A Simplified Strategy for the Estimation of the Exercise Ventilatory Thresholds

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ABSTRACT

NEDER, J. A., and R. STEIN. A Simplified Strategy for the Estimation of the Exercise Ventilatory Thresholds. Med. Sci. Sports Exerc., Vol. 38, No. 5, pp. 1007–1013, 2006. Purpose: To analyze the limits of agreement between exercise ventilatory threshold values (VT1 and VT2) estimated from a combination of pulmonary gas exchange and ventilatory variables (cardiopulmonary exercise testing) and those derived from an alternative approach based on the ventilatory response only (VE, ventilometry). Methods: Forty-two nontrained subjects (24 males, aged 18–48, peak \( \dot{V}O_2 = 33.1 \pm 8.6 \) \( \text{mL} \cdot \text{min}^{-1} \cdot \text{kg}^{-1} \)) performed a maximum incremental cardiopulmonary exercise testing on an electromagnetically braked cycle ergometer. The participants breathed through a Pitot tube (Cardio2 System™, MGC) and a fixed-resistance ventilometer (Micromed, Brazil), which were connected in series. HR values at the estimated VT (VTHR1 and VTHR2) were obtained by the conventional method (ventilatory equivalents, end-expiratory pressures for \( O_2 \) and \( CO_2 \), and the V-slope procedure) and an experimental approach (VE vs time, VE/time vs time, and breathing frequency vs time). Results: There were no significant between-method differences on VTHR1, VTTHR2, VTV1, VTV2, and peak VE (\( P > 0.05 \)). After certification of data normality, a Bland–Altman analysis revealed that the mean bias ± 95% confidence interval of the between-method differences were lower for VTHR2 than VTHR1 (2 ± 9 and 0 ± 17 bpm, respectively). VTHR2 according to ventilometry differed more than 10 bpm from the standard procedure in 3 out of 42 subjects (9%). Between-method differences were independent of the level of fitness, as estimated from peak \( \dot{V}O_2 \) (\( P > 0.05 \)). Conclusions: A simplified approach, based on the ventilatory response as a function of time, can provide acceptable estimates of the exercise ventilatory thresholds—especially VT2—during ramp-incremental cycle ergometry. This new strategy might prove to be useful for exercise training prescription in nontrained adults. Key Words: GAS EXCHANGE, VENTILOMETER, CARDIOPULMONARY EXERCISE TESTING, LIMITS OF AGREEMENT

The ventilatory response to rapid-incremental exercise is well characterized by an exponential-like function that is thought to be influenced—or at least temporarily related—by the rate of blood lactate accumulation (25,26). In this context, there seems to exist an early inflection point in the pulmonary ventilation when expressed as a function of the oxygen uptake (i.e., the first ventilatory threshold (VT1)). This parameter has been found to delimit the upper boundary of “moderate” exercise (26). More importantly, a second threshold (VT2) has been found to separate a “heavy” from a nonsustainable, “very heavy” intensity domain: VT2 is thought to be associated with a respiratory compensation point (RCP) to the ongoing metabolic acidosis (9,19). Although the precise mechanism(s) underlying these adjustments is (are) still a source of controversy (7,12,17,20), they provide a physiological framework for the evaluation of human ability to sustain whole-body exercise and, therefore, a guide to endurance exercise prescription (6–9,13–16).

Estimation of the exercise VT, however, depends on a careful evaluation of the dynamic relationships between pulmonary gas exchange and the ventilatory responses (22,23). As a consequence, cardiopulmonary exercise testing (CPET) has evolved as an useful tool for training prescription and evaluation of exercise tolerance in health (16) and disease (14,18). Unfortunately, however, standard CPET relies on cumbersome and expensive gas exchange analyzers; these shortcomings have substantially hampered the application of the test in the clinical and sport arenas. Consequently, it would be interesting to investigate the usefulness of a more practical approach for the estimation of VT with the purpose of defining the appropriate range of exercise intensity for endurance training.
This prospective study, therefore, aimed to evaluate whether a simplified strategy, based on the pulmonary ventilatory response as a function of time during ramp-incremental exercise, would provide acceptable estimates of the VT in a sample of healthy, but sedentary, males and females. We reasoned that such an investigation would be of special relevance for apparently healthy, nontrained subjects, in whom a lower level of accuracy in the VT estimation is plausibly required as compared with a sporting population.

