Determination of the velocity associated with \( \dot{V}O_2 \)max

OLIVIER BERNARD, SOUALIHO OUATTARA, FRÉDÉRIC MADDIO, CHANTAL JIMENEZ, ANNIE CHARPENET, BRUNO MELIN, and JACQUES BITTEL

Unité de Bioénergétique et Environnement, Centre de Recherches du Service de Santé des Armées, BP 87, 38702 La Tronche Cedex, FRANCE

ABSTRACT

BERNARD, O., S. OUATTARA, F. MADDIO, C. JIMENEZ, A. CHARPENET, B. MELIN, and J. BITTEL. Determination of the velocity associated with \( \dot{V}O_2 \)max. Med. Sci. Sports Exerc., Vol. 32, No. 2, pp. 464–470, 2000. Purpose: The theoretical velocity associated with \( \dot{V}O_2 \)max (v\( \dot{V}O_2 \)max) defined by Daniels (1985) is extrapolated from the submaximal \( \dot{V}O_2 -velocity relationship.\) \( \dot{V}O_2 \) is generally determined by assuming that the aerobic response reacts like a linear first-order system at the beginning of square-wave exercise, with a steady-state reached by the 4th minute. However, at supra-ventilatory threshold work rates, the steady state in \( \dot{V}O_2 \) is delayed or not attained. Methods: The present study was carried out to compare three values for v\( \dot{V}O_2 \)max determined with Daniels’ method, but with \( \dot{V}O_2 \) either measured at the 4th minute (v\( \dot{V}O_2 \)max4), the 6th minute (v\( \dot{V}O_2 \)max6), or after the attainment of the true steady-state (v\( \dot{V}O_2 \)maxSS). The metabolic response during square-wave exercise at each of the three v\( \dot{V}O_2 \)max were also assessed. Results: These velocities were significantly different (P < 0.05), but v\( \dot{V}O_2 \)maxSS and v\( \dot{V}O_2 \)max6 were highly correlated (r = 0.98; P < 0.05). Blood lactate concentrations measured after exercise at velocities very close to the three v\( \dot{V}O_2 \)max were similar and the end-exercise \( \dot{V}O_2 \) were not different from \( \dot{V}O_2 \)max but the time required to elicit 95% \( \dot{V}O_2 \)max during these three square-wave tests were significantly different. Conclusion: Therefore, when v\( \dot{V}O_2 \)max is determined by extrapolation from the submaximal \( \dot{V}O_2 -velocity relationships, submaximal \( \dot{V}O_2 \) should be measured beyond the 6th minute of square-wave exercise (at least if it takes 30 s to reach the desired velocity) to ensure that all v\( \dot{V}O_2 \)max reported in future studies describe a similar quantitative index. Key Words: INTENSE RUNNING EXERCISE, TRAINED ATHLETES, MAXIMAL OXYGEN UPTAKE, RUNNING ECONOMY, EXERCISE TEST PROTOCOL.

Maximal oxygen consumption (\( \dot{V}O_2 \)max) expressed relative to body mass (mLOz\( \cdot \)kg\(^{-1}\)\cdot min\(^{-1}\)) is an important determinant of success in distance-running (15,22). Running economy (RE), the rate of oxygen consumption (\( \dot{V}O_2 \)) for a given submaximal running velocity (13), is another determinant of distance-running performances (14). In order to express the interplay between \( \dot{V}O_2 \)max and how efficiently available aerobic energy is used, Daniels et al. (16) defined the theoretical velocity associated with \( \dot{V}O_2 \)max (v\( \dot{V}O_2 \)max) as the predicted velocity determined by extrapolation from the submaximal \( \dot{V}O_2 \) velocity relationship. Moreover, Morgan et al. (33) have shown that this v\( \dot{V}O_2 \)max is correlated with a 10-km performance, among well-trained male runners.

