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ORIGINAL ARTICLE

Endurance training guided individually by daily heart rate variability measurements

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Abstract Purpose of this study was to test utility of heart rate variability (HRV) in daily endurance exercise prescriptions. Twenty-six healthy, moderately fit males were randomized into predefined training group (TRA, $n = 8$), HRV-guided training group (HRV, $n = 9$), and control group ($n = 9$). Four-week training period consisted of running sessions lasting 40 min each at either low- or high-intensity level. TRA group trained on 6 days a week, with two sessions at low and four at high intensity. Individual training program for HRV group was based on individual changes in high-frequency R–R interval oscillations measured every morning. Increase or no change in HRV resulted in high-intensity training on that day. If there was significant decrease in HRV (below reference value [10-day mean-SD] or decreasing trend for 2 days), low-intensity training or rest was prescribed. Peak oxygen consumption (VO_{2peak}) and maximal running velocity ($Load_{max}$) were measured in maximal treadmill test before and after the training. In TRA group, $Load_{max}$ increased from 15.1 ± 1.3 to 15.7 ± 1.2 km h^{-1} ($P = 0.004$), whereas VO_{2peak} did not change significantly (54 ± 4 pre and 55 ± 3 ml kg^{-1} min^{-1} post, $P = 0.224$). In HRV group, significant increases were observed in both $Load_{max}$ (from 15.5 ± 1.0 to 16.4 ± 1.0 km h^{-1}, $P < 0.001$) and VO_{2peak} (from 56 ± 4 to 60 ± 5 ml kg^{-1} min^{-1}, $P = 0.002$). The change in $Load_{max}$ was significantly greater in HRV group compared to TRA group (0.5 ± 0.4 vs. 0.9 ± 0.2 km h^{-1}, $P = 0.048$, adjusted for baseline values). No significant differences were observed in the changes of VO_{2peak} between the groups. We concluded that cardiorespiratory fitness can be improved effectively by using HRV for daily training prescription.

Keywords Exercise training · Vagal activity · Autonomic nervous system · Exercise prescription

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Introduction

In standardized training programs, wide heterogeneity has been observed in the responsiveness of cardiorespiratory fitness to physical training (Bouchard and Rankinen 2001; Hautala et al. 2003, 2006). Age, gender, race, baseline fitness level, and genetic factors are the known determinants of individual differences in responses to endurance training (Bouchard et al. 1999; Bouchard and Rankinen 2001; Rankinen et al. 2003). In addition, the status of the autonomic nervous system plays an important role in the training response. Higher cardiac vagal outflow, measured by the high-frequency (HF, 0.15–0.4 Hz) spectral component of heart rate variability (HRV) before the training period, associates with a larger increase in peak oxygen consumption (VO_{2peak}) among sedentary subjects and athletes (Hedelin et al. 2001; Hautala et al. 2003).

Since most of the known factors behind the individual variation in the training response cannot be affected by any treatment, individualized training programs are warranted to gain better benefits from exercise training, particularly for subjects susceptible to a poor training response in standard training programs. Despite the large body of studies demonstrating an association between endurance exercise training and HRV (al-Ani et al. 1996; Pichot et al. 2000;

Hedelin et al. 2001; Iellamo et al. 2002; Iwasaki et al. 2003; Tulppo et al. 2003; Garet et al. 2004; Hautala et al. 2004; Kiviniemi et al. 2006), none have assessed prospectively HRV measurements as a tool for adjusting the endurance training program.

The purpose of this study was to test prospectively the usefulness of daily HRV measurements to dictate endurance training at an individual level. The basic idea of HRV-guided training was to decrease the training stimulus when HRV decreased and maintain training stimulus high when HRV remained the same or increased. We hypothesized that endurance training guided by daily HRV measurements would result in a more favorable training response in cardiorespiratory fitness than a standard predefined training program.

Methods

Subjects and study protocol

Thirty healthy recreational male runners were recruited from the local sports club (Table 1). The candidates were interviewed with a standardized scheme to ascertain their medical history and levels of physical activity. All smokers, subjects with BMI > 28 kg m^{-2}, subjects who had done regular physical exercise training less than twice a week during past 3 months, competing athletes, and subjects with diabetes mellitus, asthma, or cardiovascular disorders were excluded. The subjects were randomized into a predefined training group (TRA, $n = 10$), a HRV-guided training group (HRV, $n = 10$), and a control group ($n = 10$). Group size was determined based on a priori power analysis to give 80% power to the responsiveness in the maximal running performance. The Ethical Committee of the Northern Ostrobothnia Hospital District, Oulu, Finland, approved the protocol, and all subjects gave written informed consent.

The laboratory measurements were performed in the Department of Exercise and Medical Physiology at Verve (Oulu, Finland). The subjects were not allowed to eat or drink coffee for 3 h before the tests. Physical exercise or use of alcohol was prohibited during the test day and on the preceding day. Before each maximal exercise test, a resting electrocardiogram (standard 12-lead ECG) was recorded to confirm the subject's cardiac health status. The tests were performed before and after the training period at the same time of the day for each subject.

