The Work Rate Corresponding to Ventilatory Threshold During Steady-State and Ramp Exercise

Oliver Faude, Tim Meyer, and Wilfried Kindermann

Purpose: The work rate (WR) corresponding to ventilatory threshold (VT) is an appropriate intensity for regenerative and low-intensity training sessions. During incremental ramp exercise, VO₂ increase lags behind WR increase. Traditionally, a VO₂ time delay ($t_d$) of 45 seconds is used to calculate the WR at VT from such tests. Considerable inaccuracies were observed when using this constant $t_d$. Therefore, this study aimed at reinvestigating the temporal relationship between VO₂ and WR at VT.

Methods: 20 subjects (VO₂peak 49.9 to 72.6 mL · min⁻¹ · kg⁻¹) performed a ramp test in order to determine VT and a subsequent steady-state test during which WR was adjusted to elicit the VO₂ corresponding to VT. The difference in WR and heart rate at VT was calculated between the ramp and the steady-state test (WRdiff, HRdiff) as well as the time delay corresponding to WRdiff during ramp exercise.

Results: Mean values were $t_d = 85 ± 26$ seconds (range 38 to 144), WRdiff = 45 ± 12 W (range 23 to 67), HRdiff = 1 ± 9 beats/min (range –21 to +15). The limits of agreement for the difference between WR at VT during ramp and steady-state exercise were ± 24 W. No significant influence on $t_d$, WRdiff, or HRdiff from differences in endurance capacity (VO₂peak and VT; $P > .10$ for all correlations) or ramp increment ($P = .26$, .49, and .85, respectively) were observed.

Conclusion: The wide ranges of $t_d$, WRdiff, and HRdiff prevent the derivation of exact training guidelines from single-ramp tests. It is advisable to perform a steady-state test to exactly determine the WR corresponding to VT.

Key Words: exercise testing, steady-state cycling, VO₂ kinetics, time delay, training prescription

During incremental exercise, there is a certain individual metabolic rate at which blood lactate concentrations begin to rise above baseline levels. According to a traditional physiological model that was recently questioned by Robergs et al., the buffering of the resulting hydrogen ions by bicarbonate leads to an accumulation of nonmetabolic carbon dioxide, the so-called excess CO₂. This marker for the first rise in blood lactate concentrations above baseline levels during incremental exercise, which appears as a deviation from linearity when carbon-dioxide output (VCO₂) is plotted against oxygen uptake (VO₂), was originally named the anaerobic...
threshold. Unfortunately, this term is in use for other threshold concepts with different physiological backgrounds. \(^4,5\) so in this article, we use the term *ventilatory threshold* (VT). This procedure is in agreement with minute ventilation showing a proportional early rise with VCO\(_2\).

Wasserman et al\(^6\) used VT for diagnostic purposes in patients with heart or lung disease. Other investigators employed VT to estimate aerobic-endurance capacity in healthy adults and athletes.\(^4,7-9\) Moreover, professional road cyclists perform much of their training time at intensities close to VT.\(^7\) A recent review of lactate- and gas-exchange thresholds recommends a training framework in which VT represents a marker for intensity prescription during regenerative and low-intensity training sessions.\(^10\) In addition, it seems to be an appropriate intensity for cardiac-rehabilitation training\(^10,11\) and preventive training in sedentary subjects.\(^9,12\)

Oftentimes, training is monitored using ratings of perceived exertion or heart-rate measurements. These methods are subjective by nature or influenced by several internal and external factors (eg, cardiovascular drift or position on the bike). Coyle et al,\(^13\) however, stated that the central variable dictating the demands of cycling is the mechanical power output that is necessary to propel the bike. Therefore, the most valid indicator of training intensity in cycling might be the actual work rate.\(^7\) Power output has become an applicable alternative training tool, and it is currently being used by an increasing number of elite cyclists in the form of an ambulatory-power meter.\(^14\)

