Effects of Moderate and Heavy Endurance Exercise on Nocturnal HRV

Authors E. Hynynen[1], V. Vesterinen[2], H. Rusko[3], A. Nummela[4]

Affiliations
[1] KIHU-Research Institute for Olympic Sports, Sports Physiology, Jyväskylä, Finland
[2] KIHU, Research Institute for Olympic Sport, Jyväskylä, Finland
[3] University of Jyväskylä, Department of Biology of Physical Activity and Neuromuscular Research Center, Jyväskylä, Finland
[4] Research Institute for Olympic Sports, Physiology, Jyväskylä, Finland

Key words
- autonomic nervous system
- endurance running
- disturbance to homeostasis

accepted after revision
February 05, 2010

Bibliography
DOI http://dx.doi.org/10.1055/s-0030-1249625
Published online: April 23, 2010
Int J Sports Med 2010; 31: 428–432 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

Correspondence
Esa Hynynen
KIHU-Research Institute for Olympic Sports
Sports Physiology
Rautpohjankatu 6
FI-40700 Jyväskylä
Finland
Tel.: +358/40/560 4343
Fax: +358/20/781 1501
esa.hynynen@kihu.fi

Abstract

This study examined the effects of endurance exercise on nocturnal autonomic modulation. Nocturnal R-R intervals were collected after a rest day, after a moderate endurance exercise and after a marathon run in ten healthy, physically active men. Heart rate variability (HRV) was analyzed as a continuous four-hour period starting 30 min after going to bed for sleep. In relation to average nocturnal heart rate after rest day, increases to 109±6% and 130±11% of baseline were found after moderate endurance exercise and marathon, respectively. Standard deviation of R-R intervals decreased to 90±9% and 64±10%, root-mean-square of differences between adjacent R-R intervals to 87±10% and 55±16%, and high frequency power to 77±19% and 34±19% of baseline after moderate endurance exercise and marathon, respectively. Also nocturnal low frequency power decreased to 56±26% of baseline after the marathon. Changes in nocturnal heart rate and HRV suggest prolonged dose-response effects on autonomic modulation after exercises, which may give useful information on the extent of exercise-induced nocturnal autonomic modulation and disturbance to the homeostasis.

Introduction

Hard training is essential in order to improve physical performance, but what is hard training for one, may be easy for another person e.g. [21,26]. According to the overload principle the training session has to be hard enough to disturb the homeostasis of the bodily functions and the recovery time has to be good and long enough to allow an increase in the determinants of performance, i.e. the training effect. If the disturbance is small, no training effect will occur e.g. [26]. This disturbance of homeostasis may be seen in autonomic modulation even hours after an exercise session has been stopped [6]. Autonomic responses during rest are mainly seen in parasympathetic activity as it dominates normally when a person is resting. Furthermore, parasympathetic modulation has been suggested to be a physiological marker on stress vulnerability [25] and enhanced parasympathetic modulation as an increased autonomic resource for responding to stress (autonomic resource hypothesis) [11]. In other words, the higher the parasympathetic activity is at rest, the greater the changes can be, too.

Heart rate variability (HRV) has been used as a non-invasive measure of autonomic nervous system activity. HRV and especially high frequency power increases when parasympathetic activity is increased and decreases with the decrease in the parasympathetic activity. HRV has been found to recover in minutes to pre-exercise level after low- to moderate-intensity exercise but the recovery is much slower after increasing the exercise intensity to moderate- to high-intensity. The higher the intensity and the lower the physical fitness, the slower is the recovery of HRV after exercise, but the duration of exercise seems to have only a minor effect on the recovery of HRV [14,15,20,28].

