Determination of Anaerobic Threshold by Heart Rate or Heart Rate Variability using Discontinuous Cycle Ergometry

SUNG WOOK PARK†, MICHAEL BRENNEMAN†, WILLIAM H. COOKE‡, ALBERTO CORDOVA‡, DONOVAN FOGT‡

Department of Health and Kinesiology, The University of Texas at San Antonio, San Antonio, TX, USA

†Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 7(1) : 45-53, 2014. The purpose was to determine if heart rate (HR) and heart rate variability (HRV) responses would reflect anaerobic threshold (AT) using a discontinuous, incremental, cycle test. AT was determined by ventilatory threshold (VT). Cyclists (30.6±5.9y; 7 males, 8 females) completed a discontinuous cycle test consisting of 7 stages (6 min each with 3 min of rest between). Three stages were performed at power outputs (W) below those corresponding to a previously established AT, one at W corresponding to AT, and 3 at W above those corresponding to AT. The W at the intersection of the trend lines was considered each metric's "threshold". The averaged stage data for Ve, HR, and time- and frequency-domain HRV metrics were plotted versus W. The W at the "threshold" for the metrics of interest were compared using correlation analysis and paired-sample t-test. In all, several heart rate-related parameters accurately reflected AT with significant correlations (p≤0.05) were observed between AT W and HR, mean RR interval (MRR), low and high frequency spectral energy (LF and HR, respectively), high frequency peak (fHF), and HFxfHF metrics' threshold W (i.e., MRRTW, etc.). Differences in HR or HRV metric threshold W and AT for all subjects were less than 14 W. The steady state data from discontinuous protocols may allow for a true indication of steady-state physiologic stress responses and corresponding W at AT, compared to continuous protocols using 1-2 min exercise stages.

KEY WORDS: Heart rate, heart rate variability, anaerobic threshold, cycling

INTRODUCTION

Appropriate responses to exercise stressors are driven, in large part, by the autonomic nervous system (ANS) and the resultant balance between sympathetic and parasympathetic influences on peripheral tissues (sympathovagal balance). Heart rate (HR) and the variability of heart beat-to-beat intervals, i.e., heart rate variability (HRV), are indirect metrics reflecting ANS activity (19), and reflect stress level during large muscle mass, dynamic exercise like running and cycling. However, the accuracy of these metrics in the field is complicated by the disproportionate change in the sympathovagal balance versus intensity relationship at or around the anaerobic threshold (AT) (8, 14,16,17, 21, 22). Numerous studies have identified HR threshold (HRT) and "thresholds" for various HRV metrics corresponding to AT (6, 2, 10, 11, 13, 18). Expressing stress level relative to such a HR or HRV threshold

(e.g., power output eliciting 75% of HRT), as opposed to absolute cardiac metrics, would allow accurate, real-time pacing in the field. Furthermore, the ability to assess AT in the field using HR or HRV would be more applicable for athletes and coaches than established laboratory-based techniques such as lactate threshold (LT) and ventilatory threshold (VT) (6).

Most investigations that evaluate HR or HRV versus intensity use continuous incremental exercise protocols (reviewed in 6). The exercise stages for these protocols typically last 1-2 min, which does not allow time for adequate sympathovagal balance. This is due to inherent fluctuations of efferent/afferent control systems, which are more dynamic during the initial response to stress. Once the appropriate afferent/efferent balance is achieved, the recorded metric will not fluctuate greatly (i.e., "steady state") unless the stress level changes. For instance, during exercise of a given intensity, O2 consumption and HR both rise during the first minutes exercise (14). Therefore, in the first minute of a 1-2 min exercise stage, it is difficult to know if data collected during the first minutes of a given exercise stage reflect steady-state responses (5). In addition, with continuous protocols it is probable that responses to one exercise stage carryover to the next stage. Because of this, development of accurate linear relationships between HR/HRV and intensities below AT are not possible. Therefore, the ideal endurance training output at HRT derived from a continuous test protocol would be misidentified, and premature fatigue would likely occur.