VT is defined as an oxygen uptake,\(^6\) and VO\(_2\) increase lags behind the increase in work rate during incremental ramp exercise.\(^15-17\) Therefore, it is difficult to determine the work rate that corresponds to VT. Davis and coworkers\(^15\) introduced a model to relate VO\(_2\) to work rate during ramp exercise. The model is based on parallel changes between work rate and VO\(_2\) after an initial delay in the onset of VO\(_2\) increase (Figure 1). Davis et al\(^15\) described a value of approximately 45 ± 3 seconds for the initial time lag. Hence, a steady-state work rate eliciting VT is deemed to be determined by calculating the power output that is realized 45 seconds earlier than the corresponding oxygen uptake. Similar values for this early time delay (=42 seconds) were reported in a more recent study by Jones and Carter.\(^18\)

When using this procedure to prescribe a power output for 4-hour steady-state trials at VT,\(^19,20\) we noticed that the average VO\(_2\) during steady-state cycling was considerably higher than VT in all 12 subjects (unpublished observations). Therefore, the aim of the present study was to reinvestigate the calculation of this work rate from 1 single-ramp exercise test. We hypothesized that the time delay of VO\(_2\) at VT is greater than previously reported for the onset of ramp exercise.

**Methods**

**Subjects and General Design**

20 healthy male subjects (anthropometric and ergometric data are presented in Table 1) participated in this study after giving informed consent. All procedures were in accordance with the Helsinki Declaration of 1975. There was a wide range in endurance capacity in these participants (VT = 25.1 to 43.7 mL · min\(^{-1}\) · kg\(^{-1}\), and VO\(_{2\text{peak}}\) = 49.9 to 72.6 mL · min\(^{-1}\) · kg\(^{-1}\)), with a continuous transition from moderately trained students to highly fit amateur cyclists.
Figure 1 — VO₂ response of a representative subject during ramp test. Line a is parallel to the linear phase of the VO₂ response (line b) and originates from the start of ramp exercise. According to Davis et al.\textsuperscript{15} it represents the steady-state VO₂ corresponding to each work rate. The distance between intersections of lines a and b with the constant VO₂ baseline (here: cycling at 50 W) is called time constant $\tau$ and represents the initial time lag of the VO₂ response to ramp exercise (modified from ref. 15). In this example, ventilatory threshold (VT) was detected at 2.84 L/min. According to this model this corresponds to a proposed work rate of 215 W

Table 1 Anthropometric and Ergometric Data for the Subjects (N = 20)*

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
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<td>5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179</td>
<td>6</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>74</td>
<td>7</td>
</tr>
<tr>
<td>VO₂peak\textsubscript{peak} (mL · min\textsuperscript{−1} · kg\textsuperscript{−1})</td>
<td>60.2</td>
<td>8.1</td>
</tr>
<tr>
<td>HR\textsubscript{max} (beats/min)</td>
<td>188</td>
<td>8</td>
</tr>
<tr>
<td>WR\textsubscript{max} (W)</td>
<td>405</td>
<td>71</td>
</tr>
<tr>
<td>VT (mL · min\textsuperscript{−1} · kg\textsuperscript{−1})</td>
<td>35.2</td>
<td>5.7</td>
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*VO₂peak indicates peak oxygen uptake; HR\textsubscript{max}, maximal heart rate; WR\textsubscript{max}, maximal work rate; and VT, ventilatory threshold.

Subjects performed 2 tests on an electrically braked cycle ergometer (Lode Excalibur, Groningen, Netherlands) with simultaneous gas-exchange measurements (MetaMax I, Cortex, Leipzig, Germany). The first test was an incremental ramp test to determine VT. Within an average period of 6 days (maximum 15 days), subjects performed a subsequent steady-state test in order to determine the work
rate corresponding to the VO$_2$ at VT. Heart rate was measured continuously and recorded every minute (Polar, Kempele, Finland).

**Ramp Test**

The ramp test started with 3 minutes warm-up cycling at 50 W. Subsequently, power output was continuously increased until exhaustion. Ramp slope was chosen according to body weight and cycling experience to arrive at a total ramp time of about 10 minutes.$^{21,22}$ Because of the wide range in endurance capacities, ramp slopes varied between 25, 30, 35, and 40 W/min, and subjects were chosen in order to find 5 for each ramp slope. VT was determined independently by 2 investigators from the VCO$_2$–VO$_2$ plot using the V-slope method.$^3$ Work rate and heart rate at VT (WR$_{VT}$, HR$_{VT}$) were determined as the measurements that occurred simultaneously with VO$_2$ at VT. The slope of the VO$_2$–work-rate relationship ($\Delta$VO$_2$/WR) was calculated as the mean increase between minutes 2 and 8 to ensure that the initial VO$_2$ delay, as well as a VO$_2$ leveling off, did not interfere.

