



Live high–train low guided by daily heart rate variability in elite Nordic-skiers

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Abstract

Purpose To analyze if live high–train low (LHTL) effectiveness is improved when daily training is guided by heart rate variability (HRV).

Methods Twenty-four elite Nordic skiers took part in a 15-day LHTL study and were randomized into a HRV-guided training hypoxic group (H-HRV, $n=9$, sleeping in normobaric hypoxia, $FiO_2=15.0\%$) and two predefined training groups sleeping either in hypoxia (H, $n=9$, $FiO_2=15.0\%$) or normoxia (N, $n=6$). HRV and training loads (TL) were recorded daily. Prior (Pre), one (Post-1), and 21 days (Post-21) following LHTL, athletes performed a 10-km roller-ski test, and a treadmill test for determination of $\dot{V}O_{2max}$ was performed at Pre and Post-1.

Results Some HRV parameters measured in supine position were different between H-HRV and H: low and high (HF) frequency power in absolute (ms^2) (16.0 ± 35.1 vs. $137.0 \pm 54.9\%$, $p=0.05$) and normalized units (-3.8 ± 10.1 vs. $53.0 \pm 19.5\%$, $p=0.02$), HF(nu) (6.3 ± 6.8 vs. $-13.7 \pm 8.0\%$, $p=0.03$) as well as heart rate (3.7 ± 6.3 vs. $12.3 \pm 4.1\%$, $p=0.008$). At Post-1, $\dot{V}O_{2max}$ was improved in H-HRV and H ($3.8 \pm 3.1\%$; $p=0.02$ vs. $3.0 \pm 4.4\%$; $p=0.08$) but not in N ($0.9 \pm 5.1\%$; $p=0.7$). Only H-HRV improved the roller-ski performance at Post-21 ($-2.7 \pm 3.6\%$, $p=0.05$).

Conclusion The daily individualization of TL reduced the decrease in autonomic nervous system parasympathetic activity commonly associated with LHTL. The improved performance and oxygen consumption in the two LHTL groups confirm the effectiveness of LHTL even in elite endurance athletes.

Keywords Hypoxia · HRV · Endurance performance

Abbreviations

ANOVA	Analysis of variance	HRV	Heart rate variability
FFT	Fast Fourier transform	LF	Low-frequency power
FiO_2	Inspired fraction of oxygen	LFnu	Low-frequency power in normalized units
H	Hypoxic	LHTL	Live high–train low
HF	High-frequency power	N	Normoxic
HFnu	High-frequency power in normalized units	PiO_2	Partial pressure of inspired oxygen
Hb_{mass}	Hemoglobin mass	QSFMS	Questionnaire of the French Society of Sports Medicine
HR	Heart rate	SpO_2	Pulse oxygen saturation
		TL	Training load
		$\dot{V}_E/\dot{V}CO_2$	Ventilatory equivalent of carbon dioxide
		$\dot{V}_E/\dot{V}O_2$	Ventilatory equivalent of oxygen
		$\dot{V}O_{2max}$	Maximal oxygen consumption
		VT1	First ventilatory threshold
		VT2	Second ventilatory threshold

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Introduction

It is known that in a group of athletes, the same standardized training program could induce a great diversity of responses in terms of performance and physiological adaptations (Bouchard and Rankinen 2001; Hautala et al. 2003, 2006). Age, sex, ethnicity, and genetic characteristics are among different factors that influence adaptations following endurance training (Bouchard et al. 1999; Bouchard and Rankinen 2001). In addition, the initial state of autonomic nervous activity is important for the physiological response to exercise. Since a large component of the inter-individual variability of the physiological responses to a standardized training plan is related to the balance between parasympathetic and sympathetic activities (Aubert et al. 2003; Perini et al. 1990), one may assume that an individually heart rate variability-guided (HRV-guided) training could lead to improved benefits. Despite the large number of studies showing a relationship between endurance training and HRV (Hedelin et al. 2001; Iellamo et al. 2002; Kiviniemi et al. 2006), to date only Kiviniemi et al. (2007, 2010) have reported HRV-based individual adjustment of the training. Specifically, nine young male recreational athletes (HRV-guided) performed 4 weeks of training adjusted with the HF values measured daily in the standing position, resulting in a change of $\dot{V}O_{2\max}$ similar as compared with those of a control group of athletes who performed a standardized training program. The change in maximal running speed was significantly greater in the HRV-guided compared to the standardized group.

The responses to altitude training are complex since hypoxia and training stress are combined (Schmitt et al. 2006a). In hypoxia, the reduced PiO_2 (partial pressure of inspired oxygen) represents an additional stress, which has been shown to induce specific HRV responses (Schmitt et al. 2006a) with a combination of increased sympathetic and decreased parasympathetic nervous activities (Perini and Veicsteinas 2003; Schmitt et al. 2006a; Sevre et al. 2001; Zupet et al. 2009). Schmitt et al. (2006a, b, 2008) have shown that HRV parameters are modified differently depending on the intensity of training performed in altitude. Conversely, high-intensity exercise is not recommended during the first 7–10 days of an altitude training camp (Millet et al. 2010). In the different altitude training methods, live high–train low (LHTL) is widely recognized as the “gold standard”. Based on more than 15 years of research, LHTL is known for inducing a 1–3% improvement in specific endurance performance when compared to similar normoxic training (Bonetti and Hopkins 2009). It has also recently been demonstrated that normobaric and hypobaric LHTL stimulation produce a similar improvement in aerobic performance (Saugy et al. 2016) and

increased hemoglobin mass (Hauser et al. 2016). However, the debate is not complete, as some authors have recently suggested that the beneficial effect of LHTL could be very limited in elite athletes assuming that these athletes have a reduced ability to further increase their aerobic performance following altitude training (McLean et al. 2013; Robach and Lundby 2012).