Discontinuous incremental exercise protocols allow for longer stages at given intensities and brief recovery periods. In such a protocol, exercise performance metrics such as HR and VO2 are assessed late in the exercise stage (e.g., after 3-5 min of the same exercise intensity). Thus, the assessment occurs after HR and VO2 responses have plateaued, reflecting appropriately "balanced" efferent/afferent tone for a particular intensity of exercise. Additionally, the recovery period in between stages ensures that the subsequent stage data is not influenced by protracted factors from a previous stage (i.e., lactic acid, epinephrine, etc.). Because of these differences, discontinuous protocols allow for a true indication of steady-state physiologic stress responses, independent of the possible carryover effects from previous exercise stages (reviewed in 5) compared to continuous protocols. Despite the physiological benefits described above, discontinuous protocols have not been used to study simple surrogate measures of AT. Therefore, the purpose of the present study was to determine if changes in HR and/or HRV would reflect AT using a discontinuous, incremental, cycle test. To accomplish this, exercise thresholds were determined for HR and HRV metrics and compared with the criterion AT assessment, VT.

METHODS

Participants
Using a student t-based algorithm with an alpha = 0.05, and beta (power level) = 80%, a power analysis was run to determine the minimum number of subjects required for our comparison. It was determined based on available pilot data for AT (n=100, sd=20), that 15 subjects were needed to detect a 5 W difference in W at AT. Experienced cyclists, age 18-35 y, were

recruited for this study, with eight female and seven male participants subjected to the protocols described below. For this study, the term "experienced cyclist" was defined as an individual self-reporting moderate intensity cycling an average of three times per week. This study was approved by the Institutional Review Board for the Protection of Human Subjects in Research of the University of Texas at San Antonio. Written informed consent was obtained from all participants following a verbal and written briefing of all experimental procedures.

Protocol
Participants were asked to abstain from stimulants, including caffeine, exercise, and alcohol 12 h before the cycling sessions. Participants reported to the laboratory in the morning after an 8 h fasting condition on two sessions. The height and weight of the participants was recorded and their body composition was assessed using 7-site skinfolds (1). Four frame measurements were taken on each participant's bicycle were matched on a Lode Excalibur (Lode B.V., Groningen, Netherlands) cycle ergometer to reproduce the participants' training position. Participants performed all testing in their usual training attire and used their own cycle pedals and shoes. All procedures were performed in a thermoneutral environment under close supervision of laboratory assistants familiar with the testing protocol and data collection.

Following measurement of shoeless height and body mass, participants were outfitted with a breathing mask allowing for inhalation of room air and analysis of expired air for ventilation (Ve; L air•min-1), oxygen consumption (VO2; L O2•min-1)

and carbon dioxide production (VCO2; L CO2•min-1; TrueOne2400 Metabolic Measurement System, ParvoMedics Inc., Sandy, UT). Participants wore a chest HR transmitter (2-lead ECG; Polar Electro, Kempele, Finland) and wristwatch monitor (Polar model RS810) capable of measuring the time interval between successive heart beats as denoted by cardiac cycle R-waves (i.e., R-R interval).

Participants completed a traditional continuous cycle exercise test during which intensity was increased by 20 watts (W) every minute starting at 60 W and continuing until volitional fatigue (e.g., ~400 W for males and ~300 W for female cyclists). This session provided data to 1) determine of the cardiorespiratory fitness of each participant (i.e., VO2peak), 2) determine participants' individual VT using Ve versus W (i.e., VeT1W), and 3) establish the intensities for the subsequent discontinuous cycle test exercise stages. Individual's Ve data were plotted versus W for each stage to determine VT by computer linear regression to establish VeT1W (20).

The discontinuous test took place within seven days of the continuous test. Following the same instrumentation described above, participants performed a series of seven stages of exercise lasting 6 min each with 3 min of rest between each stage. Three stages were performed at intensities below VeT1W (i.e., below AT). One stage was then performed at VeT1W (i.e., at AT) followed by three stages above VeT1W (i.e., above AT). The first three stages were performed at intervals of 20% lower than VeT1W. For example, with VeT1W considered as 100%, stage 1 W were 40% of VeT1W, stage 2 W were 60% of VeT1W and stage 3 W were 80% of VeT1W.

For the stages above AT, 10% increases in intensity were used from VeT1W (i.e., stages 5, 6, and 7 were 110, 120, and 130% of VeT1W, respectively). Exercise Ve, HR, and cardiac interbeat intervals were recorded during the last 3 min of each stage. HR and interbeat interval data were downloaded to a computer for off-line analysis with Kubios HRV analysis software (Biosignal Analysis and Medical Imaging Group; Department of Physics, University of Kuopio, Finland). Averaged data from the last 3 min of each stage were analyzed.

Statistical Analysis

For HRV metrics, the following time-domain data were assessed: mean RR interval (MRR), standard deviation RR interval (STDRR), and root mean square standard deviation (RMSSD). Additionally, the following frequency-domain results were analyzed: low frequency spectral energy (LF; 0.014-0.15 Hz), high frequency spectral energy (HF; 0.15-0.4 Hz), HF frequency peak (fHF; ms2), and HF•fHF (Hz•ms2).

