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High-intensity endurance training increases nocturnal heart rate variability in sedentary participants

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ABSTRACT: The effects of endurance training on endurance performance characteristics and cardiac autonomic modulation during night sleep were investigated during two 4-week training periods. After the first 4-week training period (3 x 40 min per week, at 75% of HRR) the subjects were divided into HIGH group (n = 7), who performed three high-intensity endurance training sessions per week; and CONTROL group (n = 8) who did not change their training. An incremental treadmill test was performed before and after the two 4-week training periods. Furthermore, nocturnal RR-intervals were recorded after each training day. In the second 4-week training period HIGH group increased their VO₂max (P = 0.005) more than CONTROL group. At the same time, nocturnal HR decreased (P = 0.039) and high-frequency power (HFP) increased (P = 0.003) in HIGH group while no changes were observed in CONTROL group. Furthermore, a correlation was observed between the changes in nocturnal HFP and changes in VO₂max during the second 4-week training period (r = 0.90, P < 0.001). The present study showed that the increased HFP is related to improved VO₂max in sedentary subjects suggesting that nocturnal HFP can provide a useful method in monitoring individual responses to endurance training.

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INTRODUCTION

In order to promote and maintain health and to improve cardiorespiratory fitness, all healthy adults need either moderate-intensity aerobic physical activity a minimum of 30 min on five days each week or vigorous-intensity aerobic physical activity for a minimum of 20 min on three days each week [1]. Since a dose-response relation exists between physical activity and health, persons who exceed the minimum recommendations of physical activity may further improve their cardiorespiratory fitness, reduce their risk for chronic diseases and prevent obesity [2].

The basic overload principle of training states that training load should be high enough to disturb the homeostasis of the body. Training load of aerobic exercises is mainly determined by the intensity and the duration of the exercise. In previously untrained healthy individuals, the average improvements in VO₂max have been slightly over 10% in short-term training studies in which the intensity of the exercises has been vigorous or lower [3, 4]. It is, however, possible to attain as high as 40% increase in VO₂max over a 10-week training period, if the intensity and frequency of the exercises are high as shown by Hickson et al. [5]. Despite these 10% or higher improvements, there seems to be great variability in the individual training response [3].

Heart rate (HR) and heart rate variability (HRV) indices analyzed from RR-interval (RRI) recordings have been used as indicators of the function of the autonomic nervous system. Low resting HR and high HRV, especially high frequency power (HFP), are related to high level of endurance performance [6]. Most previous studies have reported that endurance training increases cardiac vagal control and HRV at rest [7, 8, 9]. However, this increase in vagal-related HRV indices has not been systematically observed [4, 10].

Despite the long-term effects of endurance training on HRV physical exercise is known to acutely decrease HRV. The autonomic nervous system regulates homeostatic function of the body [11], executing a rapid shift in autonomic output during the transition from exercise to recovery. The termination of exercise is known to trigger an increase in vagal activity with a simultaneous reduction in sympathetic drive [12]. Simultaneously, there is also a loss of central command and activation of the arterial baroreflex, resulting in a decrease in HR [13] and an increase in HRV [14, 15]. The recovery to the initial resting HRV level needs a few minutes up to 24 hours, depending mostly on the intensity of the exercise [14, 16]. Previous studies suggest that HRV changes during night sleep could be used

to evaluate the training load of the preceding day or the cumulated training load during a training period [16, 17].

Based on the previous studies it seems that monitoring HR and HRV during night sleep seems to provide useful information when evaluating the training load of the previous day or days and the response of cardiac autonomic control to endurance training. Therefore, the purpose of the present study was to investigate the potential of nocturnal HRV indices for evaluating the training load and training response of sedentary participants in high-intensity endurance training programs.

MATERIALS AND METHODS

Participants. Twenty sedentary men and women volunteered as participants for the present study. All the participants were untrained, healthy, non-smoking, they were not obese ($BMI < 30 \text{ kg}\cdot\text{m}^{-2}$) and they did not have any diseases or regular medication. All participants were fully informed on the procedures and possible risks of the experiments, and they gave a written informed consent and filled a brief questionnaire concerning their health and possible chronic systemic diseases. Resting ECG (Cardiofax ECG-9320, Nihon Kohden Corp., Tokyo, Japan) was analysed to ensure they had no cardiac abnormalities, which would affect HRV analysis or prevent from endurance training. The study was approved by the local ethics committee.