Table 1 Characteristics of the test subjects divided into predefined (TRA) training, heart rate variability (HRV)-guided training, and control groups

	TRA	HRV	Control
	$n = 8$	$n = 9$	$n = 9$
Age, years	32 ± 5	31 ± 6	35 ± 8
Range	26–38	22–40	24–45
Height, m	1.79 ± 0.06	1.81 ± 0.03	1.81 ± 0.04
Weight, kg	78 ± 8	80 ± 8	81 ± 5
BMI, kg m^{-2}	24 ± 2	24 ± 2	25 ± 1
Range	22–27	22–26	23–28

Values are means ± SD. BMI—Body mass index

Maximal exercise test

The subjects performed a graded maximal exercise test on a treadmill (Telineyhtymä, Kotka, Finland), starting at 8.0 km h^{-1} and followed by an increase of 0.5 km h^{-1} every minute until voluntary exhaustion. Ventilation (VE) and gas exchange (M909 ergospirometer, Medikro, Kuopio, Finland) were measured and reported as the mean value per minute. The highest 1-min mean value of oxygen consumption was expressed as the peak oxygen consumption (VO_{2peak}) since plateau of VO_2 was not observed during the test in all cases though other criteria for VO_{2max} given in the literature [i.e., respiratory exchange ratio >1.1 and maximum heart rate (HR) within 10 beats of the age-appropriate reference value] were fulfilled (Howley et al. 1995). The maximal running velocity ($Load_{max}$) was calculated as average running velocity during the last minute of the test and used as a measure of maximal running performance. Ventilatory threshold (VT) was analyzed blindly from the relation of running velocity and selected ventilatory parameters (VE, VE/VO_2 and VE/VCO_2 ratios) (Wasserman et al. 1987). VT could not be analyzed in for one subject in the HRV and one subject in the control group.

Training

The controlled 4-week training period consisted of running sessions at either a low or a high-intensity level according to recommendations of American College of Sports Medicine (ACSM 1998). Low-intensity exercise consisted of 40 min of jogging at 65% of maximal HR. High-intensity exercise included 5-min warm-up and cool-down periods at 65% of maximal HR before and after 30 min of running at 85% of maximal HR. In the TRA group, weekly training started with low-intensity exercise followed by two sessions of high-intensity exercise on successive days. This 3-day period was repeated before a day of rest. The subjects in the HRV group exercised at low or high intensity or rested based on their daily HRV measurements at home. Subjects exercised mainly outdoors at the time of day most convenient for their daily life. Training on treadmill was allowed occasionally during bad weather conditions outdoors.

All subjects were familiarized with the use of a HR and running velocity monitor during the training (Polar S625X, Polar Electro Oy, Kempele, Finland) and during the daily HRV measurements (Polar S810i). The subjects saved the training and R–R interval data in their personal computer and sent them to the laboratory by e-mail daily for verification and further analysis.

Exercise program based on daily heart rate variability

All the subjects measured R–R intervals every morning after awakening and emptying the urinary bladder at home. A HR monitor (Polar S810i) was used to record R–R intervals at a timing accuracy of 2 ms. Validity of Polar S810 to measure R–R intervals has been documented previously (Gamelin et al. 2006). The measurement started with 5 min of sitting followed by 5 min of standing. The R–R interval data were saved in a personal computer using the Polar software (Polar Precision Performance SW 4.0). The software performed an automated analysis of HRV for training prescription for the subjects in the HRV group. Measurement errors and abnormal heart beats were eliminated by an automatic process in the software. First, the error elimination process finds potential errors with moving average based criteria using both instantaneous HR and R–R intervals. Second, it marks each R–R interval as an error if it deviates more than 12 bpm or more than 4 standard deviations (SD) from the median of 7 R–R intervals in the neighborhood. Third, the previous process is repeated until no new errors are found. In the calculation of median and SD only R–R intervals that were not marked as errors by the previous filter are used. SD is calculated in a window of 32 R–R intervals. The errors were corrected according to the length of the error sequence, taking the previous and next normal R–R interval into account and maintaining the local trend in the R–R interval time series. The high-frequency (HF, 0.15–0.40 Hz) spectral component of HRV was then extracted using an autoregressive model (order 18) from the 5-min standing period. HRV measurement during orthostatic stress was chosen to avoid the saturation of HF power, expressed as plateau of HF power despite the increased cardiac vagal outflow, susceptible at low HR levels (Kiviniemi et al. 2004; 2006). The basic idea was to decrease the training stimulus when HF power was attenuated (Fig. 1). The baseline values of HF power were measured daily during the week before the laboratory tests without any exercise training. The 3 days following the laboratory tests included rest, low-intensity exercise and high-intensity exercise, respectively. A total of 10 daily HRV measurements were done before the HRV guidance was started. The standard deviation of the 10-day HF power was subtracted from the 10-day average HF power to be used as a daily reference value for HRV-guided training, which moved day by day thereafter. HF power was defined as significantly decreased if the daily value was lower than the reference value. Additionally, a decreasing trend in HF power >0.1 ln ms^2 for two successive days was considered significant.