The determination of the oxygen demand for independent bouts of constant-speed running is based on two main assumptions: that energy demand is independent of time for constant-speed running of moderate duration (less than 30 min) and that the steady-state \( \dot{V}O_2 \) occurs after 3–4 min of exercise. Therefore, one should be able to measure \( \dot{V}O_2 \) from the 4th to the 6th minute (17,33) or from the 6th to the 8th minute (18) of a constant-load exercise without effect on the calculated value. However, during constant-load cycling (4,12,23,30,39) and constant-speed running (5,38), a slow \( \dot{V}O_2 \) component appears after the 3rd minute of supra-ventilatory-threshold exercise. Therefore, the \( \dot{V}O_2 \) value measured from the 3rd to the 4th minute of exercise is not the \( \dot{V}O_2 \) at steady-state and, so, could not be used to evaluate the submaximal \( \dot{V}O_2 -velocity relationship.\) Above the ventilatory threshold intensity, the slow component delays the establishment of the steady-state (34); for severe intensities, the slow component leads \( \dot{V}O_2 \) to increase until exhaustion without establishment of a steady-state (4,5,35,36), and, therefore, the oxygen demand at steady-state cannot be determined. The difference between cycling and running is that the highest work rate leading to a submaximal steady-state in \( \dot{V}O_2 \) is about 80% \( \dot{V}O_2 \)max in cycling (4,35,36) but about 92% \( \dot{V}O_2 \)max in running (5). As a consequence, running exercises with a submaximal aerobic demand closed to \( \dot{V}O_2 \)max can be used to calculate the submaximal \( \dot{V}O_2 -velocity relationship, but in all cases, the \( \dot{V}O_2 \) at steady-state (when achievable) must be measured well after the 3rd minute of the exercise (5).

The present study was therefore done to provide guidelines for determining v\( \dot{V}O_2 \)max by extrapolation of the submaximal \( \dot{V}O_2 -velocity relationship, which ensure that similar parameters and comparable results are obtained in future.
experiments. Three $\dot{V}_O_2_{max}$ were extrapolated from three different submaximal $\dot{V}_O_2$-velocity relationships, each depending on the time at which $\dot{V}_O_2$ was measured during the constant-speed bouts. As $\dot{V}_O_2$ has frequently been measured between the 4th and the 6th minute of exercise in previous published experiments, these exercise durations were used for $\dot{V}_O_2$ measurements. The third $\dot{V}_O_2$ value was measured at the true steady-state. The effect of the different relationships on the determination of $\dot{V}_O_2_{max}$ was assessed by comparing the $\dot{V}_O_2_{max}$ values and, also, the metabolic responses at velocities close to these three velocities.

**METHODS**

**Subjects.** The 13 male volunteers who took part in this experiment were all regularly engaged in physical training. They were aged 26 yr (SD 6; range 19 – 45), height 180.0 cm (SD 5.6; range 168 – 188), and body mass 71.9 kg (SD 7.8; range 56.6 – 84.2). The study was approved by the Committee on Human Protection in Biomedical Research in Grenoble, France. All of the subjects gave their written voluntary informed consent.

**Overview.** The experiment was carried out on four separate days, at least 1 wk apart. All tests were performed on a level treadmill (Imbernon, JOGG 30, France), at the same time of day and in a climate controlled laboratory (20 – 22°C). The subjects were asked not to train hard during the last 2 d before each test and to report to the laboratory at least 2 h after the last meal. On the first day, $\dot{V}_O_2_{max}$ and $\dot{V}_O_2$ at the ventilatory threshold ($\dot{V}_O_2_{VT}$) were determined during an incremental exercise test. On the other three days, subjects performed square-wave running exercises at nine different speeds. Using Daniels’ method (16), three different $\dot{V}_O_2_{max}$ were extrapolated from three separate submaximal $\dot{V}_O_2$-velocity relationships, with $\dot{V}_O_2$ being measured either at the 4th min (to determine $\dot{V}_O_2_{max1}$), at the 6th min (to determine $\dot{V}_O_2_{max2}$), or after attainment of the true steady-state (to determine $\dot{V}_O_2_{maxSS}$) of the submaximal square-wave exercises. The $\dot{V}_O_2_{max}$ value introduced in the regressions was the value determined during the incremental test.

