Nocturnal Heart Rate Variability Following Supramaximal Intermittent Exercise

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Purpose: To assess the effect of supramaximal intermittent exercise on long-term cardiac autonomic activity, inferred from heart rate variability (HRV).

Methods: Eleven healthy males performed a series of two consecutive intermittent 15-s runs at 95% VIFT (i.e., speed reached at the end of the 30-15 Intermittent Fitness Test) interspersed with 15 s of active recovery at 45% VIFT until exhaustion. Beat-to-beat intervals were recorded during two consecutive nights (habituation night and 1st night) before, 10 min before and immediately after exercise, as well as 12 h (2nd night) and 36 h (3rd night) after supramaximal intermittent exercise. The HRV indices were calculated from the last 5 min of resting and recovery periods, and the first 10 min of the first estimated slow wave sleep period.

Results: Immediate post-supramaximal exercise vagal-related HRV indices were significantly lower than immediate pre-supramaximal exercise values ($P < .001$). Most vagal-related indices were lower during the 2nd night compared with the 1st night (e.g., mean RR intervals, $P = .03$). Compared with the 2nd night, vagal-related HRV indices were significantly higher during the 3rd night. Variables were not different between the 1st and 3rd nights; however, we noted a tendency (adjusted effect size, aES) for an increased normalized high-frequency component ($P = .06$ and aES = 0.70) and a tendency toward a decreased low-frequency component ($P = .06$ and aES = 0.74).

Conclusion: Results confirm the strong influence of exercise intensity on short- and long-term postexercise heart rate variability recovery and might help explain the high efficiency of supramaximal training for enhancing indices of cardiorespiratory fitness.

Keywords: cardiac autonomic system, vagal-related HRV indices, autonomic recovery, cardiovascular adaptation, high-intensity exercise

Repeated intermittent supramaximal exercise training is an efficient training strategy for increasing both central and peripheral components of cardiorespiratory...
fitness.\textsuperscript{1,2} For example, sprint interval training has been shown to enhance central factors such as maximal oxygen uptake and stroke volume,\textsuperscript{2} as well as peripheral components, including resting muscle glycogen content, oxidative capacity, and buffering capacity.\textsuperscript{1} Another aspect that could be related to these enhancements that occur with supramaximal training could be the large perturbation of short- and long-term postexercise autonomic function.\textsuperscript{3} However, this response has been less described.

Heart rate (HR) variability (HRV) represents a simple, accessible, and noninvasive tool to investigate the short- and long-term effects of exercise on cardiac autonomic nervous system function.\textsuperscript{3,4} Beat-to-beat HR variations in the high-frequency ranges are thought to be related to parasympathetic activity under respiratory influences, whereas low-frequency oscillations are linked to both sympathetic and parasympathetic outflow.\textsuperscript{5} It is also now believed that overnight sleep measurements over a number of days are appropriate for the tracking of changes in HRV following exercise.\textsuperscript{6} Indeed, the monitoring of slow wave sleep episodes has been proposed as a relevant recording period for the assessment of autonomic activity because it offers a steady state free from body movements and environmental disturbance and a regular respiration frequency (spontaneously in the high-frequency range) and heart rate, as well as a more pronounced vagal tone compared with other sleep episodes or awake recordings.\textsuperscript{6}

Comparison of postexercise HRV over a continuum of exercise intensities suggests that anaerobic participation might be the main factor influencing short-term postexercise cardiac autonomic function (ie, in the early minutes of recovery).\textsuperscript{3} For example, Buchheit et al\textsuperscript{3} recently showed that short-term postexercise autonomic activity was impaired to the same degree following two different supramaximal exercise training programs that contained similar levels of anaerobic contribution: either short-term repeated sprint training or more prolonged “aerobic” high-intensity interval training.\textsuperscript{3} The long-term effects of submaximal or maximal exercise on autonomic activity have also been reported. These studies have shown that, following the initial decrease in the early hours after exercise, at least 24 to 72 hours may be required for HRV parameters to return to preexercise values.\textsuperscript{3,4,7–10} Nevertheless, there is limited data available describing the cardiac autonomic response following supramaximal exercise. Niewiadomski et al\textsuperscript{10} examined the time course of HRV indices after two successive Wingate exercises (all-out 30-s efforts).\textsuperscript{10} Although results suggested a comparable effect on the time course of long-term autonomic activity compared with a 30-min submaximal exercise bout (80% VO\textsubscript{2peak}; ie, peak oxygen consumption), the supramaximal exercise bout used in this study (total exercise time: 2 × 30 s = 1 min) is not one that would be typically used in an athletic training program (ie, > 8 to 10 min). Consequently, a more prolonged or repeated supramaximal exercise stimulus might induce a greater perturbation of autonomic activity (ie, delayed recovery).