To our knowledge, the effectiveness of LHTL with daily adjustment of training load/content based on daily HRV analysis has never been investigated. The fact that the present study was performed with elite endurance athletes is of highest importance since it is known that elite athletes have smaller windows for performance improvement than their lower level counterparts and that the elite athlete's responses to training are very specific (Burtscher et al. 1996). Therefore, the first aim of the present study was to test the hypothesis that HRV-guided LHTL training would blunt both the decrease in parasympathetic and the increase in sympathetic activities classically reported during LHTL and would enhance aerobic performance when compared with a standardized (predefined training) LHTL program. In addition, the secondary aim was to confirm that LHTL is effective even in elite endurance athletes.

Methods

Subjects

Subjects were 24 elite Nordic-skiers, members of the cross-country ski and Nordic-combined French national teams with 19 men (age 23.3 ± 3.6 years; $\dot{V}O_{2\max}$ 67.8 ± 3.6 mL kg⁻¹ min⁻¹) and 5 women (age 22.8 ± 4.1 years; $\dot{V}O_{2\max}$ 58.9 ± 2.5 mL kg⁻¹ min⁻¹). All these athletes compete in European cup or World cups and some are medalists in World championships. The subjects were assigned into a HRV-guided training normobaric hypoxic group (H-HRV, $n=9$, simulated altitude of 2700 m, $FiO_2=15.0\%$), and two predefined training groups sleeping either in normobaric hypoxia (H, $n=9$, simulated altitude of 2700 m, $FiO_2=15.0\%$) or in normoxia (N, $n=6$). The three groups were randomly matched for Nordic disciplines (cross-country ski vs. Nordic combined) and gender (male vs. female). No athletes were under any medical treatment which might influence HRV during the study. The characteristics of subjects by groups in gender (men, women), age (years), mass (kg), height (cm), and fat mass (%) were:

For H-HRV: 7 men (22.9 ± 4.3 year, 68.1 ± 5.5 kg, 177.3 ± 5.8 cm, $9.5 \pm 0.9\%$) and 2 women (20.5 ± 0.7 year, 56.5 ± 5.0 kg, 163.5 ± 6.4 cm, $19.0 \pm 1.5\%$).

For H: 6 men (21.8 ± 1.3 year, 72.5 ± 6.3 kg, 180.2 ± 3.4 cm, $9.8 \pm 0.8\%$) and 3 women (24.3 ± 4.9 year, 55.0 ± 5.0 kg, 163.7 ± 5.8 cm, $18.0 \pm 1.4\%$).

For N: 5 men (25.7 ± 3.5 year, 69.7 ± 5.2 kg, 177.7 ± 6.3 cm, $10.0 \pm 1.1\%$).

Study design

The study design is shown in Fig. 1. The study was approved by the local ethical committee (French National Conference of Research Ethics Committee; N°CPP EST I: 2014/33; Dijon, France). All experimental procedures conformed to the standards set by the Declaration of Helsinki. All subjects provided written informed consent to participate in the study after having been informed in detail about the experimental procedure. Exclusion criteria for participation included any history of altitude-related sickness and health risks that could compromise the subject's safety during training and/or hypoxic exposure. The study was performed at the French National Ski-Nordic Centre located at an altitude of 1200 m which contains 11 hypoxic rooms. These hypoxic chambers were of medium size (15 ± 1 m²) and equipped with conventional beds. Two subjects were in each room and primarily spent time sleeping or resting between training sessions.

Measurements

Daily measurements

Each morning of the 15-day LHTL camp, the following parameters were recorded: duration of hypoxic exposure in hypoxic chambers, night peripheral oxygen saturation (SpO₂) and heart rate (HR), morning heart rate variability (HRV), and a questionnaire validated by the consensus group on overtraining of the French Society of Sports Medicine (QSFMS) (Maso et al. 2004) was administrated and training load (TL) calculated.

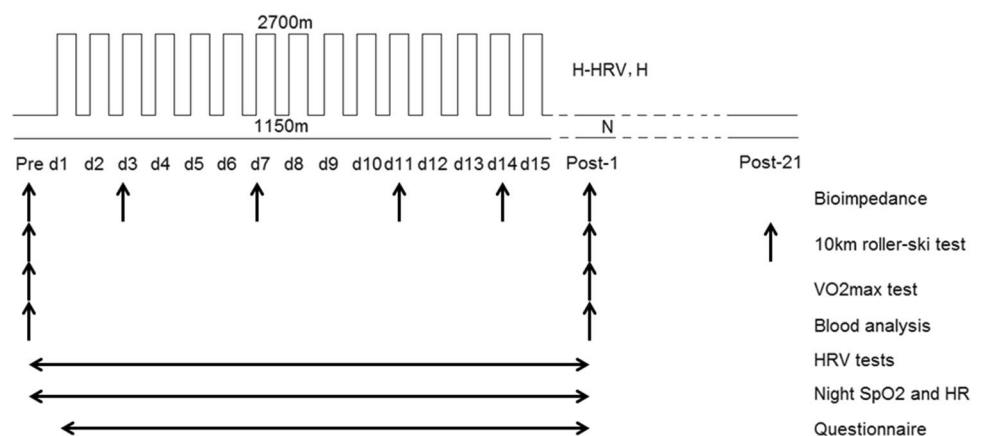
Night peripheral oxygen saturation (SpO₂) and heart rate (HR)

SpO₂ and HR were recorded continuously each night from Pre to Post-1 at 0.25 Hz with a wrist oximeter connected to a finger sensor (Wristox 3150® with 8000SM-WO Sensor, Nonin, Plymouth, MN, USA). Data were obtained and the average value was computed for further analysis.