SUBJECTS AND METHODS

Study Design and Subjects

This was a prospective, cross-sectional study performed in a single clinical laboratory of a tertiary, university-based center. Forty-seven (24 males, aged 18–48 yr) apparently healthy, nontrained subjects (i.e., those reporting no regular physical activity in the past year) were evaluated for study inclusion; subjects were actively recruited from the general population. Subjects who had medical history or physical or laboratory findings of cardiac (2), respiratory (1), metabolic (1), or neuromuscular diseases (1) were excluded from the study, and therefore, 42 subjects comprised the study population. Written informed consent (as approved by the Federal University of Sao Paulo Medical ethics committee) was obtained from all subjects.

Protocol

The participants underwent a single ramp-incremental exercise test on an electromagnetically braked cycle ergometer (Corival™, Lode, NL). Subjects wore a facial neoprene mask and breathed through a low-resistance, turbulent-flow Pitot tube (Pre-Vent Pneumotach™, Medical Graphics Corporation (MGC)) and a fixed-resistance ventilometer (Micromed, Brazil), which were connected in series, with the Pitot tube placed before the ventilometer. This experimental setting was accepted after certification that there were no significant differences on measured volumes when the ventilometer was calibrated with and without this arrangement. Volume-flow data derived from the Pitot tube and the expired fractions of oxygen and carbon dioxide were analyzed in a commercially available cardiopulmonary exercise system (Cardio2 System™, MGC) (2). In this system, a breath is defined as the interval between onset and end of CO2 washout and O2 wash-in; respirations with a total volume equal or less than 150 mL are automatically discarded. The CO2 and O2 analyzers were calibrated before each test using a two-point measure: a calibration gas (CO2 5%, O2 12%, N2 balance) and a reference gas (room air after ambient temperature and pressure, saturated (ATPS) to standard temperature and pressure, dry (STPD) correction). The Pitot tube was also calibrated with a 3-L syringe using different flow profiles. Periodically, the overall output data system was validated against a respiratory gas exchange simulator, which allows a range of metabolic rates to be established between 0.2 and 5.0 L·min⁻¹, with a resulting accuracy of ± 2%. During the exercise tests, room temperature and humidity were controlled by air conditioning. All tests were performed in the same laboratory at an altitude of 680 m above sea level (Sao Paulo, Brazil), barometric pressure of 685–699 mm Hg and ambient temperature between 18 and 22°C.

The exercise test consisted of: i) 2 min at rest; ii) 3 min with real “zero” workload, obtained through an electrical system that moves the ergometer flywheel at 60 rpm; iii) the incremental phase; and iv) a 4-min recovery period. The power (work rate, WR) was continuously increased in a linear “ramp” pattern (10–25 W·min⁻¹ in females and 15–30 W·min⁻¹ in males). The increment rate was individually selected in such a way that the ramp duration (i.e., the duration of the incremental phase) was greater than 8 and lower than 14 min in all subjects (actual values being 11.5 ± 2.1 min). Participants were free to choose the pedaling frequency provided that this was not less than 50 rpm. The following data were obtained breath-by-breath and expressed as 15-s averages: pulmonary oxygen uptake (VO2, mL·min⁻¹), carbon dioxide output (VCO2, mL·min⁻¹); minute ventilation (VE, L·min⁻¹); respiratory rate (RR); and end-tidal partial pressures for O2 and CO2 (PETO2 and PETCO2, mm Hg). Cardiac electrical activity and HR (HR, bpm) were continuously recorded.