Considering that parasympathetic activity is high during night sleep, night recordings may allow better discrimination of the changes in autonomic nervous systems equilibrium as suggested in previous studies [12,13,18,23]. Furthermore, the most important period for health seems to be sleep, when both physiological and psychological recovery happen [4]. Cumulative training effects on nocturnal HRV have been studied in endurance athletes and sedentary people during different training periods [10,23,24]. Pichot et al. [23]

found progressive decrease of up to 40% in nocturnal HRV during the hard training period, followed by rebound during the relative resting week in middle-distance runners during their usual training cycle. Decrement in nocturnal HRV after an overreaching period has also been reported by Hynynen et al. [10] in international level cross-country skiers. Pichot et al. [24] found decreased nocturnal HRV also after intensified training period of sedentary people, even though overload training period preceding the intensified training period had increased the nocturnal HRV. Influence of exercise on nocturnal sleep has also been studied in sleep laboratory and exercise has been found to be useful in improving sleep quality [22] and against general opinion, even vigorous late night exercise sessions seem not to have negative effects on sleep [31]. Taking these together it is unfortunate that almost no information on nocturnal HRV after single exercise sessions exists, even though it is well-known that changes in resting HRV after maximal dynamic exercise may last up to 24 h [6]. Only Hautala et al. [9] have previously reported declining trend in nocturnal HRV after a 75 km ski-race.

The purpose of this study was to examine the effects of a single moderate endurance exercise and a single heavy endurance exercise (a marathon) on nocturnal HRV in healthy, physically active subjects. Firstly, it was hypothesized that nocturnal HRV would be decreased after the heavy endurance exercise but no changes would be found after the moderate endurance exercise. This hypothesis is based on the findings of Furlan et al. [6], and Hautala et al. [9] Secondly, it was hypothesized that the nocturnal HRV after a rest day would be correlated with the amount of decrement in nocturnal HRV after heavy exercise [autonomic resource hypothesis; ref. 11].

Materials and Methods

Subjects

Ten healthy, physically active men were examined. Characteristics of athletes are presented in **Table 1**. These subjects took part in a marathon-training project, which had a goal of finishing a marathon run at the end of the project. This project lasted for 33 weeks during which subjects trained on average for 5 ± 1 times per week and 7 ± 2 h per week. All the subjects were fully informed of the procedures and they gave their written consent to participate in this project. The local Ethical Committee approved this study, and it has been performed in accordance with the ethical standards of the International Journal of Sports Medicine [8].

Procedure and data analysis

Nocturnal R-R interval (RRI)-collections were done after a rest day (no exercise session during the rest day), after a moderate endurance exercise session (on average 52 ± 26 min, average heart rate 133 ± 9 bpm equaling 72% of HR_{max}) and after a marathon run (on average 217 ± 28 min, average heart rate 156 ± 5 bpm equaling 85% of HR_{max}). All the exercise sessions were performed during the afternoon, but no exact standardization was used. The moderate endurance exercise session was perceived as light and easy (3 ± 1 on scale 0–10) and marathon as very hard (8 ± 2 on scale 0–10). The three test conditions (rest, moderate exercise, marathon) were not randomized, but the nocturnal HRV were measured numerous times during the 33 week training period. These three conditions presented here were measured during the last two weeks of the project, and therefore, all the subjects were familiar with the measurements.

RRI-collections were done with Suunto Memory Belt (Suunto Ltd, Vantaa, Finland) having a sampling frequency of 1 000 Hz. RRI-collections were started before going to bed to sleep and stopped after waking up in the morning. First 30 min after going to bed were excluded and the succeeding 4 h sections were analyzed. The 4 h period was selected, because it has been used in previous literature [9, 10, 12, 23, 24], and to compare HRV measurements, the selected periods should be of the same length [29]. All the erroneous RRIs, like movement artifacts, were first carefully excluded using automated software and visual inspection. In addition to average HR, following HRV indices were analyzed with time and frequency domain (autoregressive) methods: standard deviation of RRI (SDNN), root-mean-square of differences between adjacent R-R intervals (RMSSD), low frequency power (LFP; 0.04–0.15 Hz), high frequency power (HFP; 0.15–0.40 Hz), total power (TP; LFP + HFP) and low to high frequency ratio (LF/HF ratio). In addition, to minimize the heart rate dependency of HRV, the coefficients of variation (CVRRI = standard deviation of RRI/average RRI · 100) were calculated. This procedure is similar to that of Hynynen et al. [12]