Heart rate variability tests

The protocol of HRV tests is presented in detail in previous articles (Schmitt et al. 2013, 2016). Briefly, the HRV test consisted of a 15-min RR interval recording at rest with 8 min supine (SU) followed by 7 min standing (ST). The HRV recording was performed daily in the morning immediately after waking and voiding the urinary bladder. HRV analyses were performed on RR intervals between the 3rd and 8th min supine, and between the 9th and 14th min standing. Measurement of the interval duration between two R waves of the cardiac electrical activity was performed with a HR monitor (Ambit3 Peak, Suunto®, Vantaa, Finland). The spectral power was calculated with the fast Fourier transform (FFT) using a software (Nevrokard® HRV, Medistar, Ljubljana, Slovenia). The power of spectral density was measured by frequency bands in ms² Hz⁻¹ and the spectral power was expressed in ms² (Task-Force 1996). The high-frequency (HF) power band (0.15–0.40 Hz) reflects alteration of the parasympathetic influence on the heart and is related to the respiratory sinus arrhythmia (Pomeranz et al. 1985). While the low-frequency (LF) power band (0.04–0.15 Hz) is also driven by parasympathetic tone, and presently considered responsible for carrying vagal resonances to either changes in vasomotor tone (often sympathetic) or in the central modulation of sympathetic tone (Reyes Del Paso et al. 2013). Spectral power in the LF power band has also been shown to be related to fluctuations of arterial blood

Fig. 1 Experimental design. Heart rate variability (HRV), hypoxic HRV-guided group (H-HRV, $n=9$), hypoxic predefined group (H, $n=9$), normoxic predefined group (N, $n=6$), maximal oxygen uptake ($\dot{V}O_{2max}$), night peripheral oxygen saturation (SpO₂), and heart rate (HR). Vertical arrows indicate the day of the tests and horizontal arrows define the day-tests period



pressure (Akselrod et al. 1981; Pomeranz et al. 1985) and to activity of the baroreflex (Goldstein et al. 2011). Both in supine (SU) and in standing (ST) positions, LF and HF were calculated in absolute spectral power units (ms^2) and in normalized units (nu) with $\text{LF}(\text{nu}) = \text{LF}/(\text{LF} + \text{HF}) \times 100$ and $\text{HF}(\text{nu}) = \text{HF}/(\text{HF} + \text{LF}) \times 100$. The total spectral power (TP) was calculated from the sum of LF and HF.

Performance measurements at Pre, Post-1, and Post-21

A maximal roller-ski test was performed on an official FIS-accredited roller-ski asphalt track of the National French Ski-Nordic Centre, with an alternation of uphill, downhill, and flat terrain. Determined by the coaches, the women performed 2 laps in classical technique and the men 3 laps of 3.3 km in skating technique. Measurements were performed on each subjects own roller-skis and poles while maintaining the same equipment use for each test.

Incremental maximal treadmill test at Pre 1, Post-1 and Post-21

The incremental running treadmill $\dot{V}\text{O}_{2\text{max}}$ protocol used in the present study is routinely used for the medical follow-up of the French Nordic-skiers in the same laboratory. The test started with 3-min stages at 8 km h^{-1} and 2% grade, followed by 9 km h^{-1} and 2%, 9 km h^{-1} and 4%, 9 km h^{-1} and 6%, and 10 km h^{-1} and 6% grade. Every 3 min, the stage increased first by speed, then by grade until the second ventilatory threshold (VT2) was passed. After VT2, the protocol changed to 1-min stages increasing grade to a maximum of 16% until exhaustion. During all tests, heart rate (HR) was continuously monitored using a telemetry-based HR monitor (Ambit3 Peak, Suunto[®], Vantaa, Finland) and the maximum was obtained for further analysis. Oxygen (O_2) and carbon dioxide (CO_2) levels were continuously measured and monitored as breath-by-breath values in expired gas (Ultima Cardio 2[®] gas exchange analysis system, MGC Diagnostics with Breezesuite software, Saint Paul, MN, USA). The flow meter and the gas analyser were calibrated prior to each test with a 3-L volume calibration syringe (Hans Rudolph[®], Medgraphics) and with a 5% CO_2 and 12% O_2 and 21% O_2 gas mixtures (Medgraphics). The $\dot{V}\text{O}_{2\text{max}}$ was determined by the highest 30 s average value with a “plateau” or levelling off in $\dot{V}\text{O}_2$, $\text{RER} > 1.1$, and $\text{HR} > 95\%$ of theoretical age predicted HR_{max} . VT1 corresponded to the first non-linear increases in $\dot{V}\text{CO}_2$, and VT2 was determined as the first rise in the ventilatory equivalent of oxygen ($\dot{V}_E/\dot{V}\text{O}_2$) without a concurrent rise in the ventilatory equivalent of carbon dioxide ($\dot{V}_E/\dot{V}\text{CO}_2$) (Reinhard et al. 1979).

Training loads

The training load (TL) was organized into four training zones depending on the intensity, which was based on the ventilatory levels of the first ventilatory threshold (VT1) and the second ventilatory threshold (VT2). These levels were identified as: intensity I for endurance training at an intensity below VT1; intensity II for endurance training at an intensity between VT1 and VT2; intensity III for training at an intensity at VT2, interval training at intensity above VT2, and competitions; and intensity IV for strength and speed training sessions.