The VT were individually estimated by the researchers (i.e., the automatic detection of the VT by the software was not considered). The first VT (VT1) was estimated by the gas exchange method inspecting the inflection point of VOCO2 with respect to VO2 (modified V-slope) (3) and, secondarily, by the ventilatory method, when VE/VO2 and PETO2 increased while VE/VCO2 and PETCO2 remained stable, respectively. The respiratory compensation point, the second VT (VT2), was defined where VE started to change out of proportion of VCO2 (i.e., systematic increase in VE/VCO2 with a consequent decline on PETCO2 (13)). These techniques have long been validated in either patients or apparently healthy subjects (3,22).

Ventilometry. The exercise ventilatory response (VE, L·min⁻¹) and RR were also obtained from a calibrated ventilometer. A 3-L syringe calibration was performed with the Pitot tube placed before the ventilometer (as in the experimental setting); dead space values of the tube were added to the ventilometer’s dead space. In this device, a
differential pressure transducer responds to changes in pressure on both sides of a fixed resistance; according to Bernoulli’s principle, variations in pressure are proportional to the square of the turbulent flow induced by the resistance. To increase the signal-to-noise ratio, the interpolated values of two sequential data bins (each consisting of a 15-s mean) were used.

A dedicated software was used for data analysis (Ergo Pct13 version 2.4™, Micromed, Brazil). In this program, VE is plotted against exercise time; two user-controlled rulers are available for the estimation of the VT (Fig. 1, panel A). Identification of the VT is individually performed by the investigator. In addition, VE is divided by time (L·min⁻¹·min⁻¹) and expressed as a function of time (Fig. 1, panel B). The rationale for using this construct is as follows: assuming a linear relationship between VO₂ and time in response to a ramp-incremental protocol (18), when time is used as a surrogate of VO₂, the VE/VO₂ (VE/time) should decrease hyperbolically as VO₂ (time) increases with exercise progression. This is a necessary consequence of the linear VE–VO₂ relationship (at least until VT₁) with a positive y-intercept (26). Therefore, whenever VE increases out of proportion to exercise time (VO₂) after its nadir, the VE/time ratio would present with an inflection point (Fig. 1, panel B). Furthermore, RR has been found to accelerate after VT₂ in some subjects; therefore, RR is also expressed as a function of time (Fig. 1, panel C).

The following algorithm for evaluation was followed in each test (Fig. 1):

a. By manually operating the aforementioned user-controlled ruler available in the software (VE vs time graph), VT₂ was established by visually applying a “best fit” line from the end of exercise ventilation to the submaximal data (S₁ line). VT₂ was defined as the level where ventilation departed from linearity;

b. From this point, a second “best fit” line was drawn to the submaximal data registered earlier than VT₂ (S₂ line): VT₁ was defined as the level where ventilation also departed from linearity;

c. These provisional VT estimates were checked against the inflection points found on the VE/time versus time graph, as described above;

d. An additional evidence of nonlinearity was examined in the RR–time plot; that is, by looking at any consistent increase in RR at these time points.

In this analysis, the VT estimation was performed by visually checking the points of interest on the different graphs. The VE versus time plot was assumed as the criterion graph; however, an additional evidence of the VT on one of the two remaining graphs was required to be present (Fig. 1). The following variables were also recorded for analysis: HR (bpm) at VT₁ and VT₂ (VT HR₁ and VT HR₂, respectively) and VE (L·min⁻¹) at VT₁ and VT₂ (VT VE₁ and VT VE₂, respectively).

**Data Analysis**

After certification of a symmetric distribution (Kolmogorov–Smirnoff), data are reported as mean values and standard deviations (SD). Differences between males and females were compared by using a Student’s nonpaired t-test; in addition, responses to each technique in the same individual were contrasted by using a paired t-test. Correlation analysis (Pearson’s product–moment) was applied to investigate the level of association between continuous variables. The probability of Type I error was established at 0.05 for the hypothesis tests.

