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ORIGINAL ARTICLE

Heart rate variability to assess ventilatory threshold in ski-mountaineering

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Abstract

The capacity to predict the heart rate (HR) and speed at the first (VT1) and second (VT2) ventilatory thresholds was evaluated during an incremental ski-mountaineering test using heart rate variability (HRV). Nine skiers performed a field test to exhaustion on an alpine skiing track. VT1 and VT2 were individually determined by visual analysis from gas exchanges (VT1V and VT2V) and time-varying spectral HRV analysis (VT1fH, VT2fH and VT2H). VT1 could not be determined with the HRV methods used. On the contrary, the VT2 was determined in all skiers. No significant difference between HR and speed at VT2H and VT2V was observed (174.3 ± 5.6 vs. 174.3 ± 5.3 bpm, and 6.3 ± 0.9 and 6.3 ± 0.9 km h⁻¹, respectively). Strong correlations were obtained for HR ($r = 0.91$) and speed ($r = 0.92$) at VT2H and VT2V with small limits of agreement (± 3.6 bpm for HR). Our results indicated that HRV enables determination of HR and speed at VT2 during a specific ski-mountaineering incremental test. These findings provide practical applications for skiers in order to evaluate and control specific training loads, at least when referring to VT2.

Keywords: Athlete, oxygen uptake, performance, ski, training, ventilatory equivalents

Introduction

Endurance performance is linked to the capacity for the athlete to train at a specific percentage of his/her maximum oxygen uptake. The first and second ventilatory thresholds (VT1 and VT2) are landmarks to adapt the intensity of training (Boulay, Simoneau, Lortie, & Bouchard, 1997). The intensity is usually specified in terms of speed or power. During skiing, speed and power are difficult to use because of the constant variations of the terrain and velocity as well as different external conditions, such as the quality of the snow. In this case, it is more convenient to express the intensity in terms of heart rate (HR).

In practice, VT1 and VT2 can be determined using the ventilatory method (Bosquet, Leger, & Legros, 2002; Myers, 2005; Wasserman, Whipp, Koil, & Beaver, 1973). Portable devices are now available, allowing testing in field conditions even

during winter and at high altitude (Doyon, Perrey, Abe, & Hughson, 2001). However, the expense and need to determine the ventilatory thresholds using the ventilatory method limits their use to specialised centres. Recently, some studies suggest that analysis of heart rate variability (HRV) could be a reliable non-invasive and low-cost method of assessing ventilatory thresholds (Buchheit, Solano, & Millet, 2007; Cottin et al., 2006, 2007; Dourado et al., 2010; Karapetian, Engels, & Gretebeck, 2008; Sales et al., 2011) even if a better accuracy is obtained for VT2 than VT1 (Mourot et al., 2012). Unfortunately, most of these studies were conducted in a laboratory and only two of them where “field” tests performed on a 10-m and 200-m flat running tracks (Cottin et al., 2007; Dourado et al., 2010), which is still a very controlled environment and is quite unlike ski-mountaineering. Moreover, the HRV methods

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chosen [time-domain analyses (Karapetian et al., 2008; Sales et al., 2011) or the Poincaré plot analysis (Paschoal & Fontana, 2011)] do not enable the determination of VT2 and thus are less applicable for performance in endurance sports. Conversely, a time-varying spectral-analysis method that computes high-frequency power spectral density (HFp) and the frequency associated with peak frequency in high-frequency range (fHF) has been used successfully to determine both VT1 and VT2 (Buchheit et al., 2007; Cottin et al., 2006, 2007; Mourot et al., 2012).

Thus, the aim of the present study was to test the hypothesis that HRV analysis would enable the determination of the ventilatory thresholds (VT1 and VT2) during a ski-mountaineering field test with sufficient precision to be used by the athletes in their training.

Methods

Subjects

Nine elite ski-mountaineers (5 men and 4 women) participated in this study. Their mean $\pm$ standard deviation (SD) age, height and weight were 32 ± 7 years, 168 ± 6 cm and 59 ± 5 kg, respectively. All trained regularly for competitions for at least two years prior to the study with an average training of 11 ± 1 h wk^{-1} . The protocol was carried out according to the Declaration of Helsinki and was approved by a local ethical committee.

