Changes in cardiac autonomic regulation after prolonged maximal exercise

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Summary

Harmful cardiac events occurs frequently after exercise. However, the cardiac autonomic regulation after vigorous exercise is not well known. This study was designed to assess heart rate (HR) variability before and after a 75 km cross-country skiing race. HR variability was assessed by using standard statistical measures along with spectral and quantitative Poincarè plot analysis of HR variability in 10 healthy male subjects (age 36 ± 11 years). The average HR was at the same level 1 day after the race as before the race, but on the second day, HR was significantly lower ($P<0{\cdot}001$) compared with the prerace and 1 day after values. The normalized high-frequency (HF) spectral component of HR variability (nuHF) was lower ($P<0{\cdot}01$) on the first day after the maximal exercise compared with the pre-exercise values but returned to or even exceeded the prerace level on the second day ($P<0{\cdot}01$). The changes in short-term R-R interval variability analysed from the Poincaré plot were similar to those observed in the HF spectral component. The normalized low-frequency (LF) spectral component of HR variability (nuLF) was higher ($P<0{\cdot}01$) on the first day after the exercise compared with the prerace levels and it also returned to the pre-exercise level or even dropped below it on the second day after the race. The mean time it took the HF spectral component to return to the pre-exercise level was 4·2 ± 4·2 h (ranging from 0 to 12 h). This recovery time correlated inversely with the maximal oxygen consumption ($V\!O_{2max}$) measured during the bicycle exercise test before the skiing race ($r = -0{\cdot}712$, $P<0{\cdot}016$). The cardiac vagal outflow is blunted for several hours after prolonged vigorous exercise. The recovery time of reduced vagal outflow depends on individual cardiorespiratory fitness and there is an accentuated rebound of altered autonomic regulation on the second day after prolonged exercise.

Keywords: heart rate variability, long-term exercise, recovery.

Introduction

Several studies have addressed the issue of changes in cardiac autonomic regulation during physical exercise (Goldsmith *et al.*, 1992; De Meersman, 1993; Tulppo *et al.*, 1996, 1998; Iellamo *et al.*, 1999). However, harmful cardiac events, e.g. acute myocardial infarction, occurs during and after exercise (Siscovick *et al.*, 1984; Gibbons *et al.*, 1989; Willich *et al.*, 1993). Also a delayed recovery of heart rate (HR) after maximal exercise is a powerful predictor of overall mortality among population based data (Cole *et al.*, 1999). Recovery of autonomic regulation of HR has been proposed to occur within a few minutes after about 20 min short-term maximal exercise (Arai *et al.*, 1989), but there is no data on the changes and recovery time of cardiovascular autonomic function

after prolonged exercise. Therefore, this study was designed to assess the changes in cardiac autonomic regulation after prolonged exhaustive exercise. For this purpose, 24-h HR variability was measured by traditional statistical measures, spectral analysis and two-dimensional vector analysis of Poincaré plots before maximal exercise in the form of a 75 km cross-country skiing race and subsequently for 48 h after the race.

Methods

Subjects

Ten male volunteers (age 36 ± 11 years, weight 75 ± 8 kg, height 176 ± 6 cm) participated in the study. All the subjects were healthy and none were taking any medication. The subjects had participated regularly in aerobic training at least four times per week during the last 3 months. The characteristics of the subjects are presented in Table 1. The study protocol was approved by the ethics committee of the Merikoski Rehabilitation and Research Center, and all subjects gave their informed consent.

Procedure

Measurements of maximal O_2 consumption ($\dot{V}O_{2max}$) were performed 1–2 weeks before the 75 km cross-country skiing race. The subjects were not allowed to eat or drink coffee for 4 h before the test, and vigorous exercise and alcohol were forbidden for 48 h before the day of testing. All the tests were performed between 8 a.m. and 2 p.m. Measurements of oxygen consumption and HR responses were made during an incremental bicycle exercise test. HR responses were also measured during the skiing race. HR variability was measured for 24 h before the 75-km skiing race and, subsequently, for 48 h after the exercise.

Table 1 Characteristics of the subjects (n=10).