As values of HRV indices and their relations to vagal activation are highly individual, see e. g. Martinmäki et al. [19], it may be difficult to compare changes in HRV indices between different individuals. To minimize differences between individuals, following additional calculations were done: nocturnal HR and HRV indices after a rest day were set as 100% value and respective nocturnal indices after the moderate endurance exercise and after the marathon were calculated in relation to this 100% value. This procedure is similar to Pichot et al. studies [23, 24].

Ln-transformation was used with variables that were not normally distributed, and ANOVA for repeated measurements was used for statistical testing. Pearson's correlation coefficient was used to analyze the connection between nocturnal HRV after rest day, changes in nocturnal HRV after moderate and heavy exercises, and aerobic power and performance. Data are provided as Mean ± SD. Level of significance was set at $p < 0.05$.

Table 1 Characteristics of the subjects (Mean ± SD).

age	37 ± 5 years
height	1.77 ± 0.07 m
body mass	75.5 ± 6.0 kg
BMI	$24.0 \pm 1.8\ kg \cdot m^{-2}$
VO_{2max}	$52 \pm 5\ mL \cdot kg^{-1} \cdot min^{-1}$
vVO_{2max}	$16.2 \pm 1.2\ km \cdot h^{-1}$
HR_{max}	184 ± 8 bpm

Abbreviations: body mass index, BMI; maximal oxygen uptake, VO_{2max}; velocity of VO_{2max} on treadmill, vVO_{2max}; maximal heart rate, HR_{max}

Results

Absolute nocturnal HR and HRV indices

Compared to control night, nocturnal HR was higher after the moderate endurance exercise session and after the marathon ($p < 0.001$). Most HRV indices were decreased after the moderate exercise session and after the marathon. Most HRV indices were also lower after the marathon than after the moderate exercise session (**Table 2**). Similar results were found also in relative nocturnal HR and HRV (**Fig. 1**).

Table 2 Nocturnal HR and HRV after the rest day, the moderate endurance exercise and the marathon. Mean ± SD.

	Rest	Moderate exercise	Marathon
HR (bpm)	47 ± 2	$50 \pm 3^{***}$	$61 \pm 6^{***,\#\#\#}$
SDNN (ms)	142 ± 16	$126 \pm 15^{**}$	$91 \pm 19^{***,\#\#\#}$
RMSSD (ms)	61 ± 19	$53 \pm 19^{**}$	$34 \pm 18^{***,\#\#\#}$
LFP (ms^2)	1 798 ± 543	1 725 ± 780	$1031 \pm 667^{**,\#\#}$
HFP (ms^2)	1 214 ± 920	$952 \pm 754^{**}$	$445 \pm 612^{***,\#\#\#}$
TP (ms^2)	3 011 ± 1 230	$2677 \pm 1408^{*}$	$1476 \pm 1255^{***,\#\#\#}$
LF/HF ratio	2.56 ± 2.38	3.17 ± 3.51	3.75 ± 2.57
CVRRI (%)	11.0 ± 1.0	10.6 ± 1.1	$9.2 \pm 1.7^{**,\#}$

*,**,*** Statistically significant differences to rest, $p<0.05$, $p<0.01$, $p<0.001$, respectively

$^{\#,\#\#,\#\#\#}$ Statistically significant differences to moderate exercise, $p < 0.05$, $p<0.01$, $p<0.001$, respectively

Abbreviations: average heart rate, HR; standard deviation of RRI, SDNN; square root of the mean of the sum of the squares of differences between adjacent RRI, RMSSD; low frequency power, LFP; high frequency power, HFP: total power, TP; low to high frequency ratio, LF/HF; coefficient of variation of RRI, CVRRI