**Steady-State Test**

The steady-state test started with 3 minutes warm-up pedaling at 100 W. Power output was then increased to the work rate proposed to elicit VT when applying a time delay of 45 seconds (WR$_{45s}$). Work rate was rounded to multiples of 5 W. Subsequently, when the actual VO$_2$ did not meet the VO$_2$ at VT from the ramp test (difference greater than 4%), power output was adjusted until meeting the oxygen uptake at VT. Adjustments were made by assuming a VO$_2$–work-rate relationship of 10 mL · min$^{-1}$ · W$^{-1}$; that is, for every 100 mL/min that the actual VO$_2$ was different from the expected value, we adjusted work rate by 10 W. If the adjustment was not sufficient, a further adjustment was made. Representative VO$_2$ recordings from a single test are presented in Figure 2. To reach a steady-state VO$_2$ corresponding to VT, on average, 3 (1 to 6) work-rate adjustments were necessary. Steadiness was accepted to be present when measurements remained constant (within a range of ±4%) for a minimum of 6 minutes. Because of considerable gas-exchange fluctuations, sometimes VT was not exactly met (largest difference between VT and the average of the 6-minute steady-state VO$_2$: 90 mL/min). Therefore, in such cases precision of determination was increased by interpolation using the individual $\Delta$VO$_2$/WR from the ramp test. The constant heart rate, which was achieved during the last 3 minutes of constant-load cycling, was recorded and taken as HR$_{SS}$. Subjects maintained the same self-selected cadence that they chose during the ramp test.

**Gas-Exchange Measurements**

During exercise, exhaled air was collected in a mixing chamber (volume 30 mL) and analyzed for oxygen (circonium cell) and carbon-dioxide (infrared analyzer) concentrations every 10 seconds. Minute ventilation was recorded digitally using a Triple-V sensor. Volume calibration was carried out using a 3-L syringe. To calibrate gas analyzers, a control gas (FO$_2$ = 12.1%, FCO$_2$ = 5.15%), as well as environmental air, was used.
Calculations and Statistical Analysis

The following parameters were calculated:

- The difference between work rate (in Watts) at VT and work rate during steady-state cycling:
  \[ WR_{\text{diff}} = WR_{VT} - WR_{SS} \]

- The time delay (in seconds) that corresponded to \( WR_{\text{diff}} \):
  \[ t_d = (WR_{\text{diff}} / \text{ramp slope}) \times 60 \text{ s} \]

- The difference between heart rate at VT and during steady-state cycling:
  \[ HR_{\text{diff}} = HR_{VT} - HR_{SS} \]

Unless stated otherwise, all values are presented as mean ± SD. Differences in \( t_d \), \( WR_{\text{diff}} \), and \( HR_{\text{diff}} \) between ramp slopes were tested using a Kruskal–Wallis test. Pearson product–moment correlation was used to compute the relationship between the calculated parameters (\( t_d \), \( WR_{\text{diff}} \), and \( HR_{\text{diff}} \)) and endurance capacity (VT and VO\textsubscript{2peak}), as well as \( \Delta VO_2 / \Delta WR \). A Bland–Altman plot and the limits of agreement\textsuperscript{25} were used to compare the WR at VT during the steady-state tests.

**Figure 2** — \( VO_2 \) response of a representative subject during steady-state cycling. After 3 minutes of warm-up cycling, work rate was increased to the value that was predicted by the model with a constant time delay of 45 seconds from the ramp test (here: 215 W). The intended \( VO_2 \) of 2.84 L/min was not met until work rate was lowered 2 times to 190 W. \( VO_2 \) stayed constant for 6 minutes, and, therefore, 190 W was taken as the steady-state work rate (\( WR_{SS} \)) corresponding to the oxygen uptake at ventilatory threshold (VT).
and the proposed WR at VT (WR_{45s}) from ramp exercise. The level of statistical significance was set at $P < .05$.