Experimental protocol

Each participant performed a field ski-mountaineering incremental test to exhaustion on a groomed alpine

skiing track ("Poule au Pot", Font Romeu, France) in order to determine peak oxygen uptake ($\dot{V}\text{O}_{2\text{peak}}$), peak heart rate (HR_{peak}), VT1 and VT2. The weather during test day was sunny and the temperature was between 0°C and 5°C . The track was 950 m long with an ascent of 168 m and a mean grade of 9.1° (starting at 6° and then more regular at 13° as shown in Figure 1). Start altitude was 1950 m. The skiers began at 3 km h^{-1} and speed was increased by 0.5 km h^{-1} every minute until exhaustion. To be sure that the skier sustained the fixed velocity, the right side of the track was marked. The distance between two marks matched the distance that had to be completed at the fixed velocity during 30 sec. The skiers had to reach a specified mark ($\pm 2 \text{ m}$) each time they heard a sound communicated by two-way radio. If they could not reach (-2 m) the subsequent mark, the test was stopped and the maximal performance was considered to be achieved. Thus, this test involved skiing at a progressively faster pace regulated by audible signals, in a way comparable of traditional tests (Cottin et al., 2007; Dourado et al., 2010; Karapetian et al., 2008; Sales et al., 2011).

Gas exchange measurements

Minute ventilation ($\dot{V}_E$), carbon dioxide output ($\dot{V}\text{CO}_2$) and oxygen uptake ($\dot{V}\text{O}_2$) were continuously measured by a portable gas exchange measurement system (Cosmed K4b², Rome, Italy) already used during outdoor skiing (Doyon et al., 2001). Before each test, the system was calibrated with ambient air (O_2 : 20.93% and CO_2 : 0.03%) and a gas mixture (O_2 : 16.00% and CO_2 : 5.00%) and the turbine was calibrated with a 3-L syringe (Hans Rudolph Inc, Dallas, USA).

Figure 1. Profile of the alpine skiing track "Poule au Pot" at Font Romeu, France, that was used for the incremental test.

R-R intervals recording

During the test, beat-by-beat R-R intervals were recorded by telemetry (Polar T61, Polar Electro, Kempele, Finland) and a portable recorder (FRWD B100, FRWD Technologies, Oulu, Finland; Game-lin, Berthoin, & Bosquet, 2006; Nunan et al., 2009).

Data analysis

Peak oxygen uptake determination. The highest $\dot{V}O_2$ value obtained during the incremental test for 30 sec was defined as $\dot{V}O_{2\text{ peak}}$. Two or more of the following criteria had to be met to verify that the incremental test ended at skier's maximal capacity: a HR_{peak} within 10 beats of the age predicted maximal ($220 - \text{age}$); a respiratory exchange ratio superior to 1.1; and a plateau in $\dot{V}O_2$ with increasing speed (Howley, Bassett, & Welch, 1995).

Ventilatory threshold determination: assessment with the ventilatory method. VT1 and VT2 were determined with the "respiratory equivalent" (values averaged every 10 sec; Wasserman et al., 1973). VT1 and VT2 obtained with the ventilatory method were named VT1V and VT2V.

Ventilatory threshold determination: assessment with HRV. All R-R intervals were extracted from recorders and exported with FRWD Replayer software (FRWD Technologies, Oulu, Finland) for analysis using Kubios HRV analysis software (version 2.0 beta 4, University of Kuopio, Kuopio, Finland). All tachograms were examined to detect and correct artefacts (<1% of the analysed beats in the present study) before HRV analysis.