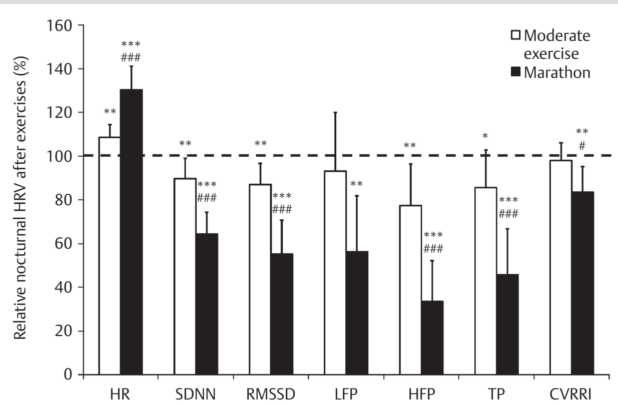

Fig. 1 The relative changes in nocturnal HR and HRV after moderate exercise and the marathon. 100% line corresponds to the respective nocturnal values after the rest day. Mean ± SD. *,**,*** Statistically significant differences from rest, $p<0.05$ $p<0.01$, $p<0.001$, respectively. $^{\#,\#\#\#}$ Statistically significant differences from moderate training, $p< 0.05$, $p<0.001$, respectively.
Abbreviations: average heart rate, HR; standard deviation of RRI, SDNN; square root of the mean of the sum of the squares of differences between adjacent RRI, RMSSD; low frequency power, LFP; high frequency power, HFP: total power, TP; low to high frequency ratio, LF/HF; coefficient of variation of RRI, CVRRI

Correlations between nocturnal HRV after rest day, and exercise induced changes in nocturnal HRV and aerobic performance

Nocturnal HFP after the rest day correlated negatively with the absolute change of HFP while no correlation was found with the relative change in HFP after the moderate endurance exercise and after the marathon. Both the absolute and relative changes of HFP after the moderate endurance exercise and after the marathon were also correlated. All the correlations of absolute changes are presented in ▶ **Table 3** and the correlations of relative changes in ▶ **Table 4**. In addition, VO_{2max} ($r=0.248$, $p=0.490$) or average velocity of marathon run ($r=-0.097$, $p=0.789$) did not correlate with nocturnal HFP after the rest day or with the change of nocturnal HFP after marathon ($r=-0.041$, $p=0.910$ and $r=-0.114$, $p=0.753$, respectively).

Table 3 Correlation coefficients between nocturnal HRV indices after rest and the absolute change in the corresponding index after moderate endurance exercise (ΔModerate) and Marathon (ΔMarathon), and between the changes.

	Rest – ΔModerate	Rest – ΔMarathon	ΔModerate – ΔMarathon
SDNN	$r=-0.486$	$r=-0.182$	$r=0.006$
RMSSD	$r=-0.428$	$r=-0.282$	$r=0.703^{*}$
LFP	$r=0.202$	$r=0.057$	$r=0.347$
HFP	$r=-0.909^{***}$	$r=-0.886^{***}$	$r=0.936^{***}$
TP	$r=-0.447$	$r=0.212$	$r=0.314$

*,*** Statistically significant correlation, $p<0.05$, $p<0.001$, respectively

Abbreviations: average heart rate, HR; standard deviation of RRI, SDNN; square root of the mean of the sum of the squares of differences between adjacent RRI, RMSSD; low frequency power, LFP; high frequency power, HFP: total power, TP; low to high frequency ratio, LF/HF; coefficient of variation of RRI, CVRRI

Table 4 Correlation coefficients between nocturnal HRV indices after rest and the relative change in the corresponding index after moderate endurance exercise (ΔModerate) and Marathon (ΔMarathon), and between the changes.