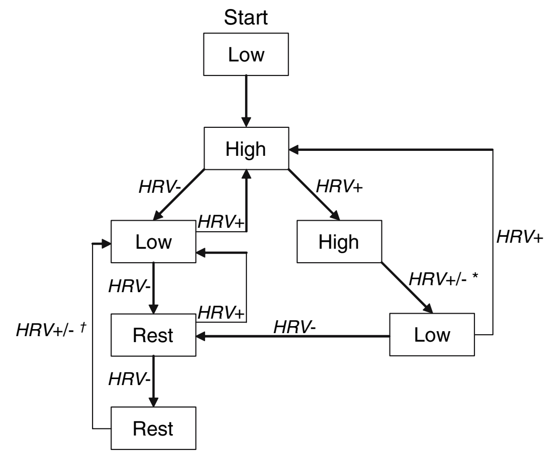

Fig. 1 Heart rate variability (HRV)-guided training scheme. The basic idea was to lower the training intensity whenever decreased high-frequency (HF) oscillation of R–R intervals was observed. Maximum two consequent high-intensity exercises (*) and resting days (†) were allowed. Resting day was prescribed after nine consequent training days despite the daily HF power. Low = exercise at 65% of maximal heart rate; High = exercise at 85% of maximal heart rate; Rest = resting day; HRV+ = increased or not changed HRV; HRV- = decreased HRV

Increased or unchanged HF power on the 11th day and thereafter resulted in high-intensity training. Low-intensity exercise was prescribed despite the HF power reading after two successive high-intensity training days. A maximum of nine successive training days were allowed before a day of rest was prescribed regardless of the daily HF power. Significantly decreased HF power led to training at low intensity, and a further decrease of HF power following a diminished training stimulus resulted in a day of rest. A maximum of two successive resting days were allowed, and low-intensity exercise was prescribed regardless of the daily HRV on the following day. By these rules, HRV-guidance could lead to either more or less training than predefined training program. The whole procedure was determined in advance and integrated into the software, which automatically provided a daily training program for each subject. A representative example of the HRV-guided training practice is presented in Fig. 2.

Retrospective analysis of heart rate variability

HF power values from daily R–R interval measurements at home were verified retrospectively by separate HRV analysis software (Heart Signal Co., Oulu, Finland) to ensure valid training prescription based on daily HRV. Data were edited by deleting artefacts (<10% for all measurements). HF power was analyzed by using autoregressive spectral method (model order 18). One subject in HRV group was excluded from final analysis since training prescription could not verified by retro-

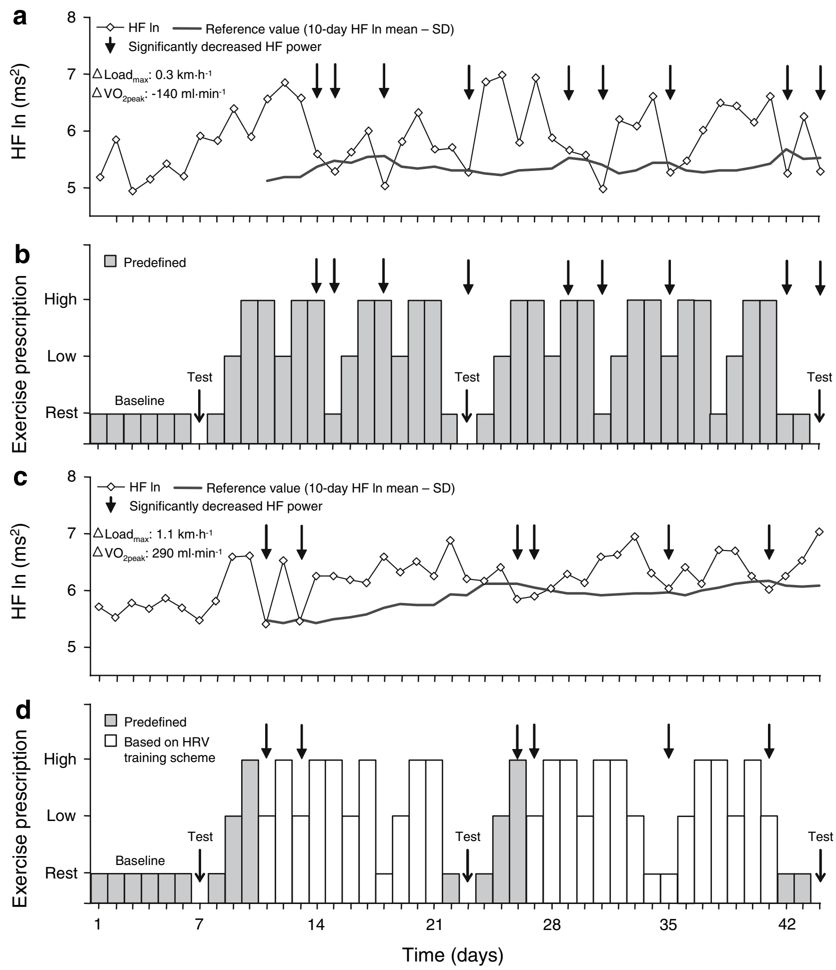

Fig. 2 Daily heart rate variability (HRV), expressed as high-frequency (HF) power, and exercise prescription during predefined (**a**, **b**) and HRV-guided training (**c**, **d**). The in HRV group, training stimulus was lowered if HF power was less than the reference value based on ten earlier measurements, or if HF power decreased >0.1 ln ms^2 for two successive days. Maximal running test after 2 weeks of training was included in the study protocol to verify an accurate training heart rate levels. The other data of this measurement did not provide additional information and are not presented in this study. Low = exercise at 65% of maximal heart rate; High = exercise at 85% of maximal heart rate; Rest = day of rest; $\Delta Load_{max}$ = change in maximal running velocity; ΔVO_{2peak} = change in peak oxygen consumption

spective analysis. Three-day average values were obtained separately for sitting and standing position at pre- and post-training conditions for all subjects to assess changes in HF power and mean HR during the intervention.