Because of cardiorespiratory coupling between HRV and ventilation, both fHF and HFp derived from the spectral analysis of HRV are governed by breathing frequency and breathing depth (tidal volume; Brown, Beightol, Koh, & Eckberg, 1993). fHF and HFp trends as a function of time over the entire exercise period were calculated using a time-varying short-term Fourier transform method with 64 sec moving windows with a time shift of 10 sec. Subsequently, HFp and the product of fHF $\times$ HFp were plotted against time; the first threshold (VT1fH) was determined as the first abrupt increase in fHF $\times$ HFp after it had reached a minimum, whereas the second threshold (VT2fH) corresponded to the final abrupt increase (Cottin et al., 2007). Moreover, VT2 was also determined from HFp only as the final abrupt increase HFp (Figure 2)

Figure 2. Simultaneous plot of the ventilatory equivalents, HF power spectral density (HFp) and R-R intervals(s) during the field test. The arrows correspond to the VT2 location according to the analysis of ventilatory and heart rate response. The curves presented in this figure were obtained in one representative skier with a final abrupt increase in HF power spectral density. Nevertheless, the slight decrease in HF power spectral density before the final increase was not always observed.

and named VT2H. HFp range was extended from resting recordings ($>0.15\text{--}0.5$ Hz to $>0.15\text{--}2$ Hz) (Cottin et al., 2007).

For each method, two experienced researchers, independently and in a blinded fashion, assessed VT1 and VT2 using the ventilatory method while two other researchers assessed the thresholds using HRV analyses. When there was a disagreement, a third experienced investigator was involved in the process. This investigator chose between the two options and the corresponding threshold was used. The HR and the speed corresponding to the thresholds determined by each method were computed.

Statistical analysis

Data are presented as mean $\pm$ SD. The Gaussian distribution of the data was verified by the Kolmogorov-Smirnov goodness-of-fit test (Z value < 1.0). When data were skewed or heteroscedastic, they were transformed by taking the natural logarithm. Statistical analyses were applied to the HR and speed values corresponding to the same threshold (VT1 or VT2) determined from different methods. Paired t -tests were used to discern any significant differences between VT1V vs. VT1fH, VT2V vs. VT2H and VT2V vs. VT2fH. The Pearson product-moment zero-order correlation coefficient was used to evaluate any significant relationships between (1) VT1V and VT1fH, (2) VT2V and VT2H or VT2V and VT2fH. Bland-Altman plots were used to assess the agreement between the measurements (Bland & Altman, 1986). Limits of agreement involved the mean difference between the two methods ± 2 SDs. Statistical significance was accepted at $p < 0.05$.

Results

Recorded values

All skiers completed the test and maximal responses were observed in every case. Field incremental test duration was 483 ± 124 sec, with a constant decrease in R-R interval as shown in a representative participant displayed in Figure 2. Maximal speed and maximal climbing speed were 7.9 ± 1.3 km h $^{-1}$ and 1255 ± 208 m h $^{-1}$. $\dot{V}O_{2\text{ peak}}$, $\dot{V}E_{\text{ peak}}$ and $HR_{\text{ peak}}$ were 67 ± 7 ml kg $^{-1}$ min $^{-1}$, 137 ± 26 L min $^{-1}$ and 181 ± 7 bpm, respectively.

First ventilatory threshold

Based on the ventilatory method, the mean HR and speed at VT1V were 153.2 ± 7.1 bpm and 5.3 ± 0.4 km h $^{-1}$. VT1V was determined in all skiers by two researchers. On the contrary, the determination of VT1fH was possible in only one skier (agreement

between the two researchers) with the corresponding values of 157 bpm and 6 km h $^{-1}$. None of the three researchers was able to determine VT1fH using fHF $\times$ HFp for the eight other skiers.

Due to the difficulty to determine VT1fH, no relationship/comparison with the Bland and Altman method could be done.

Second ventilatory threshold

Only two researchers were necessary for the determination of VT2V. The determination of VT2fH was not possible in eight skiers when using fHF $\times$ HFp. Agreement between the three researchers was obtained for the determination of VT2fH with fHF $\times$ HFp in only one skier. The determination of VT2H was possible in the nine skiers. The help of a third researcher was required in three cases. The mean HRs at VT2V and VT2H were 174.3 ± 5.3 bpm and 174.3 ± 5.6 bpm, respectively ($96 \pm 7\%$ of $HR_{\text{ peak}}$ in the two cases). The mean speeds at VT2V and VT2H were 6.3 ± 0.9 km h $^{-1}$. For both HR and speed, no significant difference ($p > 0.98$) was observed between VT2V and VT2H. Moreover, a significant and strong correlation ($p < 0.001$) were observed between the two methods (Figure 3). Bland and Altman plots showed that the biggest discrepancy between the two methods was 2.4 bpm for HR (limit of agreement ± 3.6 bpm, Figure 3) and was 0.5 km h $^{-1}$ for speed (limit of agreement ± 0.56 km h $^{-1}$, Figure 2).