	Mean ± SD	Minimum	Maximum
Age (years)	36·2 ± 10·6	22	55
Height (cm)	175·8 ± 5·5	166	185
Weight (kg)	74·8 ± 7·8	64	86
Body fat (%)	13·0 ± 3·6	9	17
Blood pressure at rest (mmHg)			
Systolic	137 ± 17	112	168
Diastolic	81 ± 6	72	90
$\dot{V}O_{2max}$			
l min^{-1}	3·8 ± 0·6	3·0	4·8
ml kg^{-1} min^{-1}	51·0 ± 6·0	39·5	58·6

$\dot{V}O_{2max}$: maximal O_2 consumption.

Measurement of maximal O_2 consumption

The subjects performed a graded maximal exercise test on a bicycle ergometer (Ergomedic 818 E, Monark Exercise, Varberg, Sweden), starting at 50 W and following an incremental protocol with the work rate increasing at a rate of 25 W at every 3 min until voluntary exhaustion. Ventilation (VE), gas exchange (M909 ergospirometer, Medikro, Kuopio, Finland) and HR responses (Polar Sport Tester, Polar Electro, Kempele, Finland) were monitored continuously. A continuous surface electrocardiogram was also recorded during the experiment to confirm the sinus origin of the beats (Nihon Kohden, TEC-7100, Japan). VE and gas exchange were calculated on a breath-by-breath basis, but were reported as mean values for 30 s. The criteria used to document that the $\dot{V}O_{2max}$ had been attained during each test were: (i) a lack of increase in oxygen consumption upon an increase in work rate and (ii) a respiratory exchange ratio >1·1 (Shephard & Åstrand, 1992).

Measurement and analysis of HR variability

R-R intervals were recorded for 24 h before the maximal exercise and continuously for 48 h afterwards (Polar R-R Recorder, Polar Electro, Kempele, Finland) with an resolution of 1 ms (Ruha *et al.*, 1997) and saved in a computer for further analysis of HR variability (Heart Signal Co., Oulu, Finland). All HR variability analyses were made from the recordings obtained 24 h before and 48 h after the maximal exercise. In addition, the analyses were made between 5 p.m. and 4 a.m. (average of 11 h) before and after the race and separately 1-h segments. The competitors woke up early on the morning of the race, which started at 9 a.m. and lasted for about 5 h. Therefore, the physical activity and sleep–awake stage were comparable between the average 11-h periods starting at 5 p.m. and between the 1-h segments during the

days before and after the race. A period of 4 h of sleep (0–4 a.m.) was analysed separately as well because the level of physical activity is largely standardized during sleep (Pikkujämsä *et al.*, 1999). During the measuring days the subjects were asked to go to bed not later than 11 p.m. The R-R interval series was passed through a filter to eliminate undesirable premature beats and noise. An R-R interval was interpreted as a premature beat if it deviated from the previous qualified interval by >30%. All the R-R intervals were edited first automatically and then by visual inspection to exclude all the undesirable beats which accounted for <2% in each case. The details of this analysis and the filtering technique have been described previously (Huikuri *et al.*, 1992, 1993).

An autoregressive model was used to estimate the power spectrum densities of R-R interval variability (Goldsmith *et al.*, 1992; Huikuri *et al.*, 1993). The power spectrum was quantified by measuring the area under two frequency bands: low-frequency (LF) power from 0·04 to 0·15 Hz and high-frequency (HF) power from 0·15 to 0·4 Hz. The LF and HF components were computed from segments of 512 R-R intervals and the average values of the entire 24-h recording interval were calculated for these components and separately for the 1-h periods (Task Force, 1996). The spectral components of HR variability were analysed both as absolute units (ln) and as normalized units (nu) (Malliani *et al.*, 1997). The ratio between LF and HF power was calculated as well. The recovery times of nuHF, nuLF and SD1 were determined by comparing the 95% values of the prerace level hour-by-hour to the values recorded on the first recovery day. The recovery time was expressed as hours when the 95% level of prerace hour-by-hour values was reached after the exercise.