In attempt to gain insight into the mechanisms underlying the high efficiency of supramaximal training, we investigated the short- and long-term changes in HRV indices observed immediately after a bout of supramaximal exercise training and during sleep over a two-night trial. We hypothesized that HRV, representative of cardiac autonomic function, would be perturbed for several days after exercise cessation.
Methods

Participants
Eleven healthy males (age 21.5 ± 2.5 y, stature 1.78 ± 0.06 m, mass 74.3 ± 7.9 kg, participating in 2 to 5 h of physical activity per week) volunteered for the study after providing written informed consent. All participants were familiar with exercise testing and supramaximal intermittent training and none were taking medication. The study conformed to the ethical guidelines outlined in the Declaration of Helsinki and was approved by the local human research ethics committee.

Study Overview
Participants exercised on two separate occasions. First, they performed an incremental intermittent aerobic test (30-15IFT)\textsuperscript{11} to determine peak oxygen uptake (VO\textsubscript{2peak}) and a reference velocity (VIFT) for the ongoing exercise session. Second, at least 5 days later they performed a supramaximal intermittent running exercise. Ambulatory HR recordings were carried out on the two nights preceding the supramaximal intermittent exercise (SIE) bout and on the two nights following the exercise day. All participants were asked to consume a last light meal at least 3 h before each test session and to refrain from smoking and consuming drinks containing caffeine.

Graded Maximal Aerobic Test
Participants performed the 30-15 Intermittent Fitness Test (30-15IFT; 30 s of running interspersed with 15 s of passive recovery),\textsuperscript{11} which is a graded intermittent shuttle field test aimed at assessing a reference maximal speed for intermittent running prescription. The test started at 8 km·h\textsuperscript{-1} and velocity increased linearly from 0.5 km·h\textsuperscript{-1} every stage (45 s) until exhaustion. The last fully completed stage was defined as the participants’ VIFT. This field test has been shown to be accurate for individualizing intermittent shuttle exercise.\textsuperscript{11}

Supramaximal Intermittent Exercise
Supramaximal intermittent exercise consisted of 15-s periods of running at 95% of VIFT—corresponding to an intensity of approximately 120% of the minimal velocity that elicits VO\textsubscript{2peak} (vVO\textsubscript{2peak}) determined during a continuous graded test\textsuperscript{11}—interspersed with 15 s of active recovery at an intensity corresponding to 45% VIFT. Participants performed two SIE sessions until exhaustion (S1 and S2) separated by 10 min of passive recovery in the sitting position. Participants were verbally encouraged and asked to run for as long as possible, and were considered exhausted when they could not accomplish the required distance on two consecutive occasions within the required time.

Cardiorespiratory Measurements
During the 30-15IFT, respiratory gas exchange values were measured breath by breath using a portable metabolic system (Cosmed K4b\textsuperscript{2}, Rome, Italy). Before
each test, the O₂ and CO₂ analyzers were calibrated using both ambient air and a
gas mixture of known O₂ and CO₂ concentrations. The calibration of the turbine
flow meter of the K4b² was carried out using a 3-L syringe (Quinton Instruments,
Seattle, WA). Peak VO₂ was defined as the highest attained in two consecutive 20-s
periods. Criteria used to determine whether VO₂peak had been attained included (1)
a respiratory exchange ratio > 1.1, (2) a lactate concentration > 9 mmol·L⁻¹, and
3) attainment of theoretical maximal HR (220 – age) ± 10 bpm.

Blood Lactate Concentration

Three minutes after the end of the 30-15IFT and after each SIE series, a fingertip
blood sample (5 µL) was collected to determine the blood lactate concentration
([La⁻]) using a portable analyzing system (Lactate Pro, Arkay Inc, Japan).