The limits of agreement between CPET and ventilometric VT estimates for the whole group were investigated by plotting the individual differences against their respective means (Bland–Altman analysis); that is, a between-technique comparison was performed. Heteroscedasticity (i.e., a non-Gaussian distribution of the residuals, usually characterized by a between-method difference proportional to the mean measured value) was examined by plotting the absolute (i.e., ignoring any sign) differences against the individual means and calculating the Spearman’s correlation coefficient (5). If the heteroscedasticity correlation was close to zero (i.e., no correlation between intermethod
TABLE 1. Resting and exercise data in subjects separated by gender.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Males (N = 24)</th>
<th>Females (N = 18)</th>
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</thead>
<tbody>
<tr>
<td><strong>Demographic/antropometric</strong></td>
<td></td>
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<tr>
<td>Age (yr)</td>
<td>33 ± 8</td>
<td>29 ± 7</td>
</tr>
<tr>
<td>BMI (kg·m⁻²)</td>
<td>24.9 ± 2.6</td>
<td>22.1 ± 2.8*</td>
</tr>
<tr>
<td><strong>Cardiopulmonary exercise testing</strong></td>
<td></td>
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<tr>
<td>Peak exercise</td>
<td></td>
<td></td>
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<tr>
<td>WR (W)</td>
<td>210 ± 44</td>
<td>125 ± 28*</td>
</tr>
<tr>
<td>VO₂ (mL·kg⁻¹·min⁻¹)</td>
<td>37.9 ± 7.7</td>
<td>26.8 ± 4.7*</td>
</tr>
<tr>
<td>R</td>
<td>1.21 ± 0.06</td>
<td>1.20 ± 0.08</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>176 ± 12</td>
<td>175 ± 12</td>
</tr>
<tr>
<td>VE (L·min⁻¹)</td>
<td>92.9 ± 19.6</td>
<td>61.1 ± 15.6*</td>
</tr>
<tr>
<td><strong>Submaximal exercise</strong></td>
<td></td>
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<tr>
<td>VT₁HR (bpm)</td>
<td>131 ± 17</td>
<td>131 ± 18</td>
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<tr>
<td>VT₁VTHR (% peak HR)</td>
<td>75.8 ± 7.1</td>
<td>73.2 ± 8.9</td>
</tr>
<tr>
<td>VT₁HR (bpm)</td>
<td>160 ± 14</td>
<td>161 ± 14</td>
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<tr>
<td>VT₁VTHR (% peak HR)</td>
<td>91.1 ± 3.8</td>
<td>91.7 ± 3.8</td>
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<tr>
<td>VT₁ (L·min⁻¹)</td>
<td>42.9 ± 10.9</td>
<td>27.9 ± 6.2*</td>
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<tr>
<td>VT₁VE (L·min⁻¹)</td>
<td>66.5 ±13.3</td>
<td>44.9 ± 8.5*</td>
</tr>
<tr>
<td>VT₂HR (bpm)</td>
<td>133 ± 17</td>
<td>128 ± 19</td>
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<tr>
<td>VT₂VTHR (% peak HR)</td>
<td>75.8 ± 7.1</td>
<td>73.2 ± 8.9</td>
</tr>
<tr>
<td>VT₂HR (bpm)</td>
<td>159 ± 13</td>
<td>158 ± 15</td>
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<tr>
<td>VT₂VTHR (% peak HR)</td>
<td>90.9 ± 4.2</td>
<td>90.3 ± 4.9</td>
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<tr>
<td>VT₂ (L·min⁻¹)</td>
<td>44.2 ± 11.6</td>
<td>23.4 ± 9.3*†</td>
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<tr>
<td>VT₂VE (L·min⁻¹)</td>
<td>65.6 ± 13.4</td>
<td>38.2 ± 11.7†</td>
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Data are presented as mean ± SD. BMI, body mass index; VO₂, pulmonary oxygen uptake; R, respiratory exchange ratio; VT₁HR, heart rate at the first ventilatory threshold; VT₁VTHR, heart rate at the second ventilatory threshold; VT₁VE, minute ventilation at the first ventilatory threshold; VT₂VE, minute ventilation at the second ventilatory threshold.