Two-dimensional return maps of Poincaré plots were generated by plotting each R-R interval as a function of the preceding R-R interval obtained from the 24-h periods before the race and on the 2 days following it. Poincaré plots were also separately analysed for the time period from 5 p.m. to 4 a.m. (average of 11 h) and separately in 1-h segments before the exercise and after the race. The analysed 1-h periods consisted of about 3600–5000 qualified beats (99% beats accepted for analysis). Two-dimensional vector analysis was used to quantify the shape of the plots as described previously (Huikuri *et al.*, 1996; Tulppo *et al.*, 1996). This quantitative method quantifies separately the instantaneous R-R interval variability (SD1) and the long-term R-R interval variability (SD2) of the plot.

Statistical methods

Analysis of variance for repeated measurements was used to compare the changes in normally distributed measures of HR variability. Normal Gaussian distribution of the data was verified by the Kolmogorov–Smirnov goodness-of-fit test. In the light of the Kolmogorov–Smirnov test (z-value > 1·0), a logarithmic transformation to the natural base was performed on the absolute values of the power spectral components. Differences in HR variability indices between the prerace day, the first day following the race and the second day following the race were compared by using analysis of variance of repeated measurements. The differences between the hourly values of HR indices before and after the race were tested for significance using paired t-test with Bonferroni correction (Altman, 1991). The statistical significance level was set at $P<0·01$. Pearson's correlation coefficients were used to estimate the bivariate correlations between the recovery parameters (nuHF, lnHF, nuLF, SD1), VO_{2max}, mean R-R interval on prerace day, age, maximal work load in the bicycle ergometer test, cardiac strain and skiing time. Cardiac strain was the percentage level of 1 h average HR in the middle of skiing race compared with maximal HR measured during the maximal bicycle ergometer test.

Results

The average skiing time of the nine subjects who covered the full 75 km distance was 4 h and 31 ± 45 min and the corresponding cardiac strain (161 ± 13 beats min^{-1}) was 87 ± 2·8% of the individual maximal HR (186 ± 13 beats min^{-1}) measured during the bicycle ergometer test. One subject was excluded from the final analysis because of technical artefacts. No significant changes were observed in the mean R-R interval 1 day after (964 ± 116 vs. 949 ± 138, ns) compared with the mean R-R interval before the skiing race, but 2 days after the race the mean R-R interval (1051 ± 153) was longer ($P<0·001$) compared with the prerace and the 1 day after values

(Table 3). Representative examples of R-R interval time series, spectral characteristics and Poincaré plots (from 3 to 4 a.m.) before the race, 1 day after and 2 days after the skiing race are shown in Fig. 1. The SD of all R-R intervals (SDNN) was at same level on the first day after the race as during the prerace day (126 ± 28 vs. 103 ± 35, ns) and returned to the prerace level on the second day (123 ± 36, $P<0{\cdot}01$) after the exercise (Table 2).

The nuHF was lower ($P<0{\cdot}01$) on the first day from midnight to 2 a.m. after the exercise compared with the pre-exercise value but returned to or even exceeded the prerace level on the second day from 6 p.m. to 4 a.m. ($P<0{\cdot}01$) (Fig. 2a, Table 2). The lnHF also showed a non-significant declining trend on the first day after the race (5·32 ± 1·17) compared with the prerace level (6·02 ± 077) and it was significantly higher ($P<0{\cdot}01$) on the second (6·26 ± 0·73) than the first day after the race (Table 3). The nuLF was higher ($P<0{\cdot}01$) at 10 p.m. and 2 a.m. on the first day after the exercise compared with the same time on the day preceding the race and it also returned to the pre-exercise level or even dropped below it between 6 and 10 p.m. and between 2 and 4 a.m. ($P<0{\cdot}01$) (Fig. 2b, Table 2). The LF/HF ratio behaved analogously to the normalized LF component (Table 2).

Instantaneous beat-to-beat R-R interval variability (SD1) showed similar changes as the HF spectral components of HR variability. During the sleep time, SD1 showed a declining trend on the first day (30 ± 11) compared with the prerace day (40 ± 22) (see Fig. 2c), but returned to or even exceeded the prerace level (second day vs. first day, $P<0{\cdot}01$) on the second day (45 ± 16) (Table 2, Fig. 2c).

