Ventilatory Threshold Prediction by Spectral Analysis of Heart Rate Variability in Incremental Maximal Tests

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Abstract

Ventilatory thresholds (VT1 and VT2) are useful in many fields of medicine and sports. Nevertheless, their measurement is cumbersome and needs trained personnel. This work proposes an alternative method to predict VT1, VT2 and maximum loads in incremental maximal tests based on heart rate variability (HRV) analysis. Twelve competitive male cyclists executed an incremental exhaustive test. During the test, RR time series and gas concentrations were recorded. After artifact correction the power spectrum was estimated in a sliding window, and central frequency (CF) and bandwidth that contains half the total power (BW) were computed. An automatic algorithm recognized the loads where CF and BW undergo a significant change. These loads were used as inputs in linear regression models to predict VT1, VT2 and maximum loads. The errors of the predictions are similar to the load resolution.

1. Introduction

The estimation of the First and Second Ventilatory Thresholds (VT1 and VT2) is useful in many fields in medicine and sport, like cardiac or pulmonary therapy or enables to program an endurance sport season [1].

VT1 and VT2 are assessed during a maximal incremental test with a gas analyzer [2]. VT1 is the ventilatory threshold and VT2 is the threshold of decompensated metabolic acidosis. VT1 is determined visually by an expert as the point where V_E'/V_{O2}' increases nonlinearly while V_E'/V_{CO2}' remains constant; and VT2 is the point where V_{CO2}' increases nonlinearly with respect to V_{O2}' (being V_E' the respiratory flow, V_{O2}' oxygen consumption and V_{CO2}' the carbon dioxide production).

VT1 and VT2 assessment is cumbersome because a gas analyzer and trained personnel are needed. During an incremental test it is very common to measure, simultaneously with gas concentrations, the heart rate or the electrocardiogram. These measurements enable us to obtain the RR time series for further analysis of heart rate variability (HRV).

VT2 has been estimated through analysis of HRV [3],[4],[5]. Nevertheless, all these studies need the complete test and an expert observer in order to ascertain the threshold location. One drawback in the traditional spectral analysis of HRV [6] is the partition of the power spectrum in bands with constant limits. In incremental tests, the breathing frequency increases with the load so it is presumable to lie above the maximum limit of the high frequency band (typically 0.4 Hz) being the result of the power of the high frequency band completely meaningless.

The aim of this work is to propose a HRV processing methodology that predicts the load at which VT1 and VT2 occur. The signal processing is based on spectral indices that don't require a band definition as opposed to the classical spectral indices.

2. Materials and methods

Twelve competitive male cyclist (34.1±5.7 years old) participated in this study. Prior to the test, each subject was familiarized with the experimental procedure and was informed of the risks associated with the protocol. All subjects gave their written voluntary informed consent. The measurement protocol was an incremental exercise test in the upright position on an electronically braked cycle ergometer (Excalibur Sport, Lode, The Netherlands) modified with clip-in pedals. Each subject performed a 25W/min incremental test [2]. The pedaling frequency was chosen at will between 70 and 100 rpm.

During the test, the RR time series was collected with a Polar RS800 (Polar Electro, Finland, OY) with a 1 kHz sampling frequency, and the gas measurement was performed with a Cosmed Quark PFT-Ergo gas analyzer (Cosmed, Italy). Before each test, ambient conditions were measured and the gas analyzers and inspiratory flowmeter were calibrated. Gas measurements were used by an expert doctor in order to estimate VT1 and VT2 loads.

Prior to processing, the artifacts of the RR time series were corrected with the software Kubios HRV 2.0 (University of Kuopio). Then, the analysis was done using a sliding window with a length of 300 beats and an incremental shift along the RR time series of one beat. Inside the window, the RR time series were first detrended with a smooth priors detrending method with λ= 100 [7] and then resampled at 10 Hz. The power spectrum was estimated using the FFT and a Hann window.