Training load and fatigue sensation

Training load was assessed by measuring running distance (Polar S625X, Polar Electro Oy, Kempele, Finland) and by calculating training impulse (TRIMP) using following formula: TRIMP = A·B·C, in which A is exercise time (min), B is HR (proportionally of HR reserve), and C is $0.64e^{1.92B}$ (Banister 1991). Additionally, the subjects filled a questionnaire where a subjective feeling of fatigue was estimated after each training session (Pichot et al. 2000). The fatigue sensation was plotted on a visual scale between 0 and 10, 0 representing the lack of fatigue and 10 the maximal feeling of fatigue.

Statistical methods

Gaussian distribution of the data was verified by the Shapiro-Wilk goodness-of-fit test. The effects of training were analyzed by two-factor ANOVA with time and interventions followed by post hoc analysis between pre- and post-training values within each group (paired Student's *t*-test). Data for VT was not normally distributed and Wilcoxon's test was used instead. ANCOVA with the Bonferroni post hoc test was used to compare the differences in the changes in VO_{2peak}, $Load_{max}$ and HRV between the groups using baseline value as covariate. Kruskal–Wallis analysis with the Mann–Whitney U-test as post hoc was used to analyze differences in the changes in VT between the groups. The differences in training realization between TRA and HRV groups were analyzed by unpaired Student's *t*-test. The data were analyzed using the SPSS software (SPSS 14.0, SPSS inc., Chicago, USA). *P*-value <0.05 was considered statistically significant.

Results

The final series consisted of eight subjects in the TRA group, nine in the HRV group, and nine in the control group. Three subjects dropped out due to personal reasons. One subject was excluded from final analysis since valid training prescription based on daily HRV could not be guaranteed. Significant main effects of training were found in $Load_{max}$, absolute and relative VO_{2peak}, and running velocity at VT ($P < 0.001$, $P = 0.045$, $P = 0.014$, and $P = 0.009$, respectively). No significant changes were observed in weight or BMI ($P = 0.192$ and $P = 0.201$, respectively). In the TRA group, $Load_{max}$ increased during the training ($P = 0.004$, Table 2), whereas absolute or relative VO_{2peak} or running velocity at VT did not change significantly ($P = 0.430$, $P = 0.224$, and $P = 0.058$, respectively). In the HRV group, significant increases were observed in $Load_{max}$, absolute and relative VO_{2peak} and running velocity at VT ($P < 0.001$, $P = 0.007$, $P = 0.002$, and $P = 0.026$, respectively). No significant changes were observed in the control group. Significant differences were found in the changes in $Load_{max}$ between the TRA and HRV group (0.5 ± 0.4 vs. 0.9 ± 0.2 km h^{-1}, $P = 0.048$, Fig. 3a) but not in the changes in VO_{2peak} (69 ± 232 vs. 242 ± 201 ml min^{-1}, $P = 0.321$, Fig. 3b) or running velocity at VT (0.4 ± 0.4 vs. 0.7 ± 0.5 km h^{-1}, $P = 0.279$). No significant differences were observed in the pre-training values of $Load_{max}$, VO_{2peak} and running velocity at VT between the groups.

The mean training frequencies were six times a week for both training groups. The mean training HR was $66 \pm 1\%$ of maximal HR for low-intensity exercise and $80 \pm 1\%$ for high-intensity exercise for both groups. No significant differences were found in the mean running velocity during low-intensity exercises (7.8 ± 1.0 and 8.3 ± 1.2 km h^{-1}, $P = 0.398$) and during high-intensity exercises (10.8 ± 1.0 and 11.0 ± 1.0 km h^{-1}, $P = 0.789$) between the TRA and HRV group, respectively. Significant differences were

Table 2 Peak oxygen consumption (VO_{2peak}), maximal running velocity ($Load_{max}$), running velocity at ventilatory threshold (VT) and HRV variables from home measurements before and after the training period in the test subjects divided into predefined (TRA) training, heart rate variability (HRV)-guided training, and control groups

	TRA, $n = 8$			HRV, $n = 9$			Control, $n = 9$		
	Pre	Post	*P*-value	Pre	Post	*P*-value	Pre	Post	*P*-value
VO_{2peak},									
l min^{-1}	4.29 ± 0.29	4.36 ± 0.34	0.430	4.35 ± 0.60	4.59 ± 0.62	0.007	4.40 ± 0.32	4.38 ± 0.39	0.794
ml kg^{-1}min^{-1}	54 ± 4	55 ± 3	0.224	56 ± 4	60 ± 5	0.002	54 ± 5	54 ± 6	0.822
$Load_{max}$, km h^{-1}	15.1 ± 1.3	15.7 ± 1.2	0.004	15.5 ± 1.0	16.4 ± 1.0	<0.001	14.9 ± 1.4	14.9 ± 1.5	0.934
VT, km h^{-1}*	11.8 ± 0.9	12.2 ± 0.9	0.058	12.0 ± 0.6	12.7 ± 0.5	0.026	12.1 ± 1.4	12.0 ± 1.5	0.414
HR_{sit}, bpm	62 ± 8	55 ± 8	–	66 ± 9	59 ± 6	–	62 ± 5	60 ± 7	–
HF_{sit}, ln ms^2	6.6 ± 0.9	6.6 ± 1.0	–	5.8 ± 1.1	6.5 ± 1.1	–	6.4 ± 1.2	6.3 ± 1.4	–
HR_{stand}, bpm	86 ± 11	77 ± 9	–	87 ± 7	80 ± 5	–	81 ± 10	77 ± 6	–
HF_{stand}, ln ms^2	4.7 ± 0.4	5.5 ± 0.8	0.004	4.8 ± 0.6	5.2 ± 0.8	0.049	5.2 ± 1.1	5.0 ± 1.0	0.471