Training loads were quantified as in Mujika et al. (1996), but slightly adapted to Nordic skiing and expressed in arbitrary units (a.u.) by multiplying the training duration (in min) spent in each intensity zone by a coefficient (i.e., 1, 2, 4, and 8 for the zones I, II, III, and IV, respectively).

Daily adjustment of training by HRV analysis

To ensure that the subjects were in a good condition at the beginning of the study period, the LHTL camp was organized at the end of the “base training” period (in July) of the yearly season, in which no training sessions had been completed that year at an intensity above VT2. In addition, the training volume was progressively increased and a recovery week was placed prior to the pre-tests in order to ensure subjects were healthy and well prepared. During the 2 months preceding the LHTL intervention, no athletes used altitude training and all lived and trained between 800 and 1200 m of altitude; i.e., typical residence. The training content was similar for each group (i.e., male cross-country skiers, female cross-country skiers, and male Nordic-combined athletes) and prescribed by the national coaches.

During the experimental period, the training adjustment was performed every morning using HRV analysis by the same highly experienced researcher. We have reported in a previous study (Schmitt et al. 2015) that the main type of fatigue can be diagnosed by a 50% minimum decrease in HF and LF spectral powers in both supine and standing positions. On the basis of these previous values, the threshold for training adjustment was chosen as 30% of the mean of the previous day in the present study.

The daily HRV-guided modulation of training load was adjusted based on the following situations:

- Maintained or increased HF induced a higher TL than the previous day.
- Decreased HF equal to or more than 30% led to lower TL.
- Two consecutive days of decreased HF prompted a resting day.
- After a rest day, a low-intensity and medium-volume session was prescribed.

The TL of the first day of the study was at medium volume and low intensity (intensity II, between VT1 and VT2). This medium volume was calculated for each subject as the mean volume of the three training weeks preceding the study.

Overall, the HRV-guided modulation of training can lead to either increased or decreased TL than in the predefined training program. In the first week of LHTL, the change in TL was only due to change in training volume since no “intense” session (i.e., at or above VT2) was scheduled to respect the acclimatization phase (Millet et al. 2010), with a 20% increase in TL when HF was either maintained or increased. In the second week of LHTL, the increase in TL was incorporated with additional training sessions lasting 45 min in duration at VT2.

Hematological parameters

Analysis of venous blood was performed from a 4.9-mL sample (4.9 mL EDTA tube, Sarstedt, Nümbrecht, Germany) to measure hematological parameters of erythrocyte concentration ($T L^{-1}$), hemoglobin (Hb, $g dL^{-1}$), hematocrit (Htc, %), mean cell volume (MCV, fL), reticulocytes ($g dL^{-1}$), and ferritin ($ng mL^{-1}$) using a blood flow cytometric analysis (Sysmex XN-2000, Sysmex, Kobe, Japan).

Data analysis and statistics

Data are reported as mean and standard deviation (SD). Data were tested for equality of variance (Fisher–Snedecor *F* test) and for normality (Shapiro–Wilk test). When both conditions were met, a two-way repeated measures ANOVA [condition (H-HRV, H and N) vs. measurement (pre, post-1, and post-21)] were performed with pairwise multiple comparison procedures (post hoc, Tukey method). Differences in percentage changes between the conditions were tested with a Wilcoxon signed rank sum test. When either equality of variance or normality were not satisfied, variables were analyzed for each condition using a Friedman test for repeated measures to determine time effects using pairwise multiple comparison procedures (Bonferroni test). In this case, differences between the H-HRV, H, and N condition at baseline (pre-) were tested using a Mann–Whitney rank sum test. Null hypotheses were rejected at $p < 0.05$. All analyses were completed using SigmaStat 3.5 software (Systat Software, San Jose, CA, USA).

Results

Hypoxic dose and nocturnal measurements

Daily hypoxic dose was similar between H-HRV and H (14.3 ± 1.6 vs. 14.1 ± 1.8 h). Total hypoxic dose in LHTL

intervention was similar between H-HRV and H (215.4 ± 6.0 vs. 211.5 ± 9.7 h). Night SpO_2 was similar between H-HRV and H, but lower than in N (90.4 ± 1.3 vs. 91.1 ± 1.6 vs. $94.2 \pm 0.8\%$, $p < 0.001$).

Training loads

Despite the potential individual daily adjustment of the training content in H-HRV, overall training loads were similar between H-HRV and H, but lower than in N (3365 ± 425 vs. 3481 ± 179 vs. 3847 ± 433 a.u., $p < 0.05$). During the 15-day LHTL period, the daily training was adjusted on 3.3 ± 2.3 days in the H-HRV subjects.

No significant differences between groups were observed in the distribution of time spent training in the different intensity zones.

Questionnaire of overtraining

No significant differences in the overtraining QSFMS scores were found at any moment of the LHTL period between H-HRV, H, and N. The values in QSFMS scores were Pre (1.4 ± 1.7 , 1.2 ± 1.9 , and 2.2 ± 1.7) and Post-1 (1.0 ± 1.1 , 1.9 ± 2.4 , and 1.8 ± 2.6) in H-HRV, H, and N, respectively.

Heart rate variability

Table 1 shows the Pre test absolute values in heart rate and HRV parameters in supine and standing positions. No differences were observed between H-HRV, H, and N in HR, LF, HF, LF + HF, LFnu, or HFnu.

Change (%) in HR and HRV parameters during LHTL and post-LHTL periods between H-HRV, H, and N are shown in Table 2 and Fig. 2.