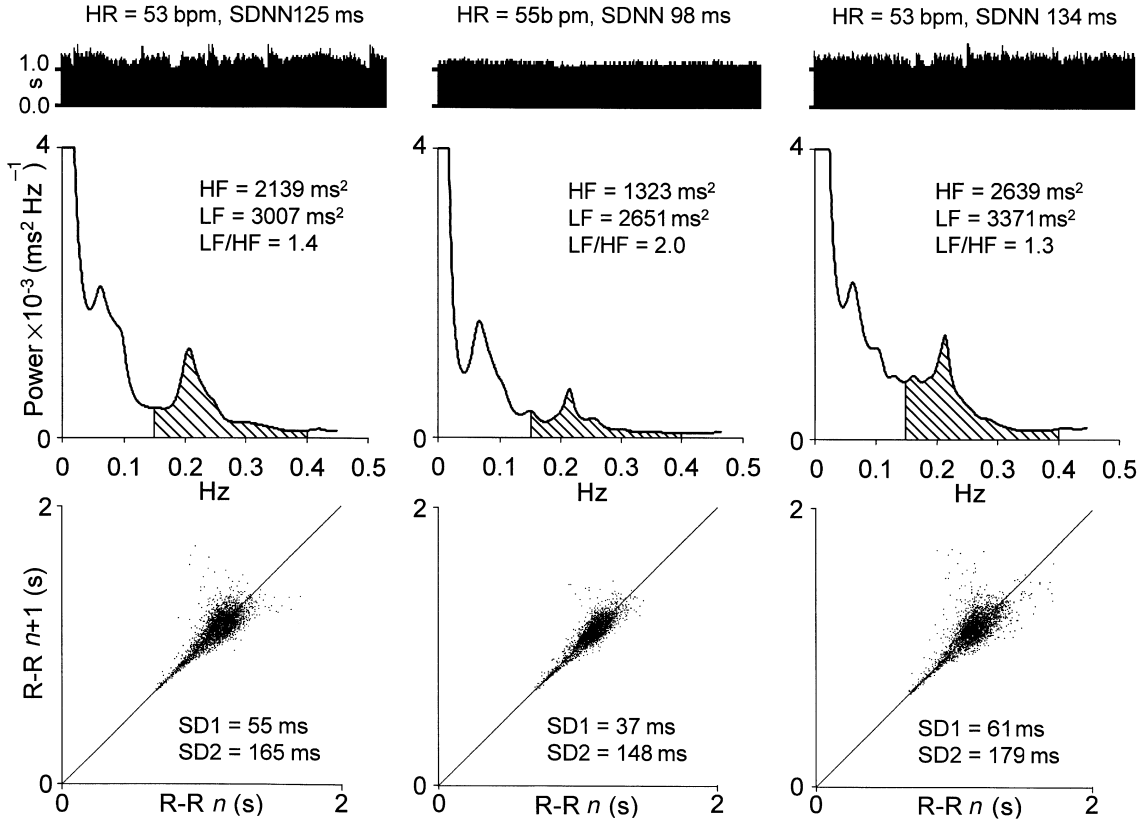

Figure 1 Representative examples of tachograms (*upper panels*), power spectra (*middle panels*) and Poincaré plots (*lower panels*) before (*left side*), first night (*middle*) and second night (*right side*) after the race. The average HR do not differ significantly after the race. However, the vagally mediated HF power is decreased and sympatho-vagal balance, expressed as LF/HF ratio, is markedly increased after the race at night. Values at night are from 3 to 4 a.m. in all cases.

Table 2 R-R interval measurements 11 h before (prerace day) and after (1 day after and 2 days after) maximal 75 km cross-country skiing.