Values are means ± SD. VO_{2peak} maximal oxygen consumption, $Load_{max}$ maximal running velocity, VT running velocity at ventilatory threshold, HR heart rate, HF high-frequency power of R–R interval, *P*-value statistical significance in differences between pre- and post-training values from post hoc analysis. *$n = 8$ for HRV and control groups

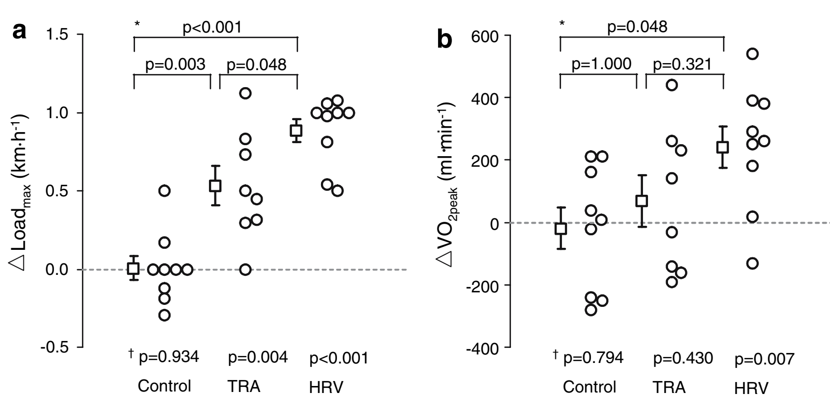

Fig. 3 The changes in maximal running velocity ($Load_{max}$, **a**) and peak consumption (VO_{2peak}, **b**) during the training intervention in the heart rate variability guided training (HRV), predefined training (TRA), and control groups. A better response to endurance training was observed in $Load_{max}$ in the HRV group compared to TRA group in the terms of $Load_{max}$. The values are means ± SE. * = statistical significances of difference between the groups from post hoc analysis; † = statistical significances of changes within the groups from post hoc analysis

found in the mean frequency of high-intensity exercises between TRA and HRV groups (4 vs. 3 times week^{-1}, $P < 0.001$, respectively). Weekly TRIMP tended to be higher among TRA group than HRV group (529 ± 49 [range 455–605] vs. 463 ± 74 [range 363–589], $P = 0.063$). No differences were found in the weekly running distance (38 ± 6 [range 31–45] vs. 36 ± 4 [range 29–43] km, $P = 0.597$) or mean fatigue sensation after training sessions (4.8 ± 1.0 [range 3.6–6.4] vs. 4.3 ± 1.3 [range 2.6–6.0], $P = 0.374$) between the TRA and HRV groups.

In HRV analysis, significant main effect of training was observed in HF power measured at standing position ($P = 0.004$) but not in HF power and mean HR at sitting position or mean heart during standing ($P = 0.065$, $P = 0.058$, and $P = 0.260$, respectively). HF power at standing position increased in the TRA and HRV groups but not in the control group ($P = 0.004$, $P = 0.049$, and $P = 0.471$, respectively, Table 2). No significant differences were found in the change of HF power at standing position between the TRA and HRV groups (0.8 ± 0.6 vs. 0.3 ± 0.5 ln ms^2, $P = 0.240$, respectively).

Discussion

The novel finding of the present study is that cardiorespiratory fitness can be efficiently improved during a training intervention by using vagally mediated HRV for exercise prescription on a daily basis. HRV measurements may help to determine the timing of intensive training sessions based on the status of autonomic regulation. In the presence of declined vagally mediated beat-to-beat HRV, a decrease in the training stimulus might be beneficial to gain favorable endurance training response.

Standardized endurance training according to the current guidelines is an effective way to improve cardiorespiratory fitness at the population level (ACSM 1998). Nevertheless, wide heterogeneity in the responsiveness to endurance training exists at the individual level revealing even negative changes in small portion of population, which was observed in the present study, as well (Bouchard and Rankinen 2001; Hautala et al. 2003, 2006). Although there are some known factors behind the individual training response (Bouchard et al. 1999; Bouchard and Rankinen 2001; Rankinen et al. 2003), an individualized training program remains the only practical tool to avoid unfavorable responses to exercise training.

Several cross-sectional and longitudinal studies indicate the association between endurance training and cardiac vagal outflow, as measured by HRV techniques (Goldsmith et al. 1992; al-Ani et al. 1996; Jensen-Urstad et al. 1997; Tulppo et al. 2003; Hautala et al. 2004; Kiviniemi et al. 2006). In athletes, an intense endurance training period results in decreased HRV which is followed by rebound of HRV beyond pre-training level during subsequent lighter training period (Pichot et al. 2000; Iellamo et al. 2002; Garet et al. 2004). The rebound of HRV is associated with improved performance in athletes (Garet et al. 2004). Similarly, vagally mediated HRV attenuates during acute endurance exercise and the early phase of recovery and rebounds above the pre-exercise level during the following days of recovery (Tulppo et al. 1996; Hautala et al. 2001). Interestingly, vagally mediated HRV before a training period is also associated with the responsiveness of cardiorespiratory fitness to endurance training (Hedelin et al. 2001; Hautala et al. 2003). Taken together, these studies suggest that HRV includes important information concerning the physiological recovery processes after training stimulus and could serve as an indicator of appropriate physiological condition for training.