The averaged stage data for Ve, HR, and each time- and frequency-domain HRV metric were plotted versus W (Microsoft Office Excel 2007, Microsoft Corporation). For each parameter, two trend lines with corresponding slope-intercept (i.e., $y=mx+b$) formulas were established for the stage data using Microsoft Excel (Microsoft Corporation). One trend line was established for data points from stages known to be below and at AT, as reflected by VeT1W, while the other trend line was established for data points collected at stages corresponding to AT and above. The intersection point of the two lines was then determined using $y=ax+b$ and $y=cx+d$

followed by $x=(d-b)•(a-c)-1$. The W corresponding to the intersection of these trend lines was considered to represent each metric's "threshold". No relationships were discernible for STDRR or RMSSD data versus W so these parameters were not evaluated further.

Once parameters' thresholds were identified, they were compared to the W corresponding to the discontinuous cycle test VT (i.e., VeT2W) using Pearson (two-tailed) and paired-sample *t*-test (IBM SPSS Statistic, Version 19; IBM Company). Our significance level was set *a priori* at *p value* < 0.05.

RESULTS

Participants' average age, height, body mass, body mass index (BMI), VeT1W, and VO2peak are provided in Table 1. The participants' BMI is classified as "normal" while the VO2peak data is consistent with that of ~80th percentile for 20-40 year olds by the American College of Sports Medicine (1).

The average observed W corresponding to VT during the continuous cycle test (VeT1W) and the discontinuous cycle test (VeT2W) were normally distributed (Shapiro-Wilk=0.931, df=15, p>0.05) highly correlated (r=0.97; p=0.000), with individual participants' VeT1W and VeT2W varying by less than 3 W (p>0.05). Participants' individual VeT2W were used in the comparison of HR and HRV metrics' threshold W. The W corresponding to the intersection of trend lines established for HR, MRR, LF, HF, fHF, HF•fHF data were considered to represent each metric's "threshold" (i.e., HRTW, MRRTW, LFTW, HFTW, fHFTW, and HF•fHFTW, respectively) (Figure 1).

Table 1. Participant age, anthropometric characteristics and endurance performance indicators.

	All subjects $n=15$	Male $n=7$	Female $n=8$
Age (years)	30.6 ± 5.9	29.3 ± 5.6	31.8 ± 6.3
Height (m)	1.72 ± 0.06	1.78 ± 0.05	1.69 ± 0.04
Body mass (kg)	69.8 ± 14.9	81.3 ± 14.8	59.8 ± 3.3
BMI (kg•(m²)⁻¹)	23.2 ± 3.7	25.6 ± 4.0	21.1 ± 1.6
Body fat (%)	22.5 ± 10.2	15.2 ± 6.8	25.2 ± 9.6
VeT1W	183.7 ± 37.1	214.0 ± 22.0	157.3 ± 24.8
Absolute VO2peak	3.3 ± 0.9	4.1 ± 0.6	2.6 ± 0.4
Relative VO2peak	46.9 ± 13.0	49.1 ± 17.3	44.1 ± 16.7

Data are means ± sd. Absolute and relative VO2peak units are L O2•min⁻¹ and ml O2•kgBW⁻¹•min⁻¹, respectively. BMI, Body Mass Index; VeT1W, ventilatory threshold watts as determined using continuous cycle ergometry.
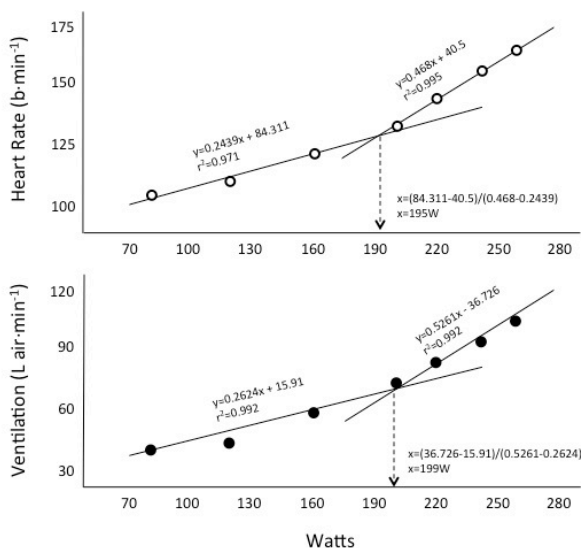

Figure 1. Average stage data for heart rate and ventilation versus W are shown for representative subject. The averaged stage data for Ve, and HR were plotted versus W. For each parameter, two trend lines with corresponding slope-intercept (i.e., y=mx+b) formulas were established for the stage data. One trend line was established for data points from stages known to be below and at AT, as reflected by VeT1W, while the other trend line was established for data points collected at stages

corresponding to AT and above. The intersection point of the two lines was then determined using y=ax+b and y=cx+d followed by x=(d-b)•(a-c)⁻¹. The W corresponding to the intersection of these trend lines was considered to represent each metric's "threshold".