**Experimental protocol.** On day 1, the initial velocity of the incremental test was set at 6 km h$^{-1}$ and was increased by 1 km h$^{-1}$ per minute until exhaustion. $\dot{V}_O_2_{max}$ was defined as the average value calculated over the last 2-min interval of the test. The criterion for accepting a value as $\dot{V}_O_2_{max}$ was a leveling off despite an increase in treadmill speed (in all subjects, a leveling off in $\dot{V}_O_2$ (an increment in $\dot{V}_O_2$ less than 2 mL min$^{-1}$kg$^{-1}$) was observed before the last two stages, meaning that $\dot{V}_O_2$ did not increase more than 2 mL min$^{-1}$kg$^{-1}$ over the final 3 min of the test), a heart rate at exhaustion within 10 beats min$^{-1}$ of the subject’s age-predicted maximum and a respiratory exchange ratio (RER) in excess of 1.10. $\dot{V}_O_2_{VT}$ was estimated from the nonlinearity of CO$_2$ output ($\dot{V}_C_0$) plotted against $\dot{V}_O_2$, as described by Sherrill et al. (37). On days 2, 3, and 4, participants performed three square-wave treadmill tests per day, at speeds differing by 0.5 km h$^{-1}$. The highest speed used in these square-wave tests (peak velocity) was the speed which elicited the highest $\dot{V}_O_2$ measured on a 30-s interval in the incremental test. The lowest speed was the peak velocity minus 4 km h$^{-1}$. Subjects performed three bouts of exercise per day, at low, medium, and high speed, in this order. A standard 5-min warm-up at 10 km h$^{-1}$ followed by a 3-min recovery preceded each exercise bout. For each running bout, the subject began to run at time 0, and the velocity was increased from 0 to the desired setting in 20 – 30 s. The subject was then required to run until exhaustion or for 15 min. Indications of elapsed time were given at 5, 9, 11, and 13 min of exercise. When the exercise proceeded until exhaustion, the end time was when the subject reached for the hand rail to stop. The tests were separated by a minimum of 70 min of recovery. This rest time between the daily exercise tests was thought to be appropriate to allow $\dot{V}_O_2$ and blood lactate to return to the basal levels. The pretest blood lactate concentrations and $\dot{V}_O_2$ were in fact quite low (6.7 (SD 0.8) mL min$^{-1}$kg$^{-1}$ for $\dot{V}_O_2$ and 1.6 (SD 0.4) mmol L$^{-1}$ for blood lactate), suggesting that the rest time was on average long enough.

**Experimental measurements.** The subjects breathed through a face mask during the exercise tests and the preceding rest periods, and respiratory gas exchanges were monitored breath-by-breath using an integrated computerized system (Medical Graphics Corporation, CPX/D, St. Paul, MN). Precision analyzed gas mixtures and a 3-L Rudolph syringe were used to calibrate the rapid gas analyzers and the pneumotachograph. Breath-by-breath expired ventilation ($\dot{V}_E$, BTPS), $\dot{V}_C_0$ (STPD), and $\dot{V}_O_2$ (STPD) were determined and stored for future analyses. Heart rate (HR) was monitored with a cardiotachometer (Hewlett-Packard, 78352 C, Avondale, PA). Blood microsamples were obtained from a fingertip before warm-up and immediately at the end of each exercise test and were analyzed for blood lactate concentration using an automatic lactate analyzer (Inceltech, Microzyme, France).