To characterize the power spectrum without a band definition, we have computed the accumulated power spectrum as:

$$AP_{RR}(n) = \frac{\sum_{i=1}^{n} P_{RR}(i)}{\sum_{i=1}^{N} P_{RR}(i)} \quad (1)$$

where $P_{RR}(i)$ is the power spectrum estimation at frequency f(i) and f(N) is the Nyquist frequency (5 Hz in our case). The central frequency (CF) was defined as the frequency where AP_{RR} is equal to 0.5. The bandwidth at 50% (BW) was defined as the difference between the frequency where AP_{RR} is equal to 0.75 and the frequency where AP_{RR} is equal to 0.25. Figure 1 shows an example of the computation of both indices.

For each power spectrum, the CF and BW were computed. So, for each test, time series of CF and BW indices were obtained. The central frequency threshold (CFT) was defined as the first sample since the start of the exercise where

$$CF(CFT)-CF(CFT-100)>0.15 \text{ Hz} \quad (2)$$

so it corresponds to a drastic change in CF. The bandwidth threshold (BWT) was defined as the sample where, starting at CFT and looking backwards, the bandwidth falls below BW(CFT)/2. Finally, the loads at which CFT and BWT occur were obtained (P_{CFT} and P_{BWT}, respectively).

P_{CFT} and P_{BWT} were considered as the independent variables in linear regression models to estimate the values of the maximum load (P_{Max}), VT2 load (P_{VT2}) and VT1 load (P_{VT1}) estimated from the gas analyzer measurements by trained personnel. Figure 2 shows an example of all this procedure.

3. Results

Table 1 shows the mean, maximum and minimum values of the loads where the different threshold occur. It is worth noting that P_{CFT} and P_{BWT} always occur for lower loads than the other thresholds.

Results for the linear regressions are shown in table 2. Each threshold can be estimated as:

$$P_i = P_o + \alpha_1 \cdot P_{BWT} + \alpha_2 \cdot P_{CFT} \quad (3)$$

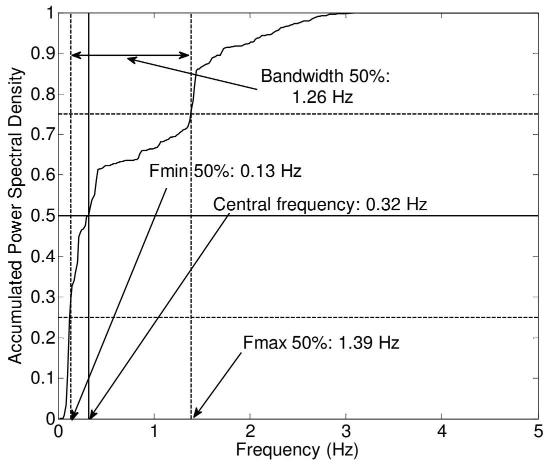

Figure 1. Example of the computation of CF and BW corresponding to the accumulated power spectral density of a subject exercising with a mild load.

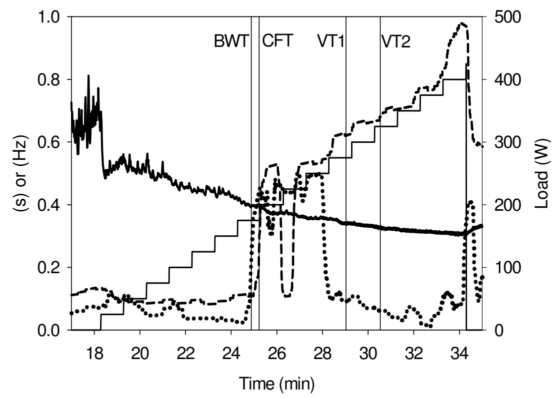

Figure 2. Example of one incremental maximal test. The thick solid line corresponds to the RR time series, the thin stepwise line corresponds to the incremental load used during the test, the dotted line shows the evolution of BW and the dashed line shows CF. VT1 and VT2 are the expert's annotations while BWT and CFT are, as described in the text, the automatically located instants were sudden changes in CF and BW occur.

Figure 3 show the Bland-Altman plots comparing the estimated loads from equation (3) and the measured loads using the gas analyzer and the expert annotations. The plots also show two horizontal lines indicating the size of the load increments (± 25 W which is the resolution of our measurements). As seen, in most of the cases the difference between the annotation and the predicted load is below the load resolution.