Experimental design

Before the study the participants were given an opportunity to become familiar with equipments and treadmill running. The familiarization was performed in an attempt to reduce error associated with participants performing unaccustomed exercise. The study included two 4-week training periods separated by a recovery week. All the participants performed an incremental treadmill test before the first 4-week training period, in the recovery week and after the second 4-week training period. Furthermore, nocturnal RRI were recorded after each training day. In the first 4-week training period all participants performed constant load aerobic exercises three times per week. After the first 4-week, the participants were divided into the experimental and control groups so that five men and five women were included in each group. The groups were matched so that the endurance performance characteristics of the two groups were equal in the first incremental test. In the second 4-week training period experimental group performed high-intensity endurance training three times per week (HIGH) and the control group continued constant load aerobic exercises three times per week (CONTROL). The results of five participants were eliminated from the final analysis since three of the participants became ill during the training program and two of the participants had incomplete RRI recordings as well as insufficient information of their exercises in their training diary. The results of the first 4-week period were reported in another study [18].

Training

In the first 4-week training period the participants were asked to run three times per week, 40 min at each time so that the total training

volume would be $2 \text{ h}\cdot\text{week}^{-1}$. They were asked to keep vigorous-intensity in their training sessions, i.e. the intensity between the individually determined aerobic and anaerobic thresholds [19]. In the second 4-week training period HIGH group performed three different high-intensity endurance training sessions on Monday, Wednesday and Friday while the training of CONTROL group remained the same as in the first 4-week training period. The three high-intensity exercises were: (1) 3 x 950-1150 m above anaerobic threshold with 2 min recovery; (2) 20 min at anaerobic threshold; and (3) Nordic walking uphill 5-7 x 2-3 min above anaerobic threshold with 3-4 min recovery. The participants controlled their exercise intensity in constant load aerobic exercises by measuring their HR during all exercises using Suunto t6 heart rate monitors and foot pod speed and distance sensor for running (Suunto Ltd, Vantaa, Finland). In high-intensity exercises HR was also recorded but the intensity was determined according to the participants' rating of perceived exertion (RPE). After each training session the participants evaluated the RPE using the scale from 0 to 10 and filled the value as well as the date, training time, average HR, duration of the exercise and running distance in the training diary. High-intensity exercises were expected to be rated between "hard" and "very hard" (5-8).

Incremental treadmill test

Before the treadmill test standing height, body mass and skinfold thicknesses from four different points (subscapular, biceps brachii, triceps brachii and iliac crest) of the participants were measured. The initial speed of $5 \text{ km}\cdot\text{h}^{-1}$ (women) or $6 \text{ km}\cdot\text{h}^{-1}$ (men) was used in the treadmill test. Thereafter, the speed was increased by $1 \text{ km}\cdot\text{h}^{-1}$ every three minutes until volitional exhaustion. The slope of the treadmill was 0.5 degrees during the entire test. The first two speeds were performed by walking and the following speeds by running. Oxygen uptake (VO_2) was measured breath-by-breath ($V_{\text{max}} 229$, Sensor Medics, Palo Alto, CA) and RRIs (Suunto t6) were measured continuously during the test. Fingertip blood samples ($20 \mu\text{l}$) for blood lactate analysis (Biosen S_line Lab+, EKF Diagnostic GmbH, Magdeburg, Germany) were taken at the end of each 3-min running period. Aerobic (AerT) and anaerobic (AnT) thresholds were determined using blood lactate, ventilation, VO_2 and VCO_2 (production of carbon dioxide) according to Aunola and Rusko [19]. The highest 60-s VO_2 value during the treadmill test was considered as maximal oxygen uptake ($\text{VO}_{2\text{max}}$). Maximal velocity of the test (v_{max}) was determined to the peak treadmill velocity. If the subject could not complete the 3-min of the last velocity, the v_{max} was calculated using the last completed velocity (v_{highest}) and the relative duration of the last uncompleted velocity (frac) as follows: $v_{\text{max}} = v_{\text{highest}} + \text{frac}$.