**Results**

Ramp-test duration ranged between 9 minutes, 10 seconds, and 12 minutes, 38 seconds, and steady-state tests lasted from 9 to 16 minutes. VT could be detected in all subjects and occurred at 58% ± 5% of VO_{2peak}, on average (range 50% to 67%). Average ΔVO_{2}/ΔWR was equal to 10.5 ± 1.0 mL · min⁻¹ · W⁻¹. Mean values for HR_{VT}, HR_{SS}, HR_{diff}, WR_{VT}, WR_{SS}, WR_{diff}, and $t_d$ are given in Table 2. HR_{diff} ranged from -21 to +15 beats/min. WR_{diff} scattered between 23 and 67 W, which corresponded to a range of 38 to 144 seconds in $t_d$. Figure 3 shows the distribution of $t_d$, WR_{diff}, and HR_{diff} as related to ramp slope. No statistically significant effect of ramp slope on $t_d$, WR_{diff}, or HR_{diff} was detected ($P = .26, .49, \text{and} .85, \text{respectively}$). The difference between WR_{VT} (196 ± 43 W; significantly different from WR_{SS}, $P < .001$) and WR_{SS} is presented according to the method introduced by Bland and Altman (Figure 4). Table 3 shows the correlation matrix of, on the one hand, VT, VO_{2peak}, and ΔVO_{2}/ΔWR and, on the other hand, WR_{diff}, $t_d$, and HR_{diff} ($P > .10$ for all correlations, ie, not significantly different from zero).

**Discussion**

The results of the present study suggest that there are no constant values for $t_d$, WR_{diff}, and HR_{diff} that can be used to derive valid intensity prescriptions for training from a single-ramp test. The present results also revealed an average $t_d$ at VT that is much greater than the originally described value of about 45 seconds for the onset of ramp exercise.

Considerable variations in WR_{diff} and $t_d$ make it difficult to accurately calculate the power output corresponding to VT. Four out of 20 subjects were located beyond a range of 15 W above and below the average value of WR_{diff}. Therefore,

### Table 2  Heart Rate and Work Rate at Ventilatory Threshold and During Steady-State Cycling (HR_{VT}, HR_{SS}, WR_{VT}, WR_{SS}), Differences in Heart Rate and Work Rate at VT and During Steady-State Test (HR_{diff}, WR_{diff}), and Time Delay ($t_d$) Corresponding to WR_{diff} During Ramp Exercise (N = 20)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
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<tbody>
<tr>
<td>HR_{VT} (beats/min)</td>
<td>144</td>
<td>13</td>
</tr>
<tr>
<td>HR_{SS} (beats/min)</td>
<td>143</td>
<td>16</td>
</tr>
<tr>
<td>HR_{diff} (beats/min)</td>
<td>1</td>
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<tr>
<td>WR_{VT} (W)</td>
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</tr>
<tr>
<td>WR_{SS} (W)</td>
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<td>45</td>
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<tr>
<td>WR_{diff} (W)</td>
<td>45</td>
<td>12</td>
</tr>
<tr>
<td>$t_d$ (s)</td>
<td>85</td>
<td>26</td>
</tr>
</tbody>
</table>
Figure 3 — Distribution of time delay (top), differences in work rate, \( \text{WR}_{\text{diff}} \) (middle); and differences in heart rate, \( \text{HR}_{\text{diff}} \) (bottom), plotted against ramp increment.
when using this average “correction,” training prescriptions for a single subject might result in an intensity markedly lower or higher than VT; that is, the training stimulus can be expected to be negligible in one athlete, whereas another might train at an intensity accompanied by a moderate lactate accumulation. The same percentage of subjects was situated outside a range of 30 seconds above and below the mean \( t_d \). This indicates the uncertainty in using \( WR_{\text{diff}} \) and \( t_d \) for intensity prescription. In addition, for 20% of the investigated subjects, deviations of more
than 10 beats/min above and below $HR_{VT}$ were observed. Moreover, taking into account the well-known biological fluctuations of HR (e.g., cardiovascular drift), intensity prescriptions near VT from a single-ramp test should be carried out with care when HR is used as a monitoring parameter.