Table 1. Mean, maximum and minimum loads measured in the twelve subjects

Load	Max	Mean	Min
P_{Max} (W)	425	394.2	350
P_{VT2} (W)	350	329.5	300
P_{VT1} (W)	300	274.5	250
P_{BWT} (W)	200	168.0	125
P_{CFT}(W)	225	198.7	175

Table 2. Linear regression models to estimate maximum, VT2 and VT1 loads. The Standard Error of Estimate is also shown.

Load	P_o (W)	α_1	α_2	SEE (W)
P_{Max}	278.2	0.299	0.384	24.3
P_{VT2}	196.0	0.313	0.395	23.6
P_{VT1}	203.4	-0.150	0.523	22.6

4. Discussion and conclusion

Results show that BW and CF can be used to predict the load events on a maximal incremental test. For the whole twelve participants, the abrupt changes in BW and CF happened always in advance of VT1 so this methodology can be applied in real time and stop the test once CFT is detected. Nevertheless, all participants were competitive male cyclist and further studies must be done in order to ascertain if this methodology is also valid for other groups.

Spectral indices without band definition could prove useful in the analysis of RR time series during exercise because the drastic physiological changes associated with physical effort cause a radical modification of the heart rate variability power spectrum.

In conclusion, BW and CF can predict VT1, VT2 and maximum loads in competitive male cyclists while performing a maximal incremental test with an error comparable to the load resolution.

Acknowledgments

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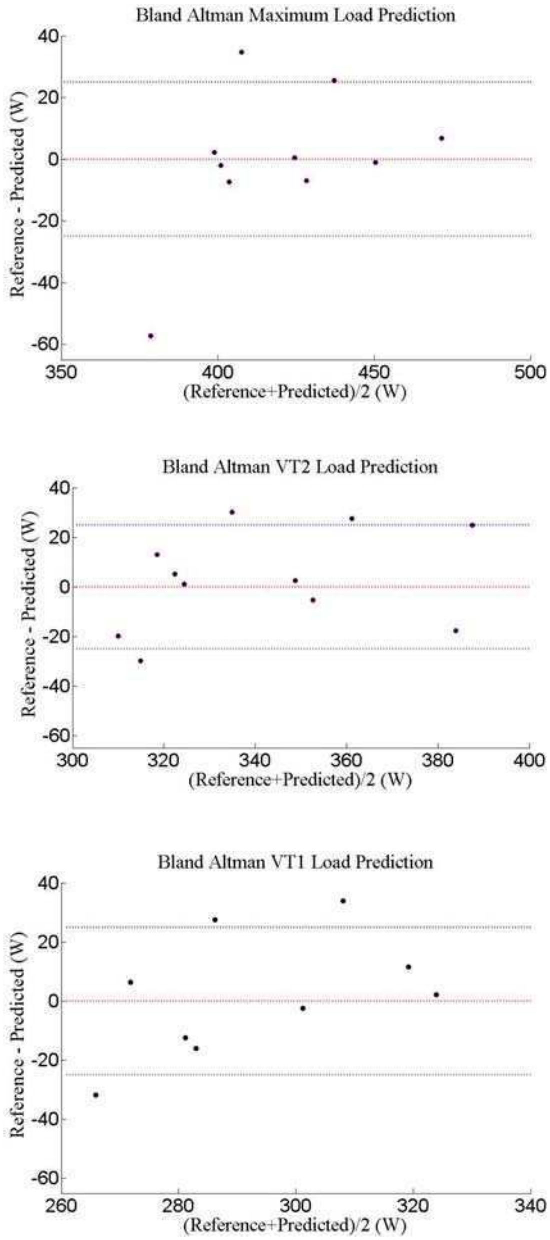

Figure 3. Bland-Altman plots for the agreement of expert annotated loads (reference measurement) and predicted loads from BW and CF measurements. Horizontal lines show the resolution of the load. Top panel: maximum load. Middle panel: VT2. Bottom panel: VT1.

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