HRV analysis

RRI data was transferred to a computer with Suunto Training Manager software (Suunto Ltd, Vantaa, Finland). Thereafter the RRI data of the exercises and the nights were processed and analyzed

using the Firstbeat PRO heartbeat analysis software version 2.0.0.9 (Firstbeat Technologies Ltd, Jyväskylä, Finland).

The Firstbeat PRO software first scanned the recorded RRI data through an artefact detection filter to exclude all falsely detected, missed, and premature heart beats [20]. The artefact corrected RRIs were then re-sampled at the rate of 5 Hz by using linear interpolation to obtain equidistantly sampled time series. From the re-sampled data the software calculated HRV indices second-by-second using the short-time Fourier Transform method, a generalization of the stationary Fourier into non-stationary time series analysis. For a given segment of data, a time window (Hanning) with a length of 256 samples was applied, and fast Fourier transform was calculated and a power spectrum was obtained. The window was then shifted one sample to another and the same process was repeated. Low frequency power (LFP, 0.04-0.15 Hz) and high frequency power (HFP, 0.15-0.40 Hz) were calculated as integrals of the respective power spectral density curve. Nocturnal HRV variables were analyzed from a continuous four hour period starting from 30 min after going to the bed for a sleep. Nocturnal HRV indices are shown to have a little day-to-day variations with intraclass correlation coefficients between 0.84 – 0.91 in four hour nocturnal HRV analysis during two consecutive nights after similar training day [21]. In order to ensure the adequate quantity for the reliable HRV analysis, all nights in which the errors exceed 50 % were excluded from the final analysis. Therefore, in the final analysis HR and HRV indices were averaged from 1 to 3 nights for each week. Total number of analysed nights was higher in HIGH group (19 ± 4) compared to CONTROL group (14 ± 5) ($P = 0.044$).

Training load variables

Training diary and exercise RRI data was used to calculate different training load variables. The highest, lowest and average HR, exercise time, running distance, average running speed and RPE were

measured and calculated from each exercise and were used to describe training volume and intensity. Furthermore, the times at the three different intensity zones (I = below aerobic threshold; II = between aerobic threshold and anaerobic thresholds; III = above anaerobic threshold) were calculated from the RRI data collected during the exercises. As additional index of training load, training impulse (TRIMP) was calculated using RRI data as follows [22]:

$$\text{TRIMP} = T \cdot \Delta\text{HR ratio} \cdot y,$$

where T = duration of the exercise; $\Delta\text{HR ratio} = (\text{HR}_{\text{ex}} - \text{HR}_{\text{rest}}) \cdot (\text{HR}_{\text{max}} - \text{HR}_{\text{rest}})^{-1}$; HR_{ex} = average heart rate during the exercise; HR_{rest} = resting heart rate; HR_{max} = maximal heart rate; $y = 0.64e^{1.92(\Delta\text{HR ratio})}$ (men); $y = 0.86 e^{1.67(\Delta\text{HR ratio})}$ (women); e = base of the natural logarithm = 2.718.

Statistical analyses

All the statistical analyses were done using SPSSWIN 17.0 (SPSS Inc., Chicago, IL). An unpaired Student's t-test was used to compare the training load variables between the groups. Repeated measures analysis of variance (ANOVA) was used to study the main effect and the interaction of the group and training on the treadmill test results. In order to meet the assumptions of parametric statistical analysis, a natural logarithmic transformation of the values of LFP and HFP was performed. Repeated measures ANOVA with contrasts was then used to study the main effect and the interaction of the group and training week on nocturnal HR and HRV indices. The magnitude of a given clear effect (Effect Size, ES) was determined from its observed standardised value (Cohen's d , the difference in means divided by the between-subject standard deviation) using the following scale: < 0.20, trivial; 0.20–0.59, small; 0.60–1.19, moderate; ≥ 1.20 , large [23]. Pearson product moment correlation coefficient was used to determine the relationships between the variables. Values are expressed as mean ± standard deviation (SD). Statistical significance was accepted as $P < 0.05$.

TABLE I. Descriptive training data of HIGH and CONTROL groups (mean ± SD) in the first and second 4-week training period.