	Mean ± SD		
	Prerace day	**1 Day after**	**2 Days after**
Mean R-R interval (ms)			
5 p.m.–4 a.m.	964 ± 116	949 ± 138	1051 ± 153(b)**
0–4 a.m.	1096 ± 111	1028 ± 112	1142 ± 149(b)*
SDNN (ms)			
5 p.m.–4 a.m.	117 ± 22	97 ± 39	126 ± 33(b)*
0–4 a.m.	126 ± 28	103 ± 35	123 ± 36
lnHF			
5 p.m.–4 a.m.	6·02 ± 0·77	5·32 ± 1·17	6·26 ± 0·73(b)*
0–4 a.m.	6·53 ± 1·28	5·90 ± 0·96	6·86 ± 0·80
nuHF			
5 p.m.–4 a.m.	45·2 ± 2·0	43·3 ± 2·8	46·3 ± 1·5(a)*,(b)*
0–4 a.m.	46·3 ± 3·1	44·1 ± 3·7	47·2 ± 1·9(b)*
lnLF			
5 p.m.–4 a.m.	7·35 ± 0·49	7·05 ± 0·77	7·41 ± 0·59
0–4 a.m.	7·47 ± 0·69	7·36 ± 0·39	7·67 ± 0·77
nuLF			
5 p.m.–4 a.m.	54·8 ± 2·0	56·7 ± 2·8	53·7 ± 1·5(a)*,(b)*
0–4 a.m.	53·7 ± 3·1	55·9 ± 3·7	52·8 ± 1·9(b)*
LF/HF-ratio			
5 p.m.–4 a.m.	1·22 ± 0·10	1·33 ± 0·18	1·16 ± 0·07(a)*,(b)*
0–4 a.m.	1·17 ± 0·15	1·30 ± 0·25	1·12 ± 0·08
SD1 (ms)			
5 p.m.–4 a.m.	26 ± 9	23 ± 20	31 ± 13
0–4 a.m.	40 ± 22	30 ± 11	45 ± 16(b)*
SD2 (ms)			
5 p.m.–4 a.m.	170 ± 41	135 ± 53	173 ± 44
0–4 a.m.	194 ± 53	143 ± 48	167 ± 49

Values are mean ± SD. Mean R-R interval, average of lengths of R-R intervals; SDNN, SD of all R-R intervals during the recording; HF, high frequency power component of HR variability; LF, low frequency power component of HR variability; ln, logarithm to the natural base of the absolute value; nu, normalized unit; SD1, instantaneous beat-to beat RR interval variability; SD2, continous beat-to-beat R-R interval variability. *P<0·01; **P<0·001, significance levels with paired t-test with Bonferroni correction for differences between the days (a) prerace day vs. 2 days after and (b) 1 day after vs. 2 days after.

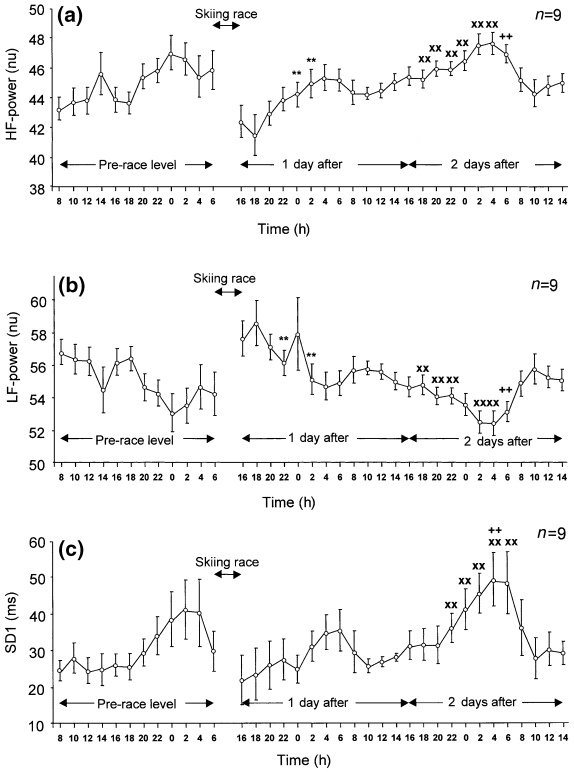

Figure 2 Changes in HR variability in 2-h periods on the prerace day and 1 day and 2 days after the skiing race. (a) Changes in the high-frequency spectral analysis (HF power (nu)), (b) changes in the low-frequency spectral analysis (LF power (nu)) and (c) changes in instantaneous beat-to-beat R-R interval variability (SD1). The values are mean ± SEM. Significance levels with paired t-test with Bonferroni correction between the days are as follows: **P<0·01 prerace day vs. 1 day after, ^{++}P<0·01 prerace day vs. 2 days after, ^{xx}P<0·01 one day after vs. two days after.