HF oscillation of R–R intervals is a widely accepted index of cardiac vagal outflow (Pomeranz et al. 1985; Hayano et al. 1991). In the present study, the main idea was to lower training load in the case of attenuated HF power on the morning following exercise. Decreased HF power reflects insufficient recovery from the previous endurance exercise (Hautala et al. 2001), which may indicate unfavorable physiological condition for high-intensity endurance exercise on that day. The practice of HRV-guided training resulted in better endurance training response in maximal running performance, compared to predefined standard training according to current guidelines. No significant differences were found in the changes in VO_{2peak} and running velocity at VT between the groups. However, VO_{2peak} and running velocity at VT increased significantly during HRV-guided training but not during predefined standard training, which may partly explain the differences in the change in maximal running performance, as well. No differences were found in weekly running distance and subjective feeling of fatigue between the HRV-guided and predefined standard training. However, HRV-guided training resulted in lower frequency of high-intensity exercises compared to predefined standard training which was shown also as a tendency of lower weekly training load according to TRIMP. Based on this data, HRV-guided training may adjust both the timing and amount of high-intensity exercises at individual level. Importance of macrocycle (weeks or months) training periodization is well-recognized in endurance training interventions (Iellamo et al. 2002; Garet et al. 2004; Zaryski and Smith 2005). However, the significance of microcycle (day-to-day) periodization of training is not well known. The present study suggests the importance of adjusting high-intensity endurance training stimulus on day-to-day basis, in which HRV measurements may provide a practical tool.

In the present study, no significant increases in VO_{2peak} were observed during predefined standard training despite the improved maximal running performance. It is known that improving VO_{2peak} by training is more difficult in the subjects at already high aerobic fitness level (Saltin 1990). However, the maximal running performance can be improved without changes in VO_{2peak} (Paavolainen et al. 1999), which was supported by the present data. One explanation for lack of increases in VO_{2peak} during predefined standard training might be the inappropriate periodization or too high total amount of high-intensity exercises. Therefore, it is possible that the training could have resulted in short-term overreaching compromising the performance during the running test in some subjects. In the present study, VO_{2peak} was evidently improved during the HRV guided training, which included similar exercises than the predefined standard training but with individual periodization and frequency. This manifests the importance of cardiac autonomic function in endurance training responses. The training groups were homogenous in terms of baseline fitness and demographic variables and, therefore, differences in the training responses are unlikely to be explained by pre-training fitness level in the present study.

In the present study, we assessed HF power during orthostatic stress at standing position since HRV is susceptible to saturation when measured at low HR (Goldberger et al. 2001; Kiviniemi et al. 2004). Saturated HF power, expressed as a plateau regardless of the lengthening of the R–R interval, is a common phenomenon among healthy subjects (Kiviniemi et al. 2004). Thus, HF power, when measured at low HR level, may be unable to detect changes in cardiac vagal outflow in training intervention studies (Kiviniemi et al. 2006). Additionally, vagal and sympathetic regulation operates in reciprocal fashion during sympathetic orthostatic stimulus (Malliani et al. 1991; Montano et al. 1994). Therefore, standing position might be practical condition to measure cardiac autonomic function since it could detect attenuated vagal outflow related to increased sympathetic activity, as well. Possibly for these reasons, changes in athletic performance has shown to associate to changes in HRV during orthostatic stress rather than at supine rest (Hedelin et al. 2001). In the present study, endurance training increased HF power measured at standing position but did not change HF power measured at sitting position. This supports our notions that orthostatic stimulus may be more favorable condition than sitting or supine positions to obtain specific information on the status of cardiac autonomic regulation in exercise intervention settings among relatively high fit subjects.

In the present study, both training regimen resulted in similar improvements in HRV among fit healthy subjects. In the clinical point of view, withdrawn cardiac vagal outflow, expressed as decreased HRV, indicates an increased risk for cardiovascular morbidity in various patient populations (Kleiger et al. 1987; Liao et al. 1998; Adamson et al. 2004; Bauer et al. 2006; Kiviniemi et al. 2007) as well as among the normal healthy subjects (Liao et al. 1995, 1996; Tsuji et al. 1996; Dietrich et al. 2006). Adamson et al. observed that the decreasing trend of day-to-day HRV is associated with following hospitalization or death among the cardiac patients (Adamson et al. 2004). Thus, monitoring of the daily status of cardiovascular autonomic function by HRV measurements may provide useful information on the physiological responses to training among various patient populations, as well. Future studies will show whether regular HRV monitoring provide new insights for exercise training in improving risk factors among patient populations.

Limitations

The measurements made at home may not be considered as highly standardized as those made in laboratory conditions. This was a trade-off to acquire daily HRV data practically and to avoid some confounding psychophysiological effects of laboratory conditions on cardiovascular measurements (Grassi et al. 1999). Additionally, even though the subjects performed the measurements in the morning, when the condition is easiest to control, there may be other factors apart from endurance training affecting the daily HRV, such as the insufficient nighttime sleep or other psychological and physiological stressors. Finally, the present study applies only to relatively fit male subjects. More studies are warranted to test the applicability of HRV in optimizing endurance training among different populations.