Discussion

In this study, we tested the hypothesis that HRV analysis allows to determine the HR at the ventilatory thresholds during a ski-mountaineering field test. Results showed that the HRV methods tested could not be used for VT1 assessment. On the other hand, the spectral analysis using HFp only, and not the product of fHF $\times$ HFp, appeared sufficiently accurate in determining VT2 and may be used in training routines by the athletes. This was confirmed by a mean HR difference with the reference method that was lower than 3 bpm with limits of agreement of ± 3.6 bpm.

For athletes and coaches, the ventilatory thresholds are boundary markers used during training and testing sessions. In a laboratory, they are usually determined from respiratory measurements during an incremental test on cycle ergometer, treadmill or specific machine (Cottin et al., 2006; Fabre et al., 2012; Karapetian et al., 2008). Such evaluations are not always specific and require expensive materials. To address this problem, we proposed to use an incremental field test to exhaustion associated with the analysis of HRV.

Figure 3. Relationships between HR (up left) and speed (bottom left) at VT2V and VT2H during field incremental ski test (square = man; triangle = woman) with the identity line. The Bland–Altman plots display lines showing mean difference (systematic bias) between methods and the limits of agreement (2 SD around the mean) are presented in the right part of the figure. Please note that symbols of three pairs of subjects overlap exactly at speeds of 6, 6.5 and 7 km h⁻¹ in the VT2H–VT2V plots.

The ski-mountaineering test, consisting in skiing at a progressively faster pace to achieve maximal exercise in about 8–10 min, was not particularly validated in itself. However, the respiratory system used is adapted for extreme conditions even during winter and in altitude (Doyon et al., 2001) and the usual cardiopulmonary criteria for assessing maximal exercise were reached, after a progressive and constant increase as shown by the decrease in R-R interval (Figure 2). The values of $\dot{V}O_{2\max}$ (67 ± 7 ml kg⁻¹ min⁻¹) obtained are consistent with the data reported in high-level skiers (Fabre et al., 2012; Mourot, Fabre, Andersson, Willis, & Buchheit, et al., 2014; Mourot, Fabre, Andersson, Willis, & Hebert-Losier, et al., 2014). Successful skiers have high-aerobic power, both in absolute and relative values and maximal oxygen uptake is considered crucial for performance (Duc, Cassirame, & Durand, 2011).

Thus, we believe our procedure enabled accurate determination of the ventilatory thresholds. Specifically, the level of VT2 achieved in our study was in agreement with the training level of the participants, as based on previously published results with similar athletes (Fabre et al., 2012; Mourot, Fabre, Andersson, Willis,

& Buchheit, et al., 2014; Mourot, Fabre, Andersson, Willis, & Hebert-Losier, et al., 2014).

Non-invasive and low-cost methods based on HR recordings and the analysis of HRV have been proposed to identify the ventilatory thresholds (Buchheit et al., 2007; Cottin et al., 2006, 2007; Dourado et al., 2010; Karapetian et al., 2008; Sales et al., 2011). The use of time-domain index to determine the VT1 is based on the idea that vagal R-R modulation is no longer present beyond this threshold (Tulppo, Makikallio, Seppanen, Laukkanen, & Huikuri, 1998; Yamamoto, Hughson, & Nakamura, 1992). However, conflicting results exist, and these indexes seem insufficient to assess the first ventilatory threshold accurately (Mourot et al., 2012).