* Males vs females (nonpaired t-test); † cardiopulmonary exercise test vs ventilometry in the same subject (paired t-test) (P < 0.05).

The Bland–Altman analysis of the between-method differences in VT₁HR is depicted in Figure 2. After certification of data homoscedasticity (see Methods), the mean bias ± 95% confidence interval of the between-method differences were found to be lower for VT₁HR2 than VT₁HR1: 2 ± 9 vs 0 ± 17 bpm. Of special note, VT₁HR2 and VT₁HR1 according to ventilometry differed more than 10 bpm from the standard procedure in 3 of 42 (9%) and 13 of 42 (31%) subjects, respectively. Using a stricter criterion (5-bpm difference), these values were 15 of 42 (36%) and 23 of 42 (59%) for VT₁HR2 and VT₁HR1. The between-method differences in VT₂HR2 from VT₁HR1 were largely independent of peak VO₂ (Fig. 3, P > 0.05). Similar results were
found in relation to VT_{VE2} and VT_{VE1}. Interestingly, peak VE by ventilometry was almost equivalent to peak VE according to the criterion test (Fig. 4).

**Usefulness of the secondary plots for estimation of the VT.** On a post hoc analysis, we investigated whether the secondary indicators of the VT (i.e., those found for the VE/time vs time and RR vs time plots) were judged useful for their determination, that is, if the different criteria helped the investigators to identify the VT with more confidence. Using an arbitrary three-point scale (0 = “not useful at all,” 1 = “moderately useful,” 2 = “very useful”), the VE/time versus time plot was scored “1” or “2” in 36 of 42 (86%) and 34 of 42 (81%) subjects for VT_{VE2} and VT_{VE1}, respectively. In contrast, the RR versus time construct was felt to be more useful for VT_{VE2}, but not for VT_{VE1}, confirmation (26 of 42 (62%) and 8 of 42 (19%), respectively).

**DISCUSSION**

This prospective study showed that a simplified, pulmonary ventilation-based algorithm could provide accurate estimates of the exercise ventilatory thresholds in nontrained adults. The limits of agreement were narrower for the second threshold (VT2), which is of special practical importance, considering that this point is more relevant for exercise prescription than VT1 in normal subjects (8,12,16). These data suggest that, by using such a user-friendly approach, the practitioner can individualize an exercise prescription program (at least for a population with similar characteristics of that evaluated in the present investigation).

The value of HR-based exercise intensity prescription. There are a number of different approaches to guide exercise prescription, ranging from predicted HR_{max}-based equations (e.g., [0.7 × (220 − age)]) to more sophisticated responses, such as VO_{2} (15). In practical terms, however, HR has been widely used for this purpose. Although general guidelines have been advocated as a valid procedure in population-based studies, several investigators have shown that an individualized approach is related to better outcomes (4,6,8,10,15,16).

In this context, the use of the VT for exercise training prescription presents with a sounder scientific rationale than an empirically estimated fraction of the maximal exercise capacity—as recently reviewed by Meyer and coworkers (16). It has been shown that the range of work rates below VT1 is not associated with a sustainable increase in blood lactate levels and, therefore, exercise tolerability is greatly enhanced (26). However, training at these intensities is not commonly related to a substantial stress for the physiological systems that are responsible to increase oxygen delivery to the exercising muscles. In contrast, exercise tolerability decreases dramatically above VT2, probably due to a combination of systemic (lactate, thermal, cardiovascular), and muscular local (contractile fatigue) and central factors—although it is currently far from clear whether there is a cause–effect relationship between lactate and fatigue (7,12). Therefore, the range of WR between VT1 and VT2 is prone to elicit a level of cardiovascular and metabolic stress that is sufficiently intense to stimulate the aerobic pathways but not excessively high to shorten exercise duration, which would reduce the total work performed on a training session.

**Ventilometry for the VT estimation and its limitations.** This study seems to be the first evaluation

![FIGURE 3](image1.png)

**FIGURE 3**—There were no correlations between the absolute intermethod differences in heart rate (HR, bpm) at the first and second ventilatory thresholds (VT: open and closed squares, respectively) and peak oxygen uptake (P > 0.05).