	Rest – ΔModerate	Rest – ΔMarathon	ΔModerate – ΔMarathon
SDNN	$r=0.415$	$r=-0.167$	$r=-0.225$
RMSSD	$r=-0.219$	$r=-0.110$	$r=0.639^{*}$
LFP	$r=-0.505$	$r=-0.016$	$r=0.257$
HFP	$r=-0.170$	$r=0.060$	$r=0.680^{*}$
TP	$r=-0.590$	$r=0.279$	$r=0.278$

* Statistically significant correlation, $p<0.05$

Abbreviations: average heart rate, HR; standard deviation of RRI, SDNN; square root of the mean of the sum of the squares of differences between adjacent RRI, RMSSD; low frequency power, LFP; high frequency power, HFP: total power, TP; low to high frequency ratio, LF/HF; coefficient of variation of RRI, CVRRI.

Discussion

The main findings of this study were decreases in nocturnal HRV and increases in nocturnal HR after the marathon and the moderate endurance exercise. The decreased nocturnal HRV after the moderate endurance exercise did not correlate with our hypothesis. This finding suggests that even an exercise session that was perceived as light and easy may have prolonged effects on nocturnal HRV during the succeeding night sleep. Furthermore, the absolute changes in nocturnal HFP after the exercise sessions were related to the nocturnal HFP after the resting day but neither of these was related to performance on marathon or VO_{2max}.

Previous findings of immediate or short-time recovery of HRV after exercise have showed that HRV recovers to the pre-exercise level in minutes after low-to moderate intensity exercise, but a significant delay in post-exercise HRV recovery has been observed following moderate- to high-intensity exercise [14, 15, 20, 28]. Only Hautala et al. [9] have studied nocturnal HRV changes after exercise and they reported decrease in normalized nocturnal HFP after a 75 km ski-race, and a similar, but non-significant trend in absolute HFP when compared to the night before the ski-race. However, the control measurements were done during the very last night before the ski-race and anticipatory mental stress might have influenced the HRV, as suggested by Hall et al. [7] The start of the ski-race was at 9 a.m. and, therefore, the subjects of Hautala et al. [9] had more time to recover after the race than the subjects of the present study. Also running vs. skiing difference may have had some effect on the responses, but on the other hand the ski-race had lasted for approximately 1 h longer than the marathon run in the present study. Decreased nocturnal HRV after the marathon in this study is in line with Furlan et al. [6], who reported decreased HRV 24 h after maximal exercise.

It was also hypothesized that nocturnal HRV would not be influenced by a moderate exercise session, but it was and the differences between moderate and heavy exercises suggest a dose-response relationship. Recently, Kaikkonen et al. [15] found that both increasing intensity and duration of the exercise reduces immediate post-exercise HRV more than moderate exercise session does. Furthermore, increasing the intensity reduced the HRV more than increase of the duration [15], which supports the present finding of the dose-response relationship of the exercise induced disturbance of homeostasis and HRV during recovery. Seiler et al. [28] proposed the first ventilatory threshold as a threshold for perturbation of autonomic nervous system. The first ventilatory threshold was actually the upper limit for the moderate exercise session in the present study, but still attenuated HRV was found. The subjects in the Seiler et al. [28] study, however, were more fit than the present subjects, which may have speeded up the rate of recovery. In another study on high level endurance athletes, there was no difference in nocturnal LFP and HFP after easy and hard training days but approximately 7% higher nocturnal HR after hard training in comparison to easy training days [10]. Intensity of exercise seems to be a key factor in the disturbance of homeostasis, as also nocturnal levels of testosterone have been found to decrease and nocturnal profiles of growth hormone and cortisol concentrations to change with increasing intensity of daytime exercise [16]. Furthermore, excess post-exercise oxygen consumption has been suggested to reflect the exercise induced disturbance of homeostasis [3], and it is strongly dependent on the intensity of the exercise. This is probably due to physiological changes that persist to recovery including "elevation in tissue temperatures, changes in intra- and extracellular ion concentrations, and changes in metabolite and hormone levels", as the authors state [3]. These same changes were most probably persistent during nocturnal rest in the present study leading to decreased nocturnal HRV. As discussed earlier, responses of nocturnal HRV after exercise sessions have a dose-response relationship. Therefore, nocturnal HRV may give information on the power of the disturbance of homeostasis, not only information on whether the disturbance is evident or not.