	HIGH (n = 7)		CONTROL (n = 8)	
	First 4-week	Second 4-week	First 4-week	Second 4-week
Sessions	11.3 ± 1.1	12.0 ± 0.0	11.5 ± 1.2	11.8 ± 1.2
Duration of exercises (min)	39.9 ± 2.1	44.3 ± 2.3***	39.5 ± 1.8	39.8 ± 1.5
Time in zone III (%)	8.2 ± 8.3	31.4 ± 5.5***	2.7 ± 3.6	2.2 ± 1.5
Time in zone II (%)	71.2 ± 18.2	24.5 ± 11.5***	86.1 ± 14.5	85.0 ± 12.8
Time in zone I (%)	20.6 ± 19.6	44.0 ± 14.8***	11.2 ± 15.7	12.8 ± 12.0
Total running distance (km)	74.4 ± 15.5	42.0 ± 3.4***	70.8 ± 15.3	71.9 ± 13.3
Average HR (%HRR)	76.1 ± 8.2	71.2 ± 7.5	74.2 ± 3.5	73.5 ± 3.8
HR peak (bpm)	170 ± 12	179 ± 10*	168 ± 7	166 ± 8
Velocity of v _{max} (%)	80.5 ± 8.2	92.9 ± 4.7***	77.3 ± 4.5	77.6 ± 6.4
RPE (0-10+)	6.5 ± 1.2	7.9 ± 0.5*	5.8 ± 1.6	5.9 ± 2.2
TRIMP	93.4 ± 14.2	84.8 ± 25.4	83.2 ± 11.4	80.3 ± 10.2

Note: HR = heart rate; HRR = heart rate reserve; v_{max} = maximal velocity in the incremental treadmill test; RPE = rating of perceived exertion; TRIMP = training impulse. Difference between groups: * $P < 0.05$; *** $P < 0.001$.

RESULTS

Training. Training data in Table 1 shows that there were no significant differences in the training between the two groups in the first 4-week training period. In the second 4-week training period both groups had equal amount of training sessions (Table 1). HIGH group had 11% longer training sessions ($P < 0.001$), when the recovery periods were included in the exercise time, but CONTROL group had 71% greater total distance of running ($P < 0.001$). The intensity of the training was higher in HIGH group, which is shown in running velocities ($P = 0.006$), RPE values ($P = 0.036$), peak heart rate ($P = 0.016$), and exercise time in zone III ($P < 0.001$) (Table 1).

Incremental treadmill test

In the first 4-week training period both HIGH and CONTROL groups increased their VO_{2max} ($P = 0.007$), v_{max} ($P = 0.002$) and velocities at AnT ($P = 0.003$), and AerT ($P = 0.009$) but there were no significant differences between the groups (Table 2). In the second 4-week training period both groups increased their v_{max} ($P = 0.006$) and peak blood lactate concentration ($P = 0.027$) but HIGH group increased their VO_{2max} ($P = 0.005$, ES = -0.91), velocities at AnT ($P = 0.016$, ES = -0.67) and AerT ($P = 0.007$, ES = -0.68) as well as their maximal ventilation ($P = 0.008$, ES = -0.42) more than CONTROL group (Table 2).

Heart rate and heart rate variability

In the first 4-week no significant changes were found in HRV-variables. In the second 4-week training period nocturnal HR decreased from 55.1 ± 7.7 bpm to 53.1 ± 5.8 bpm in HIGH group ($P = 0.039$,

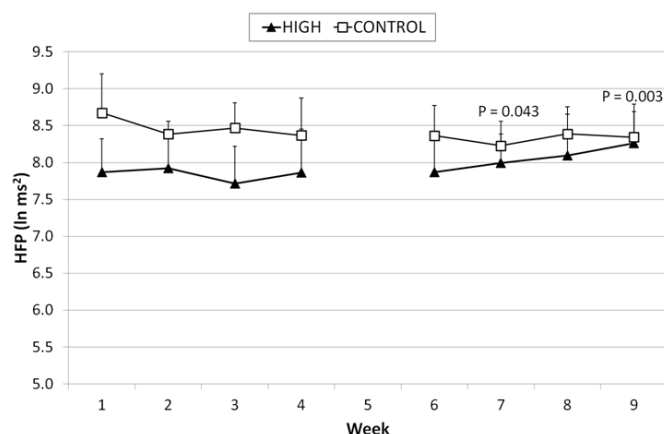


FIG. 1. HFP of nocturnal RR-intervals during the first and second 4-week training period in HIGH and CONTROL group. Group by training week interaction is shown in the figures.