The mean time in which the nuHF spectral component was restored to the pre-exercise level was 4·2 ± 4·2 h. Large interindividual variation was observed in the recovery time of nuHF (ranging from 0 to 12 h). An inverse correlation was observed between the recovery time of nuHF and the maximal oxygen consumption analysed from the bicycle exercise test ($r = -0.712$, P<0·016) (Fig. 3, Table 3). The mean recovery of the lnHF spectral component to the prerace level took 8·2 ± 5·4 h. Large interindividual variation was also observed in the recovery time of lnHF (ranging from 0 to 14 h). Analogous to the recovery times of nuHF and lnHF, large interdividual variation was observed in the recovery time of SD1 (mean 9·8 ± 8·8 h, ranging from 0 to 22 h). A mutual correlation between the recovery time of nuHF and the recovery time of SD1 ($r = 0·745$, P<0·02) was observed. The recovery time of SD1 also correlated strongly with the recovery time of lnHF ($r = 0·900$, P<0·001).

Table 3 Correlation coefficients among recovery parameters (nuHF, SD1 and nuLF), VO_{2max}, age, maximal work load in bicycle exercise test, mean R-R interval on prerace day, cardiac strain during the skiing race and skiing time.

	After the prolonged exercise		
	nuHF	**SD1**	**nuLF**
VO_{2max} (ml kg^{-1} min^{-1})	−0·712 (P < 0·016)	−0·474 (P < 0·117)	0·376 (P < 0·160)
Mean R-R interval on prerace day (ms)	−0·191 (P < 0·311)	−0·093 (P < 0·414)	0·339 (P < 0·186)
Age (years)	0·207 (P < 0·269)	−0·029 (P < 0·473)	−0·298 (P < 0·218)
Maximal work load (W) in bicycle exercise test	−0·271 (P < 0·240)	−0·368 (P < 0·185)	0·373 (P < 0·162)
HR_{max} (%)	0·187 (P < 0·315)	0·568 (P < 0·071)	−0·149 (P < 0·351)
Skiing time (min)	0·369 (P < 0·164)	0·099 (P < 0·408)	−0·104 (P < 0·396)

Values are Pearson's correlation coefficients, n=9; nuHF, value in hours when the 95% level of prerace hour-by-hour values is reached; SD1, value in hours when the 95% level of prerace hour-by-hour values is reached; nuLF, value in hours when the 95% level of prerace hour-by-hour values is reached; Hr_{max} (%), percentage level of HR during the skiing race compared with maximal HR measured during the maximal bicycle ergometer test.

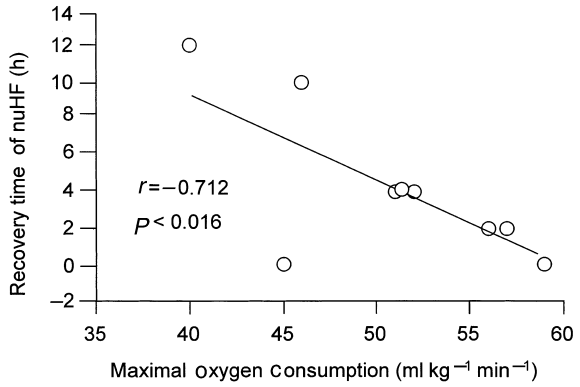

Figure 3 Correlation coefficient between recovery time of nuHF (h) and maximal oxygen consumption (ml kg^{-1} min^{-1}). Spearman's correlation coefficient is given.