The marathon run was selected to find out the upper limits of changes induced by a single exercise session. The results showed decreases in nocturnal HRV indices together with increased nocturnal HR as hypothesized. Average percentage changes in HRV seemed to be substantially greater than in HR which supports the findings of previous literature [23] suggesting that HRV has higher sensitivity in revealing the changes in autonomic modulation. When compared to previous literature on nocturnal HRV during different training periods [10, 23, 24], the present decreases of up to 66% in nocturnal HFP seem to be the greatest ever reported. In the study of Pichot et al. [23], there were also some great decreases in nocturnal HRV during the intensive training period of middle-distance runners, but the greatest changes were between 40 and 50% when compared to the beginning of the training period or to the resting values after recovery from the training period. Also in the Hynynen et al. [10] study, the nocturnal HFP was found to be decreased by approximately 40% in overreached state in comparison to well recovered state. In the Pichot et al. [23] study no VO_{2max} results were reported, but the studied athletes were ranked at the national level in France. As mentioned above, high physical fitness may speed up the rate of the recovery. Interestingly the findings of Hautala et al. [9] indicated only a non-significant 10% decline in nocturnal HFP after the 75 km ski-race. This small difference is hard to explain and further studies on nocturnal HRV after different exercises are needed.

The results showed that the greater the nocturnal HFP was in non-stressed condition (after the resting day), the greater were the responses to the stress (decrements in nocturnal HFP) after the moderate and heavy exercise sessions. These results support the previous literature on "autonomic resource hypothesis" [11, 25]. In other words, the amount of the adaptability of the autonomic nervous system, and especially the parasympathetic branch, varied between individuals as a function of their resources. The adaptation process itself, however, was similar between different individuals regardless of nocturnal HFP after resting day, since the nocturnal HFP after the resting day was not related to the relative changes of nocturnal HFP. It remains unclear what the benefit of these greater resources and responses is, since these autonomic responses were not related to the absolute performance in marathon running. Further, the differences in the aerobic capacity of the subjects were not related to the nocturnal HRV, suggesting that this autonomic resource is also dependent on some other things than physical fitness. Previously, HRV response in a cognitive test was found to be related to performance in that test, and these responses were higher in the group of control athletes when compared to overtrained athletes. There was no physical perfomance to compare with HRV or HRV responses, but the control athletes had higher HRV and higher VO_{2max} than the overtrained [11].

Interpretation of the results

The substantial decreases in nocturnal HRV indices together with remarkably increased nocturnal HR suggested powerful disturbance of autonomic nervous system equilibrium after both exercises. The changes of up to 66% in HRV after the marathon run also indicate a great adaptability of the autonomic nervous system. Sensitivity of nocturnal HRV to detect exercise induced changes in autonomic modulation seemed to be higher than the sensitivity of HR. Parasympathetic reactivation is usually fast after cessation of exercise and sympathetic activation attenuates more slowly [14, 15, 20, 28], which could have meant slightly sustained sympathetic activation during night sleep after exercise sessions. Decreased HRV during rest, however, is interpreted mainly as parasympathetic withdrawal with possibly increased sympathetic activation [19, 30]. Furthermore, HRV after marathon was found to be attenuated also after removing the HR dependency of HRV by using CVRRI. Therefore these findings could be interpreted to suggest prolonged parasympathetic withdrawal during the nocturnal sleep after moderate and especially after heavy endurance exercises. This is, however, based totally on HR and HRV findings, as we did not measure other variables, like body temperature, hormone secretions etc.