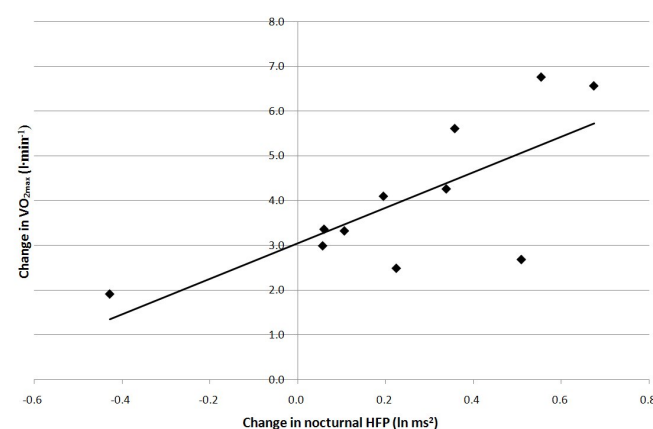


FIG. 2. The relationship between the changes in HFP of nocturnal RR-intervals and changes in VO_{2max} in the second 4-week training period.

TABLE 2. Pre and post test results of incremental treadmill test in HIGH and CONTROL group

	Group	Pre	Post		ES
			1st 4-week	2nd 4-week	
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	HIGH	38.3 ± 5.7	39.1 ± 6.0	$43.9 \pm 5.5^{**}$	-0.91
	CONTROL	38.4 ± 6.1	40.6 ± 6.3	42.3 ± 5.3	-0.66
v_{max} ($km \cdot h^{-1}$)	HIGH	12.3 ± 2.6	13.0 ± 2.3	13.6 ± 2.1	-0.56
	CONTROL	11.9 ± 2.0	12.5 ± 1.7	12.8 ± 1.7	-0.51
vAnT ($km \cdot h^{-1}$)	HIGH	9.4 ± 1.6	10.0 ± 1.7	$10.6 \pm 1.7^*$	-0.67
	CONTROL	9.4 ± 1.7	9.9 ± 1.8	10.0 ± 1.6	-0.33
vAerT ($km \cdot h^{-1}$)	HIGH	7.1 ± 1.1	7.5 ± 1.2	$7.9 \pm 1.1^{**}$	-0.68
	CONTROL	7.3 ± 1.3	7.6 ± 1.5	7.5 ± 1.4	-0.15
Ventilation max ($l \cdot min^{-1}$)	HIGH	92.3 ± 21.1	91.3 ± 23.4	$101.6 \pm 24.1^{**}$	-0.42
	CONTROL	82.9 ± 20.2	86.5 ± 21.4	86.1 ± 21.7	-0.16
HR max (bpm)	HIGH	187 ± 9	183 ± 10	$187 \pm 10^*$	0.02
	CONTROL	189 ± 8	189 ± 8	189 ± 10	0.07
Lactate peak ($mmol \cdot l^{-1}$)	HIGH	10.8 ± 2.9	10.6 ± 2.5	12.0 ± 2.2	-0.44
	CONTROL	8.5 ± 2.1	8.3 ± 1.0	9.1 ± 1.8	-0.34

Note: Abbreviations: v_{max} = maximal velocity in the incremental treadmill test; vAnT = velocity at anaerobic threshold; vAerT = velocity at aerobic threshold; HR = heart rate; ES = Effect size (Cohen's d)

Group by training interaction between 1st and 2nd 4-week value: * $P < 0.05$; ** $P < 0.001$

ES = 0.31) but no changes were observed in CONTROL group (from 53.9 ± 7.4 to 54.5 ± 5.6 bpm, ES = -0.10). Congruent results were also observed in HRV variables. Nocturnal LFP increased from 8.4 ± 0.5 to 8.6 ± 0.4 ln ms² ($P = 0.009$, ES = -0.46) in the second 4-week training period in HIGH while no changes were observed in CONTROL group (from 9.0 ± 0.4 to 9.0 ± 0.4 ln ms², ES = -0.15). Nocturnal HFP also increased in HIGH (5.0 %, ES = -0.52) but no changes were observed in CONTROL group (ES = 0.03) (Figure 1). Correlation analysis between the changes in test results and HRV in the second 4-week training period showed that a positive relationship existed between the changes in VO_{2max} and changes in HFP ($r = 0.90$, $P < 0.001$, Figure 2).