Discernible linear relationships between the HRV metric data and W were not observed for all participants. Namely, HRTW was not established for one female subject, MRRTW was not established for two male subjects and one female subject, HFTW and fHFTW were each not established for a male subject. When a HR or HRV metric threshold could not be established, the subject's data, including VeT2W, were not included in the subsequent statistical analyses. Comparisons of the established HR and HRV metric threshold W and the corresponding VeT2W are presented in Table 2. Statistically significant correlations ($p \le 0.05$) were observed between all HR and HRV metric threshold W and VeT2W when participants' data were compared.

Significant statistical differences ($p < 0.05$) were not observed for VeT2W and HRTW (2.0 ± 13.4W difference), MRRTW (10.0 ± 26.4W difference), HFTW (7.3 ± 19.0W difference), and HF•fHFTW (-2.4 ± 23.1W difference). However, the 11.3 ± 17.8W difference for LFTW and -13.9 ± 18.7W difference for fHFTW were statistically significant ($p=0.028$ and $p=0.015$, respectively).

DISCUSSION

We have demonstrated that the power output at AT can be determined using HRT and several HRV metric thresholds from a discontinuous, incremental cycling protocol. In the present study, thresholds for HRT and the related MRR correlated

Table 2. Comparisons of the established HR and HRV metric threshold W and the corresponding VeT2W.

Variable	n	VeT2W (means ± sd)	VariableTW (means ± sd)	Correl.	Sig.	Difference (means ± sd)	Sig.
HRTW	14	185.7 ± 37.6	183.8 ± 35.0	.95	.000	+2.0 ± 13.4	.591
MRRTW	12	177.6 ± 35.2	167.7 ± 38.5	.75	.005	+9.9 ± 26.4	.220
LFTW	15	182.7 ± 38.0	171.4 ± 38.5	.89	.000	+11.3 ± 17.8	.028[a]
HFTW	15	183.6 ± 39.3	176.3 ± 46.5	.92	.000	+7.3 ± 19.0	.175
fHFTW	14	178.5 ± 35.5	192.5 ± 43.7	.91	.000	−14.0 ± 18.7	.015[a]
HF•fHFTW	15	182.8± 38.0	185.1 ± 50.3	.90	.000	−2.4 ± 23.1	.689

[a] Significant difference between watts at threshold versus VeT2W. Variable metric and abbreviations are: ventilatory threshold watts (VeT2W), heart rate threshold watts (HRTW), mean RR interval threshold watts (MRRTW), low frequency spectral energy (LF; 0.014-0.15 Hz) threshold watts (LFTW), high frequency spectral energy (HF; 0.15-0.4 Hz) threshold watts (HFTW), HF frequency peak (fHF; ms^2) threshold watts (fHFTW), and HF•fHF (Hz•ms^2) threshold watts (HF•fHFTW).

significantly with W at AT as determined by VT.

The inherent fluctuation of autonomic balance makes it difficult to determine if physiologic data collected early in a given exercise stage will reflect the body's definitive response. HRT and HRV threshold investigations in cycling have utilized continuous, incremental exercise protocols consisting of 1-2 min stages. Therefore, threshold determination using blood lactate, Ve, VO2, HR, or HRV metrics may not be optimally applicable for training or competition wattage prescription in the field. For example, the HRT, or oft-termed "heart rate deflection point" (HRDP), was identified in cyclists by Bourgois and colleagues (7) using a continuous cycle test.

A subsequent 30 min test at HRDP W was performed in order to test if HRDP would elicit steady state conditions. Only 6 of 11 subjects were able to complete the 30 min with 5 subjects demonstrating accumulating blood lactate values. These findings are indicative of the HRDP W, as determined by a continuous test, over-predicting the subsequent work rate leading to premature fatigue. Such an AT over-prediction was also observed in a large cycle study by Carey et al. (9). The agreement between time trial performance and data collected during protocols using multiple, longer stages (e.g., 3 min) of exercise has also been demonstrated by Bentley DJ & McNaughton LR (4). When considering that typical endurance (i.e., ≤AT) cycle training rides or races last far longer than 30 min, the potential performance impact of an over-prediction of AT using continuous protocol-derived W from HRT is clear. Together, the findings above suggest that AT data derived from a discontinuous protocol stages that are long

enough to establish "steady-state" may be more appropriate for exercise prescription.