Incremental maximal treadmill test

Maximal oxygen uptake ($\dot{V}O_{2max}$) and oxygen consumption at the second ventilatory threshold ($\dot{V}O_{2VT2}$) obtained at Pre and Post-1 are shown in Table 3. At Post-1, $\dot{V}O_{2max}$ ($mL min^{-1} kg^{-1}$) and $\dot{V}O_{2VT2}$ ($mL min^{-1} kg^{-1}$) were improved in H-HRV ($+3.8 \pm 3.1\%$, $p < 0.05$ and $+6.7 \pm 6.1\%$, $p < 0.01$) and to a (non-significant) lesser extent in H ($+3.0 \pm 4.4\%$, $p = 0.08$ and $+5.0 \pm 5.7\%$, $p = 0.06$) but not in N ($+0.9 \pm 5.1\%$, ns and $-2.5 \pm 5.1\%$, ns).

Roller-ski performance

At Pre, Post-1, and Post-21, temperature and humidity were similar with no wind.

The roller-ski performance was not improved in any of the groups at Post-1. At Post-21, H-HRV and H groups improved roller-ski performance ($-2.7 \pm 3.6\%$, $p < 0.05$ vs.

Table 1 Absolute values in heart rate (HR) and heart rate variability (HRV) parameters measured at Pre in supine (SU) and standing (ST) positions, in HRV-guided hypoxic (H-HRV, $n=9$), standardized training hypoxic (H, $n=9$), and standardized training normoxic (N, $n=6$) groups

	HRV parameters	H-HRV	H	N	p_1	p_2	p_3
Supine	HR _{SU} (bpm)	53.4 ± 9.2	49.5 ± 3.7	47.2 ± 5.8	0.31	0.24	0.37
	LF _{SU} (ms ²)	3490 ± 3068	3175 ± 3090	2674 ± 1291	0.69	0.55	0.72
	HF _{SU} (ms ²)	4724 ± 3400	7068 ± 4867	3527 ± 2103	0.25	0.46	0.26
	(LF + HF) _{SU} (ms ²)	8214 ± 5610	10,243 ± 7045	6201 ± 2882	0.51	0.44	0.38
	LF _{SU} (nu)	40.9 ± 18.7	34.9 ± 17.6	44.6 ± 16.6	0.31	0.70	0.14
	HF _{SU} (nu)	59.1 ± 18.7	65.1 ± 17.6	55.4 ± 16.6	0.31	0.70	0.14
Standing	HR _{ST} (bpm)	77.1 ± 9.7	78.7 ± 10.9	75.2 ± 14.2	0.75	0.76	0.60
	LF _{ST} (ms ²)	6413 ± 3960	6232 ± 5170	5994 ± 3280	0.94	0.83	0.92
	HF _{ST} (ms ²)	1543 ± 2703	711 ± 488	461 ± 467	0.76	0.18	0.34
	(LF + HF) _{ST} (ms ²)	7955 ± 6071	6943 ± 5497	6455 ± 3692	0.72	0.60	0.85
	LF _{ST} (nu)	84.9 ± 12.4	88.0 ± 9.4	93.4 ± 2.9	0.51	0.13	0.20
	HF _{ST} (nu)	15.1 ± 12.4	12.0 ± 9.4	6.6 ± 2.9	0.51	0.13	0.20

With, in spectral analysis, low (LF) and high (HF) frequencies, (LF+HF), LF (LFnu) and HF (HFnu) in normalized units. Data are expressed as mean ± SD. With p_1 for statistical difference between H-HRV and H, p_2 between H-HRV and N, and p_3 between H and N, with $p < 0.05$ for significant difference

– 2.5 ± 3.5%, $p=0.07$) while there was no improvement for the N group (– 1.1 ± 2.3%, ns). When pooled together, the two LHTL hypoxic groups (H-HRV + H) improved roller-ski performance at Post-21 (– 2.6 ± 3.4%, $p < 0.01$) significantly more than the normoxic group.

Hematological parameters

The hematological parameters measured at Pre and Post-1 in the three groups are reported in Table 4.

Discussion

This study, demonstrated that the daily individualized adjustment of the training loads based on morning HRV measurement blunted both the decrease in parasympathetic and the increase in sympathetic activities in the HRV-guided hypoxic (H-HRV) group in comparison to the predefined training hypoxic (H) group in elite male and female Nordic skiers. This study also confirmed the effectiveness of the living high–training low training method.

An important finding is that the daily individualized adjustment of training loads based on morning HRV measurement blunted both the decrease in parasympathetic and the increase in sympathetic activities in the HRV-guided hypoxic (H-HRV) group in comparison to the predefined training hypoxic (H) group in elite male and female Nordic skiers. It is known that the high-frequency power (HF, ms²) in the HRV spectral analysis represents the parasympathetic influence on the sinus node of the heart (Akselrod et al. 1981), and that the low frequency (LF, ms²) is also driven by parasympathetic tone in addition to carrying vagal resonances to either changes in vasomotor tone (often