DISCUSSION

The main finding of the present study was that the nocturnal HR decreased and nocturnal HRV indices increased during high-intensity but not during constant load aerobic training program in sedentary participants (Figure 1). This finding is further strengthened by the fact that in the present study nocturnal RRI analyses were performed from the nights subsequent to each training day. High-intensity endurance training sessions in HIGH group could have increased the nocturnal HR and decreased HRV indices more than the constant load aerobic exercises in CONTROL group [24]. Together with the increased VO_{2max} and velocities at AnT and AerT the present findings indicate that the training load of HIGH group has not been too high to induce cumulative overload and consequent decreased vagal activation that has been observed in overreached or overtrained participants [24, 25, 26].

Endurance training induced changes in HRV indices

Most studies have shown that moderate endurance training increases vagal-related HRV indices [3, 7, 8, 17]. However, this increase in vagal-related HRV indices has not been systematically observed [4, 10]. The present results suggest that these conflicting results could be related to insufficient training load. In the present study 8-week constant load aerobic training did not change vagal related HRV indices but 4-week high-intensity endurance training after 4-week constant load aerobic endurance training was sufficient enough to induce changes in nocturnal HR and HRV. On the other hand, longitudinal studies during heavy training [17, 25, 27] have reported a conversion from vagal to sympathetic dominance in athletes, whereas others have failed to demonstrate any HRV changes after increased training load [28, 29, 30]. Consequently, it has been described that a bell-shaped relationship exist between exercise load and HRV changes [7, 31]. The authors have found that moderate dose of exercise is sufficient to attain a substantial change in vagal modulation of the heart, and that higher training load does not necessarily lead to greater enhancement of these changes or even lead to a return of HRV indices to pre-training values.

Although VO_{2max} as well as velocities at aerobic and anaerobic thresholds were improved in the first 4-week constant load aerobic

training period in both groups and also in the second 4-week high intensity endurance training period in HIGH group, the HRV indices were only changed in high intensity endurance training period. This suggests that the training three times per week at relatively high intensity is not hard enough to decrease HRV in sedentary individuals. However, the relationship between the training load and HRV seems to be highly individual since a great individual variation in training response was observed in the first 4-week training period in the present study. Despite the same volume and intensity of training, four out of 15 participants (27%) could not improve their VO_{2max} in the first 4-week training period. The effect of great variation in training response has been confirmed by other studies [3, 32]. Hautala et al. [3] concluded that high vagal activity at baseline is associated with the improvement in aerobic power caused by aerobic training in healthy sedentary participants. In the present study, however, nocturnal HFP measured in the first training week was not related to the improved aerobic power. Furthermore, Nummela et al. [18] showed that the HFP during night sleep was increased in the responders group but not in the non-responders group. They also observed a significant relationship between the change in the maximal velocity of the aerobic power test and the change in nocturnal HFP. This was confirmed in the present study, since a significant correlation was observed between the change in VO_{2max} and change in HFP.

Nocturnal HRV analysis for monitoring training load

Excess Post-exercise Oxygen Consumption (EPOC) [33] and HR recovery [34] have been used to determine the acute disturbance of body homeostasis after the exercises with different intensity and duration. It has been shown that a curvilinear relationship exists between the magnitude of EPOC and the intensity of the exercise, whereas the relationship between exercise duration and EPOC appears to be more linear, especially at higher intensities. In previous studies, it has also been shown that HRV recovery could also be used to evaluate the effect of training load on the disturbance of the body homeostasis [7, 14, 15, 35, 36]. The recovery to the resting HRV level needs a few minutes up to 24 hours, depending mostly on the intensity of the exercise [14, 16]. Buccheit et al. [7] proposed that nocturnal HRV analysis may provide reliable information on the effects of training on vagal related HRV indices and sympathovagal balance, since sleep constitutes a condition free from external disruptive events and it is the most critical natural episode for psychological and physiological restoration. It has also been suggested that stress and worry are associated with cardiac effects during waking and these effects are extended into nocturnal sleep [37]. This was the reason for the idea that nocturnal HRV analysis can be used as an indicator of training effect in untrained participants. In order to benefit from such a monitoring, each individual should frequently record RRI following a rest day or a constant exercise day as in the present study.