Heart Rate Measurements

Heart rate was continuously recorded (s810 heart rate monitor, Polar Electro,
Kempele, Finland) for 10 min before and after the SIE in the seated position.
Sleep recordings were made two nights before (one night for habituation and the
following night for baseline, 1st night) and two nights after SIE (2nd night and
3rd night). To improve signal quality, a conductive gel was applied to the belt’s
electrodes before participants went to bed. Recorded data were downloaded to a
computer using compatible Polar software (Polar Pro trainer 5.00.100, Polar Electro,
Kempele, Finland). All irregular heartbeats were visually identified and replaced
with interpolated adjacent RR interval values.

HRV Analysis

Short-term perturbations of the autonomic nervous system were assessed via HRV
indices calculated during the (stationary) last 5 min of the 10-min rest period before
the SIE (SIE−10) and compared with those values collected during the last 5 min
of the 10-min postexercise recovery (SIE+10; ie, from the 5th to the 10th min). Although breathing frequency is often controlled in HRV studies, we chose not to
control this in our participants, as we did not want to perturb the natural return of
HR to baseline. Nevertheless, respiratory rate was always in the high-frequency
range (>0.15 Hz).

Long-term autonomic nervous system recovery was assessed via evening
HRV indices. As previously reported, HRV was specifically analyzed during very
quiet periods of sleep, which we estimated to be a slow-wave sleep episode via the
overnight RR interval trend. Following the recommendations of Brandenberger et
al., analyzed RR data sets were selected on the basis of the following criteria (con-
firming the supposed “slow-wave sleep episode,” Figure 1: (1) the first 10 min of
the first low and regular HR episode lasting at least 15 min, (2) the lowest standard
deviation of RR intervals (SDNN) throughout the period of interest, (3) a round
Poincaré plot (ie, a round cluster of points in RR intervals plotted as a function of
the previous one) and (4) a low inter-beat autocorrelation between successive RR
intervals (ie, correlation coefficient of the Poincaré plot < 0.5).

Time-domain HRV indices computed were mean RR intervals (mRR), SDNN,
and the square root of the mean of the sum of the squares of differences between
adjacent normal R-R intervals (RMSSD). A fast Fourier transform proposed by Polar software was conducted to analyze spectral power density in the low (LF; 0.04 to 0.15 Hz) and in the high (HF; >0.15 to 0.40 Hz) frequencies as well as their ratio LF/HF. The normalized HF ratio was also calculated as HFnu = HF/(LF + HF). Mean RR intervals, RMSSD, and HF power were considered as indexes of parasympathetic activity. Low-frequency power can be considered as an index of sympathetic activity,

Figure 1 — A (top): Nocturnal HR evolution and selected HR periods during the estimated slow wave sleep episode (10-min period between lines) where HRV indices were calculated (selection criteria based on Brandenberger et al). B (bottom): Poincaré plot for the chosen episode shown in panel A.
but given its parasympathetic component, it should be used with care.\textsuperscript{5} Because the absolute values of spectral parameters are highly correlated to variance (corresponding to total power), focusing on the fractional distribution of power independently of the absolute values of variance is also necessary. The LF/HF ratio is considered to reflect sympathovagal balance, and the normalized high-frequency component (ie, HFnu) is considered to represent the parasympathetic component of the sympathovagal balance.\textsuperscript{5}

**Statistical Analysis**

For all analyses, normality of the distribution was checked with the Kolmogorov–Smirnov goodness-of-fit test. Homogeneity of variance was verified by the Levene median test. A logarithm transform (\(\ln\)) was applied for HF and LF absolute values to obtain a normal distribution. Student's \(t\) test was conducted to compare data from SIE−10 and SIE+10. To compare data obtained during different nights of sleep, a one-way ANOVA for repeated measures with Tukey's post hoc test were performed. Pearson's \(r\) was calculated to examine correlations between cardiorespiratory and HRV parameters. Results for short- and long-term recovery are presented as means ± standard errors of the mean (SE) in absolute values and as a percentage of the preexercise period (SIE−10) or night (1st night). All statistical analyses were performed using Sigma Stat software (Sigma Stat 3.11, Systat software inc., San Jose, CA, USA), with significance set at an alpha level of 0.05. If no significant effects were observed, but a tendency toward significance (\(P < .1\)) was apparent, then effect sizes (ES) and adjusted ES (aES) were calculated for percentage and absolute values, respectively; the ES and aES formulas are as follows:

\[
ES = (m_a - m_b) + \frac{\sqrt{[(SD_a^2) \times (n_a - 1)] + [(SD_b^2) \times (n_b - 1)]}}{(n_a + n_b - 2)}
\]

\[
aES = ES / \sqrt{(1 - r)}
\]

where \(b\) = before, \(a\) = after, \(m\) = group mean, \(SD\) = standard deviation, \(n\) = group subject size, and \(r\) = correlation coefficient between before and after data. The scale proposed by Cohen\textsuperscript{13} was used for interpretation. Adjusted effect sizes were used for all parameters, except for data expressed as a percentage of 1st night values, for which effect sizes were calculated. The magnitude of the difference was considered either small (>0.2), moderate (>0.5), or large (>0.8). If there was at least a moderate (a) ES (>0.50), but the statistical power was low, the likelihood of a Type II error was noted.

**Results**

Mean \(\text{VO}_{2\text{peak}}\) and VIFT were 52 ± 3.4 mL·kg\(^{-1}\)·min\(^{-1}\) and 19.6 ± 0.9 km·h\(^{-1}\), respectively. Total SIE duration was 10 min 48 s ± 1 min 30 s (6 min 48 s ± 1 min, and 4 min ± 48 s for S1 and S2, respectively), total distance covered during both series was 2330 ± 435 m. Mean [La] concentration was 13.9 ± 2.4 mmol·L\(^{-1}\) and 12.15 ± 1.6 mmol·L\(^{-1}\) for S1 and S2.

Figure 2 illustrates short-term autonomic nervous system perturbation following SIE, with values expressed as a percentage of those measured for SIE−10. Global HRV index (ie, SDNN \(P < .001\)) was significantly reduced and all vagal-related
HRV indices were significantly depressed \( (P < .001) \) at SIE+10, when compared with SIE−10. The LF/HF ratio was also significantly increased immediately after SIE \( (P < .001) \).

Long-term absolute HRV recovery indices during the three nights are reported in Table 1. Figure 3 shows changes in mRR, SDNN, LnHF, and LF/HF, expressed as a percentage of the 1st night. Compared with the 1st night, parasympathetic-related HRV indices were significantly decreased or tended to decrease during the 2nd night \( (mRR, P = .03; HFnu, P = .06 and aES = 0.73; LnHF, P = .06 and aES = 1.49) \). Also a sympathetic predominance was noted in the sympathovagal balance, where the LF/HF ratio expressed as percentage of the 1st night was significantly increased \( (P = .03) \). On the 3rd night, most parasympathetic- and sympathetic-related indices returned to baseline values, whereas some indices tended to reach higher (vagal-related) and lower (sympathetic-related) values compared with the 1st night. We also noted a tendency for an increased HFnu on the 3rd night compared with the 1st night \( (P = .06 and aES = 0.70) \). Compared with the 2nd night, vagal-related HRV indices were significantly higher on the 3rd night \( (mRR, P = .02; RMSSD, P = .04) \) or tended to be higher \( (LnHF, P = .06 and aES = 0.75; HFnu, P = .06 and aES = 1.04) \). We also noted a shift toward a parasympathetic predominance in the LF/HF ratio \( (ie, \text{expressed as percentage of the 1st night}; P = .03) \). The sympathovagal balance expressed as a percentage of the 1st night increased significantly on the 2nd night \( (P = .03) \) and decreased significantly on the 3rd night \( (2nd \text{ night} vs 3rd \text{ night}, P = .02) \).
Table 1  Evolution of heart rate variability (HRV) indices over the three nights after supramaximal intermittent exercise