Both VT1 and VT2 were determined in the present study with the time-varying method. This method computes fHF and HFp that depend on both changes in tidal volume and breathing frequency (Cottin et al., 2006, 2007). We were unable to determine VT1. On the other hand, when using HFp only, VT2 was determined in eight skiers, and the limit of agreement between the HR at VT2 from ventilatory measurements and from the time-varying analysis was low (3 bpm). This agreement (<5%) was comparable or

lower than that obtained in terms of HR (Buchheit et al., 2007), oxygen uptake (Karapetian et al., 2008) or power output (Cottin et al., 2006), suggesting that this method is promising in assessing HR associated with VT2 and thus in guiding the design of exercise intensity training in ski-mountaineering athletes. Contrary to VT1, characterised by low intensities, intensities at VT2 are quite demanding, requiring great autonomic responses that may trigger easiest points-recognition as well as better agreement between respiratory exchange methods and HRV analysis.

On the other hand, it is important to note that the use of the fHF $\times$ HFp method did not enable the determination of VT1 and rendered the determination of VT2 possible in only one skier. With the experimental design used in the present study, we could not explain the mechanisms responsible for this observation. However, this may relate to the type of locomotion studied in our study, i.e. ski-mountaineering and the involvement of the upper body.

Specifically, a mechanism involving changes in the intrathoracic pressures during dynamic exercise may be involved (Bernardi et al., 1990). In comparison to running or cycling, the contribution of the upper body during skiing alters considerably these pressures. This could trigger a specific effect on HRV. Indeed, in our study, fHF did not increase continuously during the exercise (e.g. Cottin et al., 2007). Instead, fHF followed an erratic pattern in eight of nine subjects (Figure 4). We have no explanation for this except a potential interaction between locomotion, ventilation and cardiac

activities during skiing sports (Fabre et al., 2012). It should also be noted that in previous works (Buchheit et al., 2007; Mourot et al., 2012), the fHF trend has been smoothed before being used for calculation while it was not the case in our study given that very erratic curve trend.

The number of skiers studied was rather limited to give clear and definitive results. The number of subjects in comparable studies has also been low from 10 to 12 (Cottin et al., 2006, 2007; Dourado et al., 2010; Sales et al., 2011). This may nevertheless not limit the capability of this research to find a good agreement between the two methods tested to determine VT2. Also, the determination of VT, from ventilatory measures or HRV analysis, remains subjective and operator-dependent. At least two independent observers are required for reliable determination (Meyer et al., 1996) and sometimes three are indeed involved. A valid and objective procedure is still lacking for assessing VT2 from both respiratory measurement and HRV. It is of note that in this study the version 2.0 beta 4 was used, which is an uncommon version (Tarvainen, Niskanen, Lipponen, Ranta-Aho, & Karjalainen, 2014). New studies with further versions of the Kubios software are required to confirm our findings. Finally, we extended the HFp frequency band to include high-breathing frequencies. Evidence exists that during exercise tests non-respiratory spectral peaks may appear in this band related to pedal frequencies used during the cycle-ergometer exercise (Villa, Castiglioni, Merati, Mazzoleni, & Di

Figure 4. Example of the frequency associated with high-frequency (HF) power spectral density of the subject with a regular increase during the exercise (up) or in a representative subject involved in the present study, with a very irregular pattern (down).

Rienzo, 2008). Even if unlikely, we could not exclude that similar components occur with skiing and relate to cadence since it has been observed that arm poling drives ventilation, suggesting that mechanical influences are dominant compared to the metabolic ones (Fabre et al., 2012). It could be argued that the diagonal stride technique may be associated with a lower coupling between the mechanical constraints imposed by the locomotion and the respiratory apparatus and that the ventilatory method is valid during ski-mountaineering, compared to cross-country skiing with the skating technique (Fabre et al., 2012).

Conclusions

The results showed that HRV time-varying spectral analysis during a field ski-mountaineering test could enable the determination of the HR associated with VT2 with sufficient precision to be used as part of a training routine without the need of a gas analyser device. On the other hand, the VT1 could not be determined with the HRV analyses tested in the present study. VT2 is a boundary marker to determine during a testing session and is of high importance for training. Based on the present result, we believe that HRV is a promising method for athletes and coaches.

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