sympathetic) or central modulation of sympathetic tone (Reyes Del Paso et al. 2013). We have relayed in a preceding study (Schmitt et al. 2013) that in case of fatigue, the changes in HRV parameters were mainly due to a decrease in both HF and LF spectral power accompanied by an improvement in the relative influence of the LF band (LFnu) on the total spectral activity, observed only in the supine position. A further consideration for the present results is the influence of the menstrual cycle on the autonomic activity and HR responses in female subjects. In the present study for an adequate control of the experimental factors (training content, training and testing environmental conditions, motivational aspects), it was paramount that all athletes trained together and therefore impossible to adjust the period on the basis of the individual phase of the menstrual cycle for any female athlete. We cannot rule out that this methodological flaw might have slightly modified the HRV changes in some female athletes. In order to individually modulate the daily training adaptations in H-HRV, this study followed a previously reported protocol (Kiviniemi et al. 2007). The main difference was that the present HRV measurements were in the supine position whereas HRV records were standing in the Kiviniemi's study. However in both studies, TL adjustments were based on the change in HF spectral energy. In the present study, several HRV parameters followed a different pattern of change throughout the 15-day LHTL period between H-HRV and H, showing globally a better adaptation in the H-HRV group, likely due to improved regulation of the combination between the hypoxic and the training stimuli as possible through daily HRV analysis. These results demonstrated an increase in LFnu (53.0 ± 19.5%) and HR (12.3 ± 4.1%) associated to a decrease in HFnu (– 13.7 ± 8.0%) in H, whereas these parameters remained unchanged in H-HRV with LFnu (– 3.8 ± 10.1%), HR

Table 2 Mean change (%) between Pre and the averaged values either during the 15-day LHTL period or the three weeks post-LHTL in heart rate variability (HRV) parameters and heart rate (HR) measured in supine (SU) and standing (ST) positions in hypoxic HRV-guided (H-HRV, $n=9$), hypoxic predefined (H, $n=9$), and normoxic (N, $n=6$) groups

HRV parameters	Groups	LHTL	<i>p</i>	ES	Post-LHTL	<i>p</i>	ES
HR _{SU} (bpm)	H-HRV	3.7 ± 8.9			- 2.4 ± 6.4		
	H	12.3 ± 8.1	0.008	1.00	3.9 ± 7.3	0.02	0.93
	N	- 0.2 ± 7.1	0.23	0.47	0.7 ± 7.6	0.27	0.45
LF _{SU} (ms ²)	H-HRV	16.0 ± 78.9			5.4 ± 64.5		
	H	137.0 ± 141.9	0.05	1.05	136.2 ± 121.4	0.09	1.35
	N	50.1 ± 112.0	0.40	0.37	61.3 ± 90.1	0.22	0.74
HF _{SU} (ms ²)	H-HRV	22.1 ± 78.3			- 8.7 ± 46.6		
	H	- 8.2 ± 52.2	0.13	0.44	4.5 ± 51.3	0.65	0.27
	N	11.3 ± 65.9	0.86	0.15	17.9 ± 65.8	0.16	0.49
(LF+HF) _{SU} (ms ²)	H-HRV	16.4 ± 68.2			- 4.0 ± 49.3		
	H	19.1 ± 60.3	0.54	0.04	28.9 ± 51.6	0.36	0.65
	N	20.0 ± 71.9	0.89	0.05	32.9 ± 63.6	0.12	0.67
LF _{SU} (nu)	H-HRV	- 3.8 ± 26.9			8.7 ± 26.6		
	H	53.1 ± 47.3	0.02	1.48	48.8 ± 45.8	0.11	1.14
	N	12.1 ± 30.1	0.25	0.56	18.5 ± 31.0	0.44	0.35
HF _{SU} (nu)	H-HRV	6.3 ± 19.6			- 0.3 ± 17.9		
	H	- 13.7 ± 21.5	0.03	0.97	- 6.8 ± 19.4	0.09	0.35
	N	8.3 ± 23.5	0.26	0.09	- 7.2 ± 24.5	0.32	0.33
HR _{ST} (bpm)	H-HRV	8.8 ± 8.0			- 1.7 ± 9.2		
	H	6.9 ± 8.5	0.62	0.23	0.9 ± 8.7	0.52	0.29
	N	0.1 ± 6.3	0.05	1.21	- 1.4 ± 6.7	0.94	0.04
LF _{ST} (ms ²)	H-HRV	- 7.9 ± 39.6			1.1 ± 43.4		
	H	5.9 ± 59.5	0.90	0.29	49.4 ± 78.1	0.79	0.82
	N	11.7 ± 42.7	0.38	0.48	43.7 ± 56.6	0.26	0.87
HF _{ST} (ms ²)	H-HRV	- 9.7 ± 53.3			3.8 ± 65.2		
	H	72.6 ± 125.9	0.91	0.85	149.3 ± 145.5	0.86	1.40
	N	85.6 ± 81.0	0.11	1.39	127.7 ± 117.1	0.06	1.39
(LF+HF) _{ST} (ms ²)	H-HRV	- 9.3 ± 38.7			- 0.6 ± 39.4		
	H	8.9 ± 60.3	0.93	0.36	54.2 ± 80.9	0.86	0.94
	N	15.2 ± 42.8	0.38	0.60	48.2 ± 57.5	0.26	1.03
LF _{ST} (nu)	H-HRV	- 0.9 ± 7.4			1.0 ± 8.8		
	H	- 1.2 ± 7.6	0.03	0.01	- 0.4 ± 8.5	0.09	0.19
	N	- 2.8 ± 3.4	0.26	0.33	- 2.9 ± 4.2	0.32	0.53
HF _{ST} (nu)	H-HRV	15.6 ± 49.3			10.6 ± 50.2		
	H	57.9 ± 77.9	0.48	0.65	37.7 ± 63.8	0.19	0.49
	N	68.9 ± 70.9	0.15	0.87	60.5 ± 73.3	0.08	0.83

Data are expressed as mean ± SD. *p* for difference of change between H-HRV and H, and H-HRV and N, ES for effect size

(3.7 ± 6.3%), and HF_{nu} (6.3 ± 6.8%) during the LHTL period. These latter results indicated a stronger sympathetic predominance and a decreased parasympathetic activity in H as is classically observed in hypoxic conditions (Passino et al. 1996; Perini et al. 1996). Conversely, in H-HRV, a better response to the hypoxic stimulus was possible, due to the daily TL adaptation as follows: the inclusion of moderate aerobic training when HF (ms²) decreased by more than 30% or the increase in TL when HRV was improved. Similarly, the increase in HR as well as the increase in LF_{nu} and LF (ms²) was observed in H but not in H-HRV, which provides

clear evidence of the moderation of the hypoxia-induced sympathetic predominance in the latter group. Finally, the subjective feeling of fatigue was not statistically different between the groups. In our view, this point highlights the need for both objective (i.e., HRV) and subjective assessment of fatigue in athletes. This is especially needed during the acclimatization period (i.e., first week) in altitude.