Conclusion

Cardiorespiratory fitness can be effectively improved during endurance training by using daily HRV for exercise prescription. A lower-intensity training stimulus, whenever attenuated vagally mediated HRV occurs, might be beneficial to gain favorable response in endurance training.

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References

ACSM (1998) American College of Sports Medicine Position Stand. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. Med Sci Sports Exerc 30(6):975–991

Adamson PB, Smith AL, Abraham WT, Kleckner KJ, Stadler RW, Shih A, Rhodes MM (2004) Continuous autonomic assessment in patients with symptomatic heart failure: prognostic value of heart rate variability measured by an implanted cardiac resynchronization device. Circulation 110(16):2389–2394 al-Ani M, Munir SM, White M, Townend J, Coote JH (1996) Changes in R-R variability before and after endurance training measured by power spectral analysis and by the effect of isometric muscle contraction. Eur J Appl Physiol Occup Physiol 74(5):397–403

Banister EW (1991) Modeling elite athletic performance. In: Green HJ, McDougal JD, Wenger H (eds) Physiological testing of elite athletes. Human Kinetics, Champaign, IL, pp 403–424

Bauer A, Kantelhardt JW, Barthel P, Schneider R, Mäkikallio T, Ulm K, Hnatkova K, Schomig A, Huikuri H, Bunde A, Malik M, Schmidt G (2006) Deceleration capacity of heart rate as a predictor of mortality after myocardial infarction: cohort study. Lancet 367(9523):1674–1681

Bouchard C, Rankinen T (2001) Individual differences in response to regular physical activity. Med Sci Sports Exerc 33(6 Suppl):S446–S451 discussion S452–453

Bouchard C, An P, Rice T, Skinner JS, Wilmore JH, Gagnon J, Perusse L, Leon AS, Rao DC (1999) Familial aggregation of *V*O(2max) response to exercise training: results from the HERITAGE Family Study. J Appl Physiol 87(3):1003–1008

Dietrich DF, Schindler C, Schwartz J, Barthelemy JC, Tschopp JM, Roche F, von Eckardstein A, Brandli O, Leuenberger P, Gold DR, Gaspoz JM, Ackermann-Liebrich U (2006) Heart rate variability in an ageing population and its association with lifestyle and cardiovascular risk factors: results of the SAPALDIA study. Europace 8(7):521–529

Gamelin FX, Berthoin S, Bosquet L (2006) Validity of the polar S810 heart rate monitor to measure R-R intervals at rest. Med Sci Sports Exerc 38(5):887–893

Garet M, Tournaire N, Roche F, Laurent R, Lacour JR, Barthelemy JC, Pichot V (2004) Individual interdependence between nocturnal ANS activity and performance in swimmers. Med Sci Sports Exerc 36(12):2112–2118

Goldberger JJ, Challapalli S, Tung R, Parker MA, Kadish AH (2001) Relationship of heart rate variability to parasympathetic effect. Circulation 103(15):1977–1983

Goldsmith RL, Bigger JT Jr, Steinman RC, Fleiss JL (1992) Comparison of 24-hour parasympathetic activity in endurance-trained and untrained young men. J Am Coll Cardiol 20(3):552–558

Grassi G, Turri C, Vailati S, Dell'Oro R, Mancia G (1999) Muscle and skin sympathetic nerve traffic during the "white-coat" effect. Circulation 100(3):222–225

Hautala A, Tulppo MP, Mäkikallio TH, Laukkanen R, Nissilä S, Huikuri HV (2001) Changes in cardiac autonomic regulation after prolonged maximal exercise. Clin Physiol 21(2):238–245

Hautala AJ, Mäkikallio TH, Kiviniemi A, Laukkanen RT, Nissilä S, Huikuri HV, Tulppo MP (2003) Cardiovascular autonomic function correlates with the response to aerobic training in healthy sedentary subjects. Am J Physiol Heart Circ Physiol 285(4):H1747–H1752

Hautala AJ, Mäkikallio TH, Kiviniemi A, Laukkanen RT, Nissilä S, Huikuri HV, Tulppo MP (2004) Heart rate dynamics after controlled training followed by a home-based exercise program. Eur J Appl Physiol 92(3):289–297

Hautala AJ, Kiviniemi AM, Mäkikallio TH, Kinnunen H, Nissilä S, Huikuri HV, Tulppo MP (2006) Individual differences in the responses to endurance and resistance training. Eur J Appl Physiol 96(5):535–542

Hayano J, Sakakibara Y, Yamada A, Yamada M, Mukai S, Fujinami T, Yokoyama K, Watanabe Y, Takata K (1991) Accuracy of assessment of cardiac vagal tone by heart rate variability in normal subjects. Am J Cardiol 67(2):199–204

Hedelin R, Bjerle P, Henriksson-Larsen K (2001) Heart rate variability in athletes: relationship with central and peripheral performance. Med Sci Sports Exerc 33(8):1394–1398

Howley ET, Bassett DR Jr, Welch HG (1995) Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc 27(9):1292–1301

