(1):e27487. PubMed ID: 35040799 doi:10.2196/27487
8. Nuuttila O-P, Korhonen E, Laukkanen J, Kyröläinen H. Validity of the wrist-worn polar vantage V2 to measure heart rate and heart rate variability at rest. *Sensors*. 2021;22(1):137. PubMed ID: 35009680 doi:10.3390/s22010137
9. Mishica C, Kyröläinen H, Hynynen E, Nummela A, Holmberg H-C, Linnamo V. Evaluation of nocturnal vs. morning measures of heart rate indices in young athletes. *PLoS One*. 2022;17(1):e0262333. PubMed ID: 34986202 doi:10.1371/journal.pone.0262333
10. Costa JA, Brito J, Nakamura FY, Dores H, Rebelo A. Associations between 24-hr heart rate variability and aerobic fitness in high-level female soccer players. *Scand J Med Sci Sports*. 2022;32(suppl 1):140–149. doi:10.1111/sms.14116
11. Al Haddad H, Laursen P, Chollet D, Ahmaidi S, Buchheit M. Reliability of resting and postexercise heart rate measures. *Int J Sports Med*. 2011;32(08);598–605.
12. Cipryan L, Litschmannova M. Intra-day and inter-day reliability of heart rate variability measurement. *J Sports Sci*. 2013;31(2): 150–158. PubMed ID: 22963409 doi:10.1080/02640414.2012.721931
13. Nakamura FY, Pereira LA, Esco MR, et al. Intraday and interday reliability of ultra-short-term heart rate variability in rugby union players. *J Strength Cond Res*. 2017;31(2):548–551. PubMed ID: 27243917 doi:10.1519/JSC.0000000000001514
14. Nummela A, Hynynen E, Vesterinen V. Nocturnal heart rate and heart rate variability as a method for monitoring training load. Paper presented at: 15th Annual Congress of the European College of Sport Science; June 23–26, 2010. Antalya (Turkey). Book of Abstracts; 2010;516.
15. Costa JA, Brito J, Nakamura FY, Oliveira EM, Rebelo AN. Effects of late-night training on "slow-wave sleep episode" and hour-by-hour-derived nocturnal cardiac autonomic activity in female soccer players. *Int J Sports Physiol Perform*. 2018;13(5):638–644. PubMed ID: 29345542 doi:10.1123/ijspp.2017-0681
16. Hynynen E, Vesterinen V, Rusko H, Nummela A. Effects of moderate and heavy endurance exercise on nocturnal HRV. *Int J Sports Med*. 2010;31(6):428–432. doi:10.1055/s-0030-1249625
17. Nuuttila O-P, Kyröläinen H, Häkkinen K, Nummela A. Acute physiological responses to four running sessions performed at different intensity zones. *Int J Sports Med*. 2021;42(6):513–522. PubMed ID: 33176386 doi:10.1055/a-1263-1034
18. Seiler S, Haugen O, Kuffel E. Autonomic recovery after exercise in trained athletes: intensity and duration effects. *Med Sci Sports Exerc*. 2007;39(8):1366–1373. PubMed ID: 17762370 doi:10.1249/mss.0b013e318060f17d
19. Al Haddad H, Laursen PB, Ahmaidi S, Buchheit M. Nocturnal heart rate variability following supramaximal intermittent exercise. *Int J Sports Physiol Perform*. 2009;4(4):435–447. PubMed ID: 20029095 doi:10.1123/ijspp.4.4.435
20. Myllymäki T, Kyröläinen H, Savolainen K, et al. Effects of vigorous late-night exercise on sleep quality and cardiac autonomic activity: late-night exercise and sleep. *J Sleep Res*. 2011;20(1/2):146–153. doi:10.1111/j.1365-2869.2010.00874.x
21. Thomas C, Jones H, Whitworth-Turner C, Louis J. High-intensity exercise in the evening does not disrupt sleep in endurance runners. *Eur J Appl Physiol*. 2020;120(2):359–368. PubMed ID: 31813044 doi:10.1007/s00421-019-04280-w
22. Holt AC, Plews DJ, Oberlin-Brown KT, Merien F, Kilding AE. Cardiac parasympathetic and anaerobic performance recovery after high-intensity exercise in rowers. *Int J Sports Physiol Perform*. 2019;14(3):331–338. PubMed ID: 30160561 doi:10.1123/ijspp.2018-0200
23. Stanley J, Peake JM, Buchheit M. Cardiac parasympathetic reactivation following exercise: implications for training prescription. *Sports Med*. 2013;43(12):1259–1277. PubMed ID: 23912805 doi:10.1007/s40279-013-0083-4
24. Nuuttila O-P, Nummela A, Kyröläinen H, Laukkanen J, Häkkinen K. Physiological, perceptual, and performance responses to the 2-week block of high- versus low-intensity endurance training. *Med Sci Sports Exerc*. 2022;54(5):851–860. PubMed ID: 35072660 doi:10.1249/MSS.0000000000002861
25. Foster C, Daines E, Hector L, Snyder AC, Welsh R. Athletic performance in relation to training load. *Wis Med J*. 1996;95(6): 370–374. PubMed ID: 8693756
26. Lipponen JA, Tarvainen MP. A robust algorithm for heart rate variability time series artefact correction using novel beat classification. *J Med Eng Technol*. 2019;43(3):173–181. PubMed ID: 31314618 doi:10.1080/03091902.2019.1640306

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC

27. Nummela A, Hynynen E, Kaikkonen P, Rusko H. Endurance performance and nocturnal HRV indices. *Int J Sports Med*. 2010;31(3): 154–159. doi:10.1055/s-0029-1243221
28. Plews DJ, Laursen PB, Meur YL, Hausswirth C, Kilding AE, Buchheit M. Monitoring training with heart-rate variability: how much compliance is needed for valid assessment? *Int J Sports Physiol Perform*. 2014;9(5):783–790. PubMed ID: 24334285 doi:10.1123/ijspp.2013-0455
29. ten Haaf T, van Staveren S, Oudenhoven E, et al. Prediction of functional overreaching from subjective fatigue and readiness to train after only 3 days of cycling. *Int J Sports Physiol Perform*. 2017;12-(suppl 2):S2-87–S2-94. doi:10.1123/ijspp.2016-0404
30. Chinoy ED, Cuellar JA, Huwa KE, et al. Performance of seven consumer sleep-tracking devices compared with polysomnography. *Sleep*. 2021;44(5):zsaa291.

Brought to you by JYVASKYLAN YLIOPISTO | Unauthenticated | Downloaded 07/11/22 05:44 AM UTC