Another finding of the present study, is the significant improvement in performance and aerobic capacity both in H-HRV and H, without significant differences of change between these groups. Many potential reasons could be

Fig. 2 Changes (%) during the 15-day LHTL period and three weeks post-LHTL of low-frequency power in normalized units (LFnu) and heart rate (HR) in the hypoxic HRV-guided (H-HRV, $n=9$), hypoxic predefined (H, $n=9$), and normoxic predefined (N, $n=6$) groups

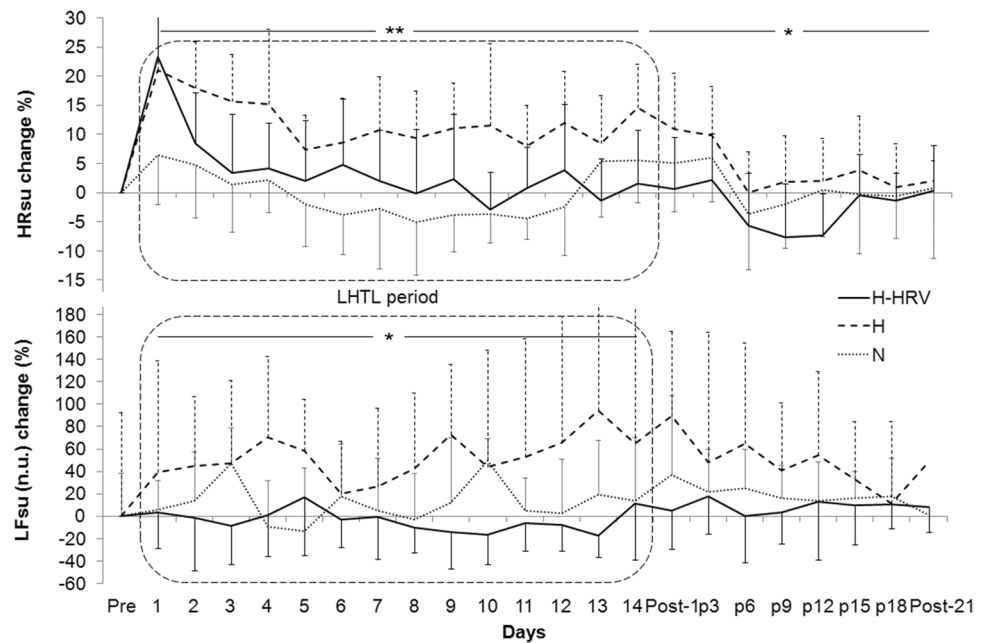


Table 3 Maximal oxygen uptake ($\dot{V}O_{2max}$, $\text{mL min}^{-1} \text{kg}^{-1}$) and oxygen consumption at the second ventilatory threshold ($\dot{V}O_{2VT2}$, $\text{mL min}^{-1} \text{kg}^{-1}$) at Pre and Post-1 in HRV-guided hypoxic (H-HRV, $n=9$), standardized training hypoxic (H, $n=9$), (H and HRV + H pooled) and standardized training normoxic (N, $n=6$) groups

Groups	$\dot{V}O_{2max}$ ($\text{mL min}^{-1} \text{kg}^{-1}$)			$\dot{V}O_{2VT2}$ ($\text{mL min}^{-1} \text{kg}^{-1}$)		
	Pre	Post-1	ES	Pre	Post-1	ES
H-HRV %	66.7 ± 5.9	$69.2 \pm 6.5^*$	0.40	55.8 ± 4.0	$59.6 \pm 5.9^{**}$	0.75
	–	$3.8 \pm 3.1^*$		–	$6.7 \pm 6.1^{**}$	
H %	63.7 ± 4.4	65.6 ± 4.9	0.06	54.5 ± 5.3	57.1 ± 4.7	0.52
	–	3.0 ± 4.4		–	5.0 ± 5.7	
H-HRV + H %	65.2 ± 5.3	$67.4 \pm 5.9^{**}$	0.39	55.1 ± 4.6	$58.4 \pm 5.4^{***}$	0.66
	–	$3.4 \pm 3.7^{**}$		–	$5.9 \pm 5.8^{***}$	
N %	68.2 ± 3.2	68.8 ± 4.2	0.16	60.2 ± 2.9	58.6 ± 3.2	0.52
	–	0.9 ± 5.1		–	$-2.5 \pm 5.1^{##}$	