Practical considerations

The findings of this study may be useful in planning training programs and evaluating the training induced disturbance to homeostasis and, consequently, training effect of a single exercise. Kiviniemi et al. [17] were the first to use HRV measurements in the morning to tailor individual training program in a very successful way. Analyzing nocturnal HRV, however, has special benefits, as it does not require any special test and it has some independence of external disturbance, as night sleep is a kind of a controlled situation [12, 13, 18, 23]. As even the moderate exercise session, experienced as a light one, resulted in a slight disturbance in the equilibrium of nocturnal autonomic modulation, it is possible that these kinds of moderate exercise sessions are important not only as an active recovery or warm-up [1], but also to achieve a training effect. Therefore, it should be recognized, that an athlete's own perception is not always right. If the exertion of exercise sessions is underestimated, the risk of overreaching-overtraining may increase. With the help of nocturnal HRV analysis, the training programs may be adjusted individually. Based on the scientific literature and "best practice", the subject's physical fitness may have an effect on the required intensity and volume of training to achieve a training effect. The higher level athletes seem to need higher intensities to further improve their VO_{2max} [21], but on the other hand, they seem to train the highest volume at low intensities [2, 5, 27]. Even though VO_{2max} is an important factor in endurance capacity, it is not the only one, and also low- to moderate-intensity exercises may have an essential role in the training of endurance athletes.

RRI collection can be easily done with modern HR recording belts or wrist computers and HRV softwares are also easily available. Even though the greatest changes in nocturnal HRV, or the best sensibility, were found in HFP, also simpler calculations may give the same information. SDNN and RMSSD can be calculated quite easily without special software, and therefore this information is available practically for any active exerciser, athlete or coach.

Conclusions

Both moderate exercise session and marathon led to decreased nocturnal HRV and increased nocturnal HR in ten healthy, physically active men when compared to nocturnal HRV and HR after a rest day. These findings extend previous knowledge on acute HRV responses to stress of physical exercise indicating prolonged parasympathetic withdrawal hours after the effect of the stressor itself had ceased. Responses found in the present study had a dose-response relationship, which may be applied in practice by physically active persons, athletes and coaches in evaluating the amount of disturbance of homeostasis induced by different training sessions.

References

1 *American College of Sports Medicine (ACSM).* ACSM's guidelines for exercise testing and prescription 8th edition. Philadelphia: Lippincott Williams & Wilkins; 2009; 152–182

2 *Billat VL, Demarle A, Slawinski J, Paiva M, Koralsztein J-P.* Physical and training characteristics of top-class marathon runners. Med Sci Sports Exerc 2001; 33: 2089–2097

3 *Brooks G, Fahey T.* Exercise Physiology; Human Bioenergetics and its Applications. New York: Macmillan Publishing Company; 1985; 191–202

4 *Brosschot J, van Dijk E, Thayer J.* Daily worry is related to low heart rate variability during waking and the subsequent nocturnal sleep period. Int J Psychophysiol 2007; 63: 39–47

5 *Esteve-Lanao J, San Juan AF, Earnest CP, Foster C, Lucia A.* How do endurance runners actually train? Relationship with competition performance. Med Sci Sports Exerc 2005; 37: 496–504

6 *Furlan R, Piazza S, Dell'Orto S, Gentile E, Cerutti S, Pagani M, Malliani A.* Early and late effects of exercise and athletic training on neural mechanisms controlling heart rate. Cardiovasc Res 1993; 27: 482–488

7 *Hall M, Vasko R, Buysse D, Ombao H, Chen Q, Cashmere JD, Kupfer D, Thayer JF.* Acute stress affects heart rate variability during sleep. Psychosom Med 2004; 66: 56–62

8 *Harriss DJ, Atkinson G.* International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. Int J Sports Med 2009; 30: 701–702

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

10 *Hynynen E, Nummela A, Rusko H, Hämäläinen I, Jylhä R.* Effects of training on cardiac autonomic modulation during night sleep in cross country skiers. In: Linnamo V, Komi PV, Müller E. (eds.). Science and Nordic Skiing. Meyer & Meyer Sport (UK) Ltd; 2007; 90–98