<table>
<thead>
<tr>
<th></th>
<th>First Night</th>
<th>Second Night</th>
<th>Third Night</th>
<th>(P) (ANOVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m RR (ms)</td>
<td>1179.0 ± 48.3</td>
<td>1095.7 ± 47.3*</td>
<td>1195.5 ± 54.4#</td>
<td>0.02</td>
</tr>
<tr>
<td>SDNN (ms)</td>
<td>49.6 ± 3.0</td>
<td>44.2 ± 9.8</td>
<td>48.3 ± 4.1</td>
<td>0.17</td>
</tr>
<tr>
<td>RMSSD (ms)</td>
<td>56.3 ± 5.0</td>
<td>46.7 ± 4.6</td>
<td>62.5 ± 7.3#</td>
<td>0.04</td>
</tr>
<tr>
<td>LnHF (ms2)</td>
<td>6.90 ± 0.17</td>
<td>6.49 ± 0.18(†)</td>
<td>7.00 ± 0.79‡</td>
<td>0.09</td>
</tr>
<tr>
<td>HFnu</td>
<td>0.61 ± 0.05</td>
<td>0.52 ± 0.04(†)</td>
<td>0.68 ± 0.05(†)‡</td>
<td>0.06</td>
</tr>
<tr>
<td>LnLF (ms2)</td>
<td>6.41 ± 0.21</td>
<td>6.36 ± 0.17</td>
<td>6.12 ± 0.21</td>
<td>0.31</td>
</tr>
<tr>
<td>LF/HF</td>
<td>85.5 ± 22.7</td>
<td>106.8 ± 17.2</td>
<td>56.9 ± 14.0</td>
<td>0.17</td>
</tr>
</tbody>
</table>

*Note. Values are mean ± SE. Mean RR interval (mRR), standard deviation of RR intervals (SDNN), the square root of the mean of the sum of the squares of differences between adjacent normal R-R intervals (RMSSD), log-transformed high-frequency power (LnHF), normalized unit in high-frequency range (HFnu), log-transformed low-frequency power (LnLF) and sympathovagal balance (LF/HF). HRV was analyzed during sleep for the night before (1st night) and two nights after the supramaximal intermittent exercise (2nd night and 3rd night). *Significant difference vs 1st night. #Significant difference vs 2nd night. \(†\)Differences vs 1st night with adjusted effect size considered as moderate (>0.5). ‡Differences vs 2nd night with adjusted effect size considered as moderate (>0.5).

Figure 3 — Changes in HRV indices throughout the three consecutive nights (before supramaximal intermittent exercise (1st night), during the first (2nd night), and second (3rd night) after supramaximal intermittent exercise nights. Data are mean (±SE) for mean RR interval (mRR), standard deviation of RR intervals (SDNN), natural logarithm of the high-frequency component (LnHF) and sympathovagal balance index (LF/HF). *Significant difference vs 1st night. #Significant difference vs 2nd night. *, #, \(P\) < .05. Effect size considered as moderate (>0.5) \(†\)compared with 1st night, ‡compared with 2nd night.
There was no correlation between HRV indices on the 2nd night and VO_{2peak} or [La]. However, significant correlations were found between [La] and parasympathetic indices measured on the 3rd night (eg, [La] vs RMSSD, \( r = .63 \) and \( p = 0.04 \), vs LnHF, \( r = .63 \) and \( P = .04 \)).

**Discussion**

The current study is the first to show the short- and long-term responses of cardiac autonomic nervous system function following a bout of supramaximal intermittent exercise. Because supramaximal training has been shown to markedly impair postexercise cardiac autonomic function,3 and because such exercise has been reported as being effective at enhancing cardiovascular fitness,1,2,14 we hypothesized that HRV indices would be perturbed for several days after exercise cessation. Using non-confounded HRV recordings taken immediately after exercise and during selective quiet periods of sleep, we observed a significant reduction of vagal-related HRV indices and a shift in sympathovagal balance toward a sympathetic predominance at 10 min and 12 h after SIE. All HRV indices had returned to preexercise levels by the 36 h post-SIE measurement period.