Discussion

Spectral and Poincaré plot analyses of HR variability showed that HF oscillations of HR, which reflect the cardiac vagal outflow are attenuated for several hours after the exercise. On the second day after the race, however, an accentuated rebound phenomenon was observed with enhanced vagal regulation compared with the pre-exercise level. Wide interindividual variations were observed at the time of recovery of the reduced vagal outflow, so that the subjects with better cardiorespiratory fitness had a more rapid recovery of altered autonomic function than those with poorer fitness. The results of this study provide novel information about cardiac autonomic regulation after prolonged heavy exercise.

Cardiac autonomic regulation after physical exercise

There has been relatively little information on the recovery of cardiovascular autonomic function after various types of physical exercise. Arai *et al.* (1989) assessed the dynamics of autonomic nervous activity during and after a maximal bicycle exercise test by measuring the power spectrum of HR variability. The recovery data were collected 9 min after the exercise test. They found a marked reduction in the absolute LF power of HR variability during the exercise with a return to the baseline within few minutes after the exercise. Similar changes were observed in the HF power spectral component after the exercise. However, the effects of long-term maximal exercise on cardiovascular regulation may be different compared with those during the short-term exercise. To our knowledge, no previous studies have assessed the cardiac autonomic function after long-term heavy exercise.

The changes in cardiovascular autonomic function probably reflect a compensation for altered cardiovascular haemodynamics after exercise. Previous studies have shown that the left ventricular systolic function and the cardiac filling patterns are altered for a long time after prolonged exhaustive exercise (Niemelä *et al.*, 1984; Douglas *et al.*, 1987). More sympathetic drive may be needed to compensate for the reduced cardiac performance, to maintain the effective cardiac output and to activate sufficient blood flow. After the haemodynamics and cardiac function have returned to normal, sympathetic drive

decreases and vagal dominance returns. It is also evident that these compensatory autonomic responses are protective during the recovery phase of normal cardiovascular homeostasis after prolonged exercise.

Effects of cardiorespiratory fitness

The altered sympatho-vagal balance returned to the baseline level earlier in the subjects with better cardiorespiratory fitness. It is widely accepted that good physical fitness and regular exercise training induce adaptation of the autonomic nervous system, which is most commonly observed in the form of a decrease in the basal HR. It is assumed that cardiac vagal tone increases in well-trained individuals compared with sedentary controls (Katona *et al.*, 1982; Goldsmith *et al.*, 1992; De Meersman, 1993; Davy *et al.*, 1996). Recently, it was also observed that the vagal regulation of HR was higher during exercise in subjects with better exercise capacity (Tulppo *et al.*, 1998). The present observations highlight the importance of cardiovascular fitness in cardiovascular autonomic regulation, implying that also the rate of recovery of altered autonomic regulation after prolonged exercise is related to individual fitness.

Rebound phenomenon

A rebound of reduced vagal outflow was observed on the second day after the prolonged exercise. The HR variability indices actually differed most prominently between the first and second days after the race. A rebound effect has been previously described after short-term exercise by Arai *et al.* (1989), who found a return in the HF spectral component during the early recovery above the levels observed late after the recovery, suggesting a 'hypervagal' phase.

The precise mechanism behind the rebound effect of cardiac autonomic function is unclear. One possibility is that the pre-exercise mental excitement may have some influence on the autonomic regulation. In this case, the measures of cardiac autonomic function obtained several days earlier or after the exercise may better reflect the normal baseline autonomic regulation of each subject. More experimental work with different study designs will be needed to verify the physiological background for this effect.

Implications

Experimental data have shown that vagal activation prevents ischaemia-induced ventricular fibrillation after exercise (Schwartz *et al.*, 1984; Bilmann & Hoskins, 1989; Vanoli *et al.*, 1991), and that exercise training confers anticipatory protection from sudden death by enhancing cardiovascular vagal function (Hull *et al.*, 1994). Sudden cardiac deaths have also been reported after prolonged exercise and sports activities (Zipes & Wellens, 1998). The present data indicate that the possible cardioprotective effects of cardiac vagal regulation are diminished for a long time after a period of heavy exercise, and that the vagal outflow is reduced for an even longer time in the subjects with poorer cardiovascular fitness. Further research may be needed to find out whether these changes in autonomic regulation have any importance for the occurrence of cardiac events in individuals with an increased risk for such events.

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