11 *Hynynen E, Uusitalo A, Konttinen N, Rusko H.* Cardiac autonomic responses to standing up and cognitive task in overtrained athletes. Int J Sports Med 2008; 29: 552–558

12 *Hynynen E, Uusitalo A, Konttinen N, Rusko H.* Heart rate variability during night sleep and after awakening in overtrained athletes. Med Sci Sports Exerc 2006; 38: 313–317

13 *Jeukendrup A, Hasselink M, Snyder A, Kuipers H, Keizer H.* Physiological changes in male competitive cyclists after two weeks of intensified training. Int J Sports Med 1992; 13: 534–541

14 *Kaikkonen P, Rusko H, Martinmäki K.* Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions. Scand J Med Sci Sports 2008; 18: 511–519

15 *Kaikkonen P, Hynynen E, Mann T, Rusko H, Nummela A.* Can HRV be used to evaluate training load in constant load exercises? Eur J Appl Physiol 2009, DOI 10.1007/s00421-009-1240-1

16 *Kern W, Perras B, Wodick R, Fehm HL, Born J.* Hormonal secretion during nighttime sleep indicating stress of daytime exercise. J Appl Physiol 1995; 79: 1461–1468

17 *Kiviniemi AM, Hautala AJ, Kinnunen H, Tulppo M.* Endurance training guided individually by daily heart rate variability measurements. Eur J Appl Physiol 2007; 101: 743–751

18 *Lehmann M, Dickhuth H, Gendrisch G, Lazar W, Thum M, Kaminski R, Aramendi JF, Peterke E, Wieland W, Keul J.* Training – overtraining: a prospective, experimental study with middle-and long-distance runners. Int J Sports Med 1991; 12: 444–452

19 *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: H640–H647

20 *Martinmäki K, Rusko H.* Time-frequency analysis of heart rate variability during immediate recovery from low and high intensity exercise. Eur J Appl Physiol 2008; 102: 353–360

21 *Midgley AW, McNaughton LR, Wilkinson M.* Is there an optimal training intensity for enhancing the maximal oxygen uptake of distance runners? Sports Med 2006; 36: 117–132

22 *O'Connor PJ, Youngstedt SD.* Influence of exercise on human sleep. Exerc Sport Sci Rev 1995; 23: 105–134

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

24 *Pichot V, Busso T, Roche F, Garet M, Costes F, Duverney D, Lacour JR, Barthélémy JC.* Autonomic adaptations to intensive and overload training periods: a laboratory study. Med Sci Sports Exerc 2002; 34: 1660–1666

25 *Porges SW.* Vagal tone: a physiological marker of stress vulnerability. Pediatrics 1992; 90: 498–504

26 *Rusko H.* Training for cross country skiing. In: Rusko H. (ed). Cross Country Skiing. Malden, MA, USA: Blackwell Science; 2003; 62–65

27 *Seiler KS, Kjerland GØ.* Quantifying training intensity distribution in elite endurance athletes: is there evidence for an "optimal" distribution? Scand J Med Sci Sports 2006; 16: 49–56

28 *Seiler S, Haugen O, Kuffel E.* Autonomic recovery after exercise in trained athletes: Intensity and duration effects. Med Sci Sports Exerc 2007; 39: 1366–1373

29 *Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology.* Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. Circulation 1996; 93: 1043–1065

30 *Uusitalo ALT, Tahvanainen KUO, Uusitalo AJ, Rusko HK.* Non-invasive evaluation of sympathovagal balance in athletes by time and frequency domain analyses of heart rate and blood pressure variability. Clin Physiol 1996; 16: 575–588

31 *Youngstedt SD, Kripke DF, Elliott JA.* Is sleep disturbed by vigorous late-night exercise? Med Sci Sports Exerc 1999; 31: 864–869