**Short-Term Recovery (Within 10 min)**

Five minutes after the supramaximal intermittent exercise, all parasympathetic-related indices (eg, RMSSD) were significantly decreased compared with immediate preexercise values, whereas those representative of sympathetic activity were increased (ie, LF/HF; Figure 2). It is worth noting that while HRV offers a qualitative marker of cardiac parasympathetic regulation, care should nevertheless be taken when interpreting sympathovagal balance indices (ie, LF/HF), because the LF component reflects some unknown interactions between sympathetic and parasympathetic inputs.5 However, these results are in accord with previous studies that have reported comparable levels of depressed vagal-related HRV indices (and conversely increased sympathetic-related ones) after either submaximal9 or supramaximal3,15 exercise. Indeed, HRV has been shown to be impaired for 5 to 10 min following 30 to 46 min at 79% VO_{2peak},9 for 1 h subsequent to six 3-min intermittent runs performed at the running speed associated with VO_{2peak},8 for 9 min after a maximal graded test,16 for 10 min after a 30-s all-out Wingate test,15 and for 5 min following repeated sprint running.3

The strong perturbations of postexercise parasympathetic activity observed here might be related to the supramaximal nature of the exercise and associated anaerobic participation and system stress metabolic accumulation.3,17,18 Indeed, the [La] values measured in the current study (13.9 ± 2.4 mmol·L⁻¹ and 12.15 ± 1.6 mmol·L⁻¹ for S1 and S2) are comparable to those recently shown under similar exercise conditions, after which parasympathetic reactivation was significantly impaired.3 In this study, supramaximal exercises inducing a high anaerobic participation (10.9 ± 0.9 mmol·L⁻¹) were associated with a low level of parasympathetic reactivation, whereas exercise of moderate intensity (3.5 ± 0.2 mmol·L⁻¹) induced a faster level of parasympathetic reactivation.3 This finding is consistent with other studies that have investigated postexercise autonomic activity following submaximal exercise.19-21 Indeed, minimal disturbances of HRV indices have
been shown following 60 and 120 min of submaximal exercise completed at an intensity below the first ventilatory threshold (55% to 65% VO$_{2peak}$; postexercise [La] = 1 ± 0.1 mmol·L$^{-1}$),$^{21}$ following 25 min at 50% VO$_{2peak}$,$^{19}$ and following 5 min at an intensity lower than 30% VO$_{2peak}$. These findings combined suggest that anaerobic participation, rather than mean aerobic power and exercise duration, is the most likely determinant of short-term autonomic activity after exercise. Other possible contributors to the perturbation of autonomic state after exercise (ie, over sympathetic activity) include activation of muscle metaboreflex,$^{22}$ oxygen debt repayment,$^{23}$ and core temperature regulation,$^{24}$ however, these variables were not monitored in the current study.

**Long-Term Recovery (12 and 36 h After Exercise)**

This study is the first to investigate the long-term effect of supramaximal exercise on nocturnal HRV using an exercise stimulus representative of a training session typically used by athletes. During the first night following supramaximal exercise (ie, 2nd night), parasympathetic-related indices were significantly decreased (mRR) or tended to be lower (LnHF) compared with the preexercise night (ie, 1st night) readings (Table 1). Sympathovagal balance expressed as percentage of the 1st night was significantly increased, suggesting a sympathetic predominance. During the 3rd night of recording (ie, 2nd night after exercise), parasympathetic indices were increased (ie, RMSSD, mRR) or tended to increase (ie, LnHF) compared with 2nd night indices. Absolute HRV indices measured on the 3rd night were comparable to those measured during the preexercise night, suggesting that cardiac autonomic function had returned to baseline levels; however a shift toward parasympathetic predominance in the sympathovagal balance was noted (ie, LF/HF, Table 1 and Figure 3). We also found a correlation between [La] and parasympathetic-related indices measured the second night after exercise. These results are consistent with previous diurnal recordings performed after either submaximal,$^{7–9}$ maximal$^4$ or supramaximal$^{10}$ exercises.