Iellamo F, Legramante JM, Pigozzi F, Spataro A, Norbiato G, Lucini D, Pagani M (2002) Conversion from vagal to sympathetic predominance with strenuous training in high-performance world class athletes. Circulation 105(23):2719–2724

Iwasaki K, Zhang R, Zuckerman JH, Levine BD (2003) Dose-response relationship of the cardiovascular adaptation to endurance training in healthy adults: how much training for what benefit? J Appl Physiol 95(4):1575–1583

Jensen-Urstad K, Saltin B, Ericson M, Storck N, Jensen-Urstad M (1997) Pronounced resting bradycardia in male elite runners is associated with high heart rate variability. Scand J Med Sci Sports 7(5):274–278

Kiviniemi AM, Hautala AJ, Seppänen T, Mäkikallio TH, Huikuri HV, Tulppo MP (2004) Saturation of high-frequency oscillations of R-R intervals in healthy subjects and patients after acute myocardial infarction during ambulatory conditions. Am J Physiol Heart Circ Physiol 287(5):H1921–H1927

Kiviniemi AM, Hautala AJ, Mäkikallio TH, Seppänen T, Huikuri HV, Tulppo MP (2006) Cardiac vagal outflow after aerobic training by analysis of high-frequency oscillation of the R-R interval. Eur J Appl Physiol 96(6):686–692

Kiviniemi AM, Tulppo MP, Wichterle D, Hautala AJ, Tiinanen S, Seppänen T, Mäkikallio TH, Huikuri HV (2007) Novel spectral indexes of heart rate variability as predictors of sudden and non-sudden cardiac death after an acute myocardial infarction. Ann Med 39(1):54–62

Kleiger RE, Miller JP, Bigger JT Jr, Moss AJ (1987) Decreased heart rate variability and its association with increased mortality after acute myocardial infarction. Am J Cardiol 59(4):256–262

Liao D, Cai J, Brancati FL, Folsom A, Barnes RW, Tyroler HA, Heiss G (1995) Association of vagal tone with serum insulin, glucose, and diabetes mellitus—The ARIC Study. Diabetes Res Clin Pract 30(3):211–221

Liao D, Cai J, Barnes RW, Tyroler HA, Rautaharju P, Holme I, Heiss G (1996) Association of cardiac autonomic function and the development of hypertension: the ARIC study. Am J Hypertens 9(12 Pt 1):1147–1156

Liao D, Sloan RP, Cascio WE, Folsom AR, Liese AD, Evans GW, Cai J, Sharrett AR (1998) Multiple metabolic syndrome is associated with lower heart rate variability. The Atherosclerosis Risk in Communities Study. Diabetes Care 21(12):2116–2122

Malliani A, Pagani M, Lombardi F, Cerutti S (1991) Cardiovascular neural regulation explored in the frequency domain. Circulation 84(2):482–492

Montano N, Ruscone TG, Porta A, Lombardi F, Pagani M, Malliani A (1994) Power spectrum analysis of heart rate variability to assess the changes in sympathovagal balance during graded orthostatic tilt. Circulation 90(4):1826–1831

Paavolainen L, Häkkinen K, Hämäläinen I, Nummela A, Rusko H (1999) Explosive-strength training improves 5-km running time by improving running economy and muscle power. J Appl Physiol 86(5):1527–1533

Pichot V, Roche F, Gaspoz JM, Enjolras F, Antoniadis A, Minini P, Costes F, Busso T, Lacour JR, Barthelemy JC (2000) Relation between heart rate variability and training load in middle-distance runners. Med Sci Sports Exerc 32(10):1729–1736

Pomeranz B, Macaulay RJ, Caudill MA, Kutz I, Adam D, Gordon D, Kilborn KM, Barger AC, Shannon DC, Cohen RJ et al (1985) Assessment of autonomic function in humans by heart rate spectral analysis. Am J Physiol 248(1 Pt 2):H151–H153

Rankinen T, Rice T, Boudreau A, Leon AS, Skinner JS, Wilmore JH, Rao DC, Bouchard C (2003) Titin is a candidate gene for stroke

volume response to endurance training: the HERITAGE Family Study. Physiol Genomics 15(1):27–33
Saltin B (1990) Maximal oxygen uptake: limitations and malleability. In: Nazar K, Terjung RL (eds) International perspectives in exercise physiology. Human Kinetics Publishers, Champaign, IL, pp 26–40
Tsuji H, Larson MG, Venditti FJ Jr, Manders ES, Evans JC, Feldman CL, Levy D (1996) Impact of reduced heart rate variability on risk for cardiac events. The Framingham Heart Study. Circulation 94(11):2850–2855
Tulppo MP, Mäkikallio TH, Takala TE, Seppänen T, Huikuri HV (1996) Quantitative beat-to-beat analysis of heart rate dynamics during exercise. Am J Physiol 271(1 Pt 2):H244–H252
Tulppo MP, Hautala AJ, Makikallio TH, Laukkanen RT, Nissilä S, Hughson RL, Huikuri HV (2003) Effects of aerobic training on heart rate dynamics in sedentary subjects. J Appl Physiol 95(1):364–372
Wasserman K, Hansen JE, Sue DY, Whipp BJ (1987) Principles of exercise testing and interpretation. Lea & Febinger, Philadelphia, PA
Zaryski C, Smith DJ (2005) Training principles and issues for ultra-endurance athletes. Curr Sports Med Rep 4(3):165–170