Accurate representation of the initial, sub-AT, linear relationship between intensity and Ve, HR, and HRV metrics is paramount to subsequent identification of the non-linear deflection in the data collected at intensities above AT. The data from the present study were collected during the last 3 min of cycling at each 6 min exercise intensity stage. Furthermore, several minutes of rest between each stage ensures that no lingering effects from an earlier stage the physiological response to a subsequent workrate. Therefore, data from the sub-AT intensity stages can be considered as steady-state conditions and reflective of the appropriate response level of the fast-responding physiological metrics of interest. The highest observed absolute difference in VeT2W and the HRTW and HRV metrics' W was >16 W with several comparisons differing by as little as 2 W. This range is notable as bicycles used for endurance training and competition commonly will change by ~20 W per sprocket/gear shift at the same cadence. A low degree of error of the appropriate sub-AT power output determined in the laboratory to the field allows cyclists to determine the optimal sprocket and cadence combination to suit their performance.

We are not aware of any study reporting comparisons between HRV and Ve thresholds using a discontinuous exercise protocol. Several studies have focused on evaluation of HRV changes near AT using continuous protocols (2, 10, 11, 13, 18). Spectral analysis of HRV has proven useful in these investigations because cardiorespiratory parameters' temporal series, namely HR and Ve, fluctuate dramatically during load increases. Observed changes in the increment of increase in the HF domain (>0.15 Hz) appear to correlate to workrates above AT. The HF parameter reflects the amplitude of the sinus arrhythmia (RSA) and vagal tone. High frequency increases in vagal tone above the intrinsic sinus depolarization rate (i.e., ~100bpm) is perhaps a response to venous return-mediated stretch of the right atrium and sinus node. Thresholds identified in the present study using HF HRV metrics (i.e., HFTW, fHFTW, HF•fHFTW) all correlated with VeT2W.

Spectral LF variations in R-R intervals reflect changes in both SNS and PSNS activity (19). Like HF results, the LFTW correlated with VeT2W in the present study. It is unclear why HRV LF would change measurably at AT. This finding was somewhat surprising from a physiological perspective as the overall PSNS influence is minimal above low intensity exercise (HR > 100 bpm). In such, changes in LF above AT would be influenced predominantly by SNS, possibly decreasing the predictive potential of LF for ATW. Additionally, other, non-neural factors such asepinephrine or respiratory pump on HR increase with intensity which may play a role as well, which could impact the reliability of the LF parameter to predict AT.

There are a few key limitations to our generalizing our findings to all adult cyclists. Firstly, this was a relatively small sample of experienced cyclists. Whether or not the findings would apply across a wider range of experience levels or age groups is not known. Secondly, discernible relationships between the HRV metric data

and W were not observed for all participants. Namely, HRTW was not established for one female subject, MRRTW was not established for two male subjects and one female subject, HFTW was not established for one male subject, and fHFTW was not established for one male subject. When a HR or HRV metric threshold could not be established, the subject's data, including VeT2W, were not included in the statistical analyses. This procedure could have biased the findings. Furthermore, the inability of identifying a threshold in 30% of participants has important implications for the consistency of these metrics in the field. The low number of participants makes extrapolation of the findings to similar populations difficult at best. Further studies are needed to ascertain if failure to identify a threshold results from the protocol, data collection techniques, or participants individual differences.

AT is the best predictor of performance in endurance activities such as cycling and running (reviewed in 12). Knowing the W associated with AT is especially relevant when cyclists want to maintain a given % of AT for extended periods of time. Cycling at or just under AT allows for sustained performance without premature fatigue due to effects of lactic acid. Using a HRV metric threshold would allow detection of changes in ANS balance (cardiac drift, dehydration, fatigue, metabolic status, etc.) preceding premature fatigue. In such a case, appropriate adjustments to power output could be made to avoid performance detriments. Future studies will need to compare the HRTWs from continuous and discontinuous protocols to maximal lactate steady state (MLSS) during a prolonged performance test. This will

have further relevance to the field as MLSS and MLSS velocity are highly correlated with prolonged endurance performance in cyclists (3, 12).

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