After submaximal or maximal exercise, autonomic activity has been shown to return to basal values within 48 h after 30 min of high-intensity exhaustive exercise,$^4$ after 30 to 46 min at 79% VO$_{2peak}$,$^9$ and within at least 72 h following six 3-min intermittent runs performed at vVO$_{2peak}$ − 1 km·h$^{-1}$. Interestingly, within the same time period (48 h), Hautala et al$^7$ observed a rebound of parasympathetic activity (ie, increased HF power density) after 75 km of cross-country skiing. In the current study, although we noted a tendency for a shift in sympathovagal balance toward parasympathetic predominance (higher HF ratio, aES = 0.70), a similar rebound effect was not as clearly apparent, probably owing to an insufficient exercise load or to our participants’ training status. Even if exercise intensity was well individualized (prescribed at a percentage of their VIFT), it is worth noting the important interindividual differences in the autonomic nervous system response observed (inferred from high SE values, ie, 3rd night LF/HF = 56.9 ± 14.0). These interindividual responses might be due to distinct training backgrounds$^{25}$ and may explain why, from a global observation, no marked rebound of parasympathetic activity was observed. Nevertheless, the present HRV response, which occurred in response to a total exercise duration of less than 10 min on average, is comparable with those described in the literature following prolonged submaximal exercise.
Although a control trial using continuous moderate-intensity exercise would have helped draw definitive conclusions regarding the influence of exercise intensity on cardiac autonomic function, the present results nevertheless suggest that supramaximal exercise is an efficient stimulus for perturbing long-term cardiac autonomic activity. Regarding the long-term HRV recovery following supramaximal exercise, our results are comparable with those reported by Niewiadomski et al.\textsuperscript{10} after two all-out 30-s Wingate efforts. However, because two Wingate exercises represent a very limited training stimulus (1 min),\textsuperscript{10} we aimed to investigate the effects of a longer and more practical training session on long-term autonomic recovery. We hypothesized that a longer supramaximal exercise training stimulus would induce a greater perturbation of autonomic activity (ie, delayed recovery). Present results do not support such a hypothesis because HRV values were already comparable to preexercise values during the night 36 h following exercise. This finding could indicate that exercise duration does not significantly influence postexercise autonomic recovery, with exercise intensity being the more likely key factor. Indeed, correlations showed that a high \([\text{La}]\) response was related to the greater level of vagal-related indices during long-term recovery (ie, 36 h later). The degree of the body’s homeostasis perturbation through system stress metabolite accumulation (eg, lactate), as well as exercise-induced plasma volume expansion,\textsuperscript{11} might be responsible for the long-term changes in HRV indices observed. For instance, elimination of plasma catecholamine, which is known to occur within at least 24 h,\textsuperscript{26} might be responsible for triggering sympathetic activity during the early hours after supramaximal exercise and help explain the delayed long-term recovery of HRV observed. The tendency to observe a shift toward parasympathetic predominance during the 3rd night can also be related to an increase in plasma volume,\textsuperscript{27} which could have activated baroreflex-mediated parasympathetic activity (and conversely, inhibited sympathetic activity). The physiological determinants of long-term autonomic nervous system recovery have not been extensively investigated, but normalization of blood pressure or baroreflex-mediated control of plasma volume expansion consecutive to exercise dehydration might also be involved.\textsuperscript{28}

**Practical Applications**

Recent studies have reported autonomic nervous system status to be an important factor governing the training response. This is because assessment of autonomic nervous system function effectively includes important information concerning acute and chronic physiological processes that occur before, during, and after aerobic exercise training. Our present results confirm that (nocturnal) heart rate variability monitoring can be used as a simple noninvasive tool to evaluate, at the individual level, the autonomic/homeostatic impact of a given exercise type. This information might be of interest to practitioners’ intent on monitoring the response of specific training prescriptions. For instance, Iellamo et al.\textsuperscript{29} assessed cardiac autonomic nervous system evolution (ie, diurnal recording) in world-class athletes throughout a 9-month training period and showed heart rate variability measures to follow training loads and performance. Along the same line of thinking, Hautala and coworkers\textsuperscript{30} suggest that daily assessment of autonomic nervous system activity could serve as an indicator of a recovered physiological condition before aerobic training. Compared with a “classic” training program (ie, without heart rate vari-
ability feedback), the heart rate variability–guided athletes displayed significantly superior improvements in maximal oxygen uptake and physical performance. Since a 10-min supramaximal exercise bout might not induce higher autonomic nervous system disturbances compared with long and moderate exercises as described in the literature,4,7–10 its use as a time-efficient alternative training method should be considered by coaches and exercise practitioners alike.

**Conclusion**

Via non-confounded heart rate variability recordings (ie, immediately after exercise and during selective quiet periods of sleep), we have shown that a single supramaximal exercise bout, lasting no more than 12 min, can perturb the autonomic nervous system for about 36 h. This confirms the strong influence of exercise intensity on short- and long-term postexercise heart rate variability recovery and might help explain the high efficiency of supramaximal training for enhancing indices of cardiorespiratory fitness.

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**References**