In recent investigations, there was disagreement about the influence of the ramp slope on parameters of aerobic function, especially on the initial time lag. Although Davis and colleagues\textsuperscript{15} arrived at the result that different ramp slopes do not affect this early $t_d$, others found that it decreases with increasing ramp slope.\textsuperscript{27} In the present study the initial $t_d$ was not investigated, but the $t_d$ at VT was. No relationship between ramp increment and $t_d$, $WR_{diff}$ or $HR_{diff}$ was detected. Although $P$ values are far from being significant, it should be mentioned that the low number of subjects in each group ($n = 5$) might reduce the statistical power of this result. Ranges in ramp slope in the present investigation were not as large as in the cited studies, which used ramp slopes between 20 and 100 W/min\textsuperscript{15} and 20 and 80 W/min.\textsuperscript{27} Nonetheless, ramp increments between 25 and 40 W/min, as were used in this study, are more appropriate for routine testing when a total ramp duration of about 10 minutes is intended.\textsuperscript{21} Weston et al\textsuperscript{26} also investigated the influence of ramp slope (10, 30, and 50 W/min) on VT and found that there were no differences when VT was expressed as VO\textsubscript{2} or percentage VO\textsubscript{2peak}. In contrast, WR measured at VT varied with ramp slope. In accordance with our results, these authors concluded that WR at VT obtained through ramp tests should be used cautiously when prescribing training or evaluating performance. It is noteworthy, however, that Weston et al\textsuperscript{26} did not use the V-slope method to determine VT.

In addition, there are reports indicating an influence of endurance capacity on VO\textsubscript{2} kinetics during incremental exercise, predicting that fitter athletes might show a faster VO\textsubscript{2} response to increasing WR than subjects of lower aerobic capacity.\textsuperscript{28} Our results do not support this view, regardless of whether aerobic capacity is assessed by VO\textsubscript{2max} or VT. In addition, $\Delta VO_{2}/\Delta WR$, as an indicator for the rapidity of VO\textsubscript{2} adjustment to WR increase, does not correlate with the chosen parameters to describe the VO\textsubscript{2} delay.

**Limitations of the Study**

In contrast to the work of Davis et al,\textsuperscript{15} who used breath-by-breath analysis, respiratory data in the present study were obtained using a mixing-chamber system measuring in 10-second intervals. This might have had a minor systematic influence on the $t_d$ of VO\textsubscript{2}. Therefore, it seems possible that the real $t_d$ was slightly overestimated. Nevertheless, the observed average $t_d$ is approximately 40 seconds higher than the predicted value. In addition, it is not tenable that the wide ranges in $t_d$, $WR_{diff}$, and $HR_{diff}$ were considerably influenced by measuring with a mixing-chamber system.

During the steady-state tests, VT was initially approximated from the value proposed by the model based on a 45-second time constant. In 19 out of 20 cases $t_d$ was larger than 45 seconds, and, hence, the initial WR was mostly situated above VT. Therefore, a VO\textsubscript{2} slow component might have occurred. In most cases the initial WR was adjusted within the first 3 minutes of exercise and the majority of time of the steady-state test was performed at an intensity near VO\textsubscript{2} at VT, and, therefore, an interference of a VO\textsubscript{2} slow component might have had a negligible influence on the observed results.
The investigated subjects cover a wide range of endurance capacity, even though professional athletes were not examined. Results were independent from endurance capacity, however, and some subjects were highly fit. This seems to enable a careful transfer of the results to competitive cyclists.

**Conclusion**

We concluded that prescribing an exercise intensity of VT from ramp exercise tests results in an average overestimation of the intended intensity range, when assuming a constant $t_d$ for VO$_2$ of 45 seconds. In addition, values for $t_d$, WR$_{diff}$, and HR$_{diff}$ vary considerably among individuals. This prevents giving exact training guidelines from gas-exchange measurements during a single ramp exercise test. In competitive cyclists, it seems more appropriate to prescribe training intensities from steady-state conditions.

**References**