Endurance training for sedentary people

There were also some results of the training response in this study, which may be useful when programming training for previously untrained participants. The frequency, duration and intensity of exercise all contribute to the nature and magnitude of the training effect. Relatively little research has been conducted into the quantification of training programs and their effects on physiological adaptation and subsequent performance. In the present study, HIGH group attained greater improvements in VO_{2max} and similar improvements in the velocities at aerobic and anaerobic thresholds in the second 4-week training period when they changed their training from vigorous to high intensity endurance training. There are several possible explanations why VO_{2max} was more improved in HIGH group than in CONTROL group. One is that some individuals may not benefit from constant load aerobic exercises but they can improve their VO_{2max} by high intensity endurance training. All four non-responders in the first 4-week training period could improve their VO_{2max} in the second 4-week training period, when they increased their training intensity and decreased the total running distance.

The second explanation for the greater improvements in VO_{2max} in HIGH group could be that high intensity endurance training improves both central and peripheral components of VO_{2max} whereas constant load aerobic training is mainly associated with greater oxygen extraction [38, 39]. Burgomeister *et al.* [40] have also suggested that high-intensity interval training is a time-efficient strategy to increase skeletal muscle oxidative capacity and induce specific metabolic adaptations during exercise that are comparable to traditional constant load aerobic training.

The third explanation for the great improvement of VO_{2max} in the HIGH group could be the periodization of the training, since the increase in aerobic performance characteristics was slackened in CONTROL group who continued similar training at constant load for the additional 4-week training period. This suggests that training stimulus should be changed periodically to attain continuous improvement in performance. Previous studies have shown that during the initial stages of an endurance training program, rapid increases in VO_{2max} may occur [41] and can be elicited with training intensities as low as 40-50% of VO_{2max} [42].

Limitations of the study and future research

The present study is limited by its relatively small sample size, partly due to drop outs because of illness during the training program, incomplete RRI recordings as well as the lack of information in the training diary. Another limitation in this study was the low number

of nocturnal HRV recordings. Plews *et al.* [43] have suggested that practitioners using HRV to monitor training adaptation should use a minimum of 3 (randomly selected) valid data points per week. In the present study 1-3 data points per week were used for analysis. However, Plews *et al.* [43] analysed R-R intervals data from the last 5 min of the 6 min supine rest recordings in the morning. In the present study, the analysis were done from 4 hours period in the beginning of the night sleep, which may be more reliable than short-term morning measurement. Nocturnal HRV indices are shown to have a little day-to-day variations with intraclass correlation coefficients between 0.84 – 0.91 in four hour nocturnal HRV analysis during two consecutive nights after easy training day or rest day [21]. In order to improve the quality of HRV analysis, all nights in which the errors exceed 50 % were excluded from the final analysis in the present study. One possible limiting factor of the present study was also the difference in total number of the analysed nights between HIGH and CONTROL groups. CONTROL group had significantly lower number of nocturnal data points than HIGH group suggesting that the reliability of the HRV measures in CONTROL group is not as high as in HIGH group.

Because of the great individual variation in the results of the present study and the relatively small sample size, more research is needed to determine the relation between cardiac autonomic vagal activity and training adaptation both in sedentary people and in high level endurance athletes.

CONCLUSIONS

In conclusion, the 4-week high intensity endurance training induced greater increases in VO_{2max} and nocturnal HRV than vigorous intensity endurance training. The changes in VO_{2max} were related to the changes in nocturnal HRV suggesting that nocturnal HRV analysis can provide useful method in evaluating individual responses to endurance training and building up an optimal training program for different individuals.

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