![FIGURE 4](image2.png)

**FIGURE 4**—Pulmonary ventilation (VE, L min⁻¹) at peak exercise were seen to be remarkably similar when the two techniques were compared (ventilometry and cardiopulmonary exercise test, CPET); note the close proximity with the line of identity (r = 0.99, P < 0.001).
of the validity of isolated ventilatory responses in estimating the VT during incremental exercise. Although our data are consistent with the notion that ventilometric data can be used for this purpose with an acceptable degree of accuracy (especially for VT2), there are a number of aspects that should be carefully observed to obtain reliable estimates. Firstly, a ramp-incremental test (or, at least, a rapid-incremental test—a maximum of 2-min increments of equal size) must be used: only in these exercise paradigms, time can be used as a surrogate of VO2 (24). More specifically, the ventilatory response during traditional treadmill “cardiovascular” protocols (Bruce, Naughton, Ellestad) is known to be highly variable; this is prone to produce spurious VT when gas exchange data is not simultaneously recorded and, therefore, should be formally discouraged. Due to the same issue of ventilation variability, it is recommended that whenever a treadmill is used, the subject should not be allowed to change from walking to running, since this increases ventilation out of proportion of the work actually performed. Therefore, treadmill ramp protocols should start with mild jogging and, afterwards, a progressive and continuous increase in speed and/or grade should be imposed; these preliminary recommendations, however, await further experimental confirmation. More importantly, however, this investigation validated a formal algorithm for VT estimation (see Methods); it is crucial that such a procedure be followed each time that the VT are estimated by ventilometry using the system under evaluation.

A note of caution should also be made in relation to hypothesis tests to evaluate intermethods agreement (Table 1). It is well known that they are quite insensitive to random variation; that is, they are less likely to detect significant differences if they are accompanied by large amounts of random error between estimates (1). On the other hand, an analytical goal analysis tries to estimate the implications of measurement error. This is better accomplished by the Bland and Altman procedure (Fig. 2), in which the limits of between-method (dis)agreement are provided and the practitioner should decide whether the observed discrepancies are, or are not, of practical relevance. In the present study, the authors defined a 10-bpm difference between VT values by ventilometry and CPET as “acceptable” in practical terms; these values fall inside the between-day, intrasubject HR variability during exercise training programs (typically 10–15 bpm) (11). However, this range is likely to be excessive for competitive athletes in whom a higher degree of precision on VT estimation is usually required.

**Practical relevance of the method.** The present investigation has demonstrated that a practical method could be used to determine the ventilatory thresholds and the related heart rate values during an incremental test. This approach seems to open a new perspective for exercise prescription in healthy individuals. Therefore, this may constitute a useful strategy for the development of an individualized aerobic exercise training program in the real world. The ventilometric approach, when used systematically in the same individual with the purpose of optimizing the aerobic training, may serve as a tool for periodized exercise prescription, especially for nonathletes. In fact, the procedures for VT estimation in the software under analysis is considerably simpler than those required using data from a CPET; in the authors’ experience, most practitioners are able to correctly identify the VT after a few hours of training. Additionally, the cost of the entire system (hardware and software) compares favorably with that of a standard, stationary metabolic cart for CPET ($3500–$5000 vs $30,000–$40,000).

**CONCLUSIONS**

A relatively simple and inexpensive approach, based on the ventilatory response as a function of exercise duration, provided acceptable estimates of the exercise ventilatory thresholds—especially VT2—during ramp-incremental cycle ergometry in males and females.

This study was supported by a Research Grant from Micromed™, Brasilia (DF), Brazil. The authors have received funds from Micromed to attend national meetings. The authors do not profit from any product sold by the company. The results of the present study do not constitute endorsement of the product by the authors or the American College of Sports Medicine.

J. Alberto Neder is an Established Investigator (level II) of the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazil.

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