Data are expressed as mean \pm SD in absolute and relative (%) values. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ for differences between Pre and Post-1. ## $p < 0.01$ for difference of change between (H-HRV + H) and N. ES for effect size between pre and post

suggested. Firstly, the training was prescribed by a highly qualified national coach with therefore very little “room” for improvement, even if the study was performed in the “base training” phase. This is attested by the large improvement in $\dot{V}O_{2max}$ in the H group, following the current dose–response consensus of 1.1% increase of Hb_{mass} for 100 h of adequate altitude exposure (Gore et al. 2013). With around 211 h of total hypoxic dose it could be expected an improvement of 2.2% in $\dot{V}O_{2max}$. As we observed an increase in $\dot{V}O_{2max}$ of 3.0%, that this difference is likely due to the additional effect of the training performed. In addition, since these athletes are performing at a high level, there are smaller possibilities of physiological change (Burtscher et al. 1996). Further, the quantity (3.3 ± 2.3 a.u. per subject) of daily TL change in the H-HRV group was moderate and mainly performed during the first week of LHTL. Moreover, the sample size

was relatively low as often in studies with elite athletes since by definition these athletes are scarce. Finally, one cannot rule out that the favorable HRV responses observed in the H-HRV group could translate to larger performance enhancement over time and/or at least would minimize the risks of overreaching in these athletes (Halson and Jeukendrup 2004; Hedelin et al. 2000).

The present study confirms the beneficial effects of LHTL (in the present case, in normobaric hypoxia) even in “true” (competing at European and World cup levels) elite Nordic skiers. There was a large improvement ($2.6 \pm 3.4\%$, $p < 0.01$) in the hypoxic groups while the normoxic group did not improve the endurance performance measured in a sport-specific way (i.e., a roller-ski time-trial) 21 days after the LHTL period. This result is in accordance with the 1–3% of aerobic capacity or performance improvement (Bonetti and

Table 4 Blood parameters change between Pre and Post-1 in hypoxic HRV-guided (H-HRV, $n=9$), hypoxic predefined (H, $n=9$), and normoxic (N, $n=6$) groups

Blood parameters	Pre	Post-1	p	ES
Erythrocytes ($T L^{-1}$)				
H-HRV	5.2 ± 0.3	5.3 ± 0.3	0.22	0.33
H	5.4 ± 0.5	5.3 ± 0.4	0.23	0.22
N	5.2 ± 0.3	5.2 ± 0.2	0.91	–
Hb (g dL^{-1})				
H-HRV	15.3 ± 0.9	15.7 ± 0.6	0.03	0.52
H	16.0 ± 1.1	15.9 ± 0.9	0.76	0.10
N	15.3 ± 1.0	15.5 ± 0.9	0.19	0.21
Htc (%)				
H-HRV	46.3 ± 3.0	47.8 ± 2.5	0.001	0.54
H	47.9 ± 2.7	48.6 ± 2.3	0.09	0.28
N	46.8 ± 2.3	47.8 ± 2.2	0.07	0.44
MCV (fL)				
H-HRV	88.7 ± 2.0	91.2 ± 2.0	0.001	1.25
H	89.5 ± 3.5	92.2 ± 3.5	0.001	0.77
N	90.7 ± 2.3	92.5 ± 2.1	0.001	0.82
Reticulocytes (g L^{-1})				
H-HRV	72.8 ± 28.7	71.8 ± 26.6	0.81	0.04
H	70.0 ± 14.2	64.1 ± 13.4	0.22	0.43
N	52.8 ± 12.5	44.8 ± 7.8	0.09	0.77
Ferritin (ng mL^{-1})				
H-HRV	128.6 ± 119.3	113.0 ± 99.2	0.08	0.14
H	102.3 ± 37.1	93.3 ± 34.1	0.30	0.25
N	147.7 ± 56.3	135.6 ± 49.2	0.26	0.23

With erythrocytes ($T L^{-1}$), hemoglobin (Hb, g dL^{-1}), hematocrit (Htc, %), mean cell volume (MCV, fL), reticulocytes (g dL^{-1}), and ferritin (ng mL^{-1}). Data are expressed as mean \pm SD. p for difference of change between Pre and Post-1, ES for effect size

Hopkins 2009; Brocherie et al. 2015; Hauser et al. 2016) associated with LHTL and confirms that LHTL is effective also when using chambers in normobaric condition (Saugy et al. 2016). The present results contradict a recent view that elite endurance athletes with initial elevated values of hemoglobin mass (Hb_{mass}) would not benefit from LHTL (Robach and Lundby 2012). Regarding the physiological responses to LHTL in the present study, there were several beneficial adaptations ($\dot{V}O_{2max}$; $\dot{V}O_{2VT2}$; roller-ski performance) in the two groups who slept in hypoxia. Further, there were no significant differences between H-HRV and H, and additionally no improvement in the control normoxic group. Specifically, in the two LHTL groups, $\dot{V}O_{2max}$ and $\dot{V}O_{2VT2}$ at Post-1 and roller-ski time-trial performance at Post-21 have been significantly enhanced. These changes in $\dot{V}O_{2max}$ and $\dot{V}O_{2VT2}$ are in line with the change in blood parameters shown in Table 4, particularly a significant increase in hemoglobin in H-HRV group. The positive changes observed in the hypoxic groups are similar to a vast body of literature

that consistently report the effectiveness of LHTL (Levine and Stray-Gundersen 1997; Schmitt et al. 2006b; Stray-Gundersen et al. 2001), but also with Kiviniemi et al. (Kiviniemi et al. 2007, 2010) who have demonstrated similar improvements in $\dot{V}O_{2peak}$ between HRV-guided and standardized training groups.

Conclusion

This study demonstrated that the daily individualized adjustment of the training loads based on morning HRV measurement blunted both the decrease in parasympathetic and the increase in sympathetic activities commonly associated with LHTL in H-HRV vs. H. We confirmed the first hypothesis and speculate that this result would reduce the overreaching risk. In addition, the second hypothesis was also validated in that LHTL is effective even with “true” elite endurance athletes since this study showed an improved performance and oxygen consumption in the two LHTL groups.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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