**Experimental calculations: determination of the three $\dot{V}_O_2_{max}$.** For each participant, the square-wave exercises used to determine the three separate submaximal $\dot{V}_O_2$-velocity relationships had to be characterized by the achievement of a $\dot{V}_O_2$ steady-state and by a submaximal end-exercise $\dot{V}_O_2$ above the individual ventilatory threshold. The following mathematical method was used to determine when a $\dot{V}_O_2$ steady-state was achieved. Breath-by-breath $\dot{V}_O_2$ data obtained during each square-wave exercise were smoothed with a 5-breath moving average filter. Then, the data were fitted by a two-component exponential model derived from Barstow and Molé (2). This model incorporated the resting level of $\dot{V}_O_2$ (mL min$^{-1}$) determined with the subject standing on the treadmill ($A_0$), and each component was described by an asymptotic increment above $A_0$ ($A_1$ and $A_2$ in mL min$^{-1}$) and $\tau_1$ in s) and a time delay ($T_d_1$ and $T_d_2$ in s). Because the increase in $\dot{V}_O_2$ during the first ~30 s of exercise were influenced by both the time to achieve the desired velocity and the initial rapid response called phase I (40), the values measured during this period were not taken into account in the fitting procedure: the start of the first exponential component was visually inspected.
and represented the first data introduced in the fitting procedure (Fig. 1). Thereafter, a steady-state VO₂ (i.e., no further increase in VO₂) was considered to be achieved before exhaustion when the time to achieve 99% of the asymptotic increment in VO₂ above resting (Tss) was less than the time to exhaustion. The asymptotic increment above resting equaled A₁, so Tss equaled (Td₁ + 5·τ₁) when the computation reduced the VO₂ kinetics to a monoeponential response. The asymptotic increment above resting equaled (A₁ + A₂) when the VO₂ kinetics were double-exponential. In that case, it was assumed that the asymptotic value of the fast component (A₁) was attained at Tss. Therefore, it follows that:

\[ A₁ + A₂ \cdot \left(1 - e^{-(T - Td₁)\frac{1}{τ₁}}\right) = 0.99 \cdot (A₁ + A₂) \]

By rearranging this equation, we obtain:

\[ T_s = -\ln(0.01 \cdot A₁/A₂ + 0.01) \cdot τ₁ + Td₁ \]

This method has been described and discussed elsewhere (5). Thereafter, the square-wave running tests in which there was a submaximal steady-state were identified and the VO₂ data from only these tests were used to calculate the three VO₂ values incorporated in the three separate VO₂-velocity regressions: 1) the VO₂ measured over a 30-s interval centered on the end of the 4th minute was used to extrapolate vVO₂max4; 2) the VO₂ measured over a 30-s interval centered on the end of the 6th minute was used to extrapolate vVO₂max6; and 3) the average VO₂ calculated from Tss to the end of the exercise was used to extrapolate vVO₂maxSS.

**Experimental calculations: determination of the metabolic response at the three vVO₂max.** For each calculated vVO₂max, the square-wave exercise with the nearest velocity was used to assess the VO₂ and RER responses: the difference between the calculated vVO₂max and the closest velocity was less than 0.25 km h⁻¹. The VO₂ and RER values reached at the end of these exercises were either the average values calculated from Tss to the end of the exercise when a VO₂ steady-state was mathematically detected or the average values over the last 30 s of the exercise when no steady-state was reached. The times from the onset of exercise until a desired fraction of VO₂max was reached (80, 85, 90, or 95% VO₂max) were also recorded. These times were estimated using the VO₂ kinetic exponential model.

**Statistical analyses.** All data are given as means ± SD. The estimated parameters of the VO₂-velocity regressions (slopes and y-intercepts), the vVO₂max, the VO₂, RER, and blood lactate concentrations at the end of the exercise tests at vVO₂max, the times to reach a fraction of VO₂max, and the times to exhaustion (Tlim) were compared using one-way repeated measures analysis of variance (ANOVA) and Newman-Keuls post hoc tests. Correlation coefficients were also calculated between the three different vVO₂max values. Statistical significance was set at P < 0.05 for all tests.

**RESULTS**

The mean value of VO₂max was 60.4 ± 2.7 mL·min⁻¹·kg⁻¹, and that of VO₂VT was 48.8 ± 6.4 mL·min⁻¹·kg⁻¹ (80.2 ± 8.2% VO₂max). Figure 2 shows the time course of the VO₂ responses (panel A), the submaximal VO₂-velocity relationships measured at 4 min, 6 min, and at steady-state, and the corresponding extrapolated vVO₂max (panel B) for a typical subject. Figure 3 shows the average values of VO₂ (expressed in %VO₂max) measured at 4 min, 6 min, and at the end of the exercise (VO₂end) for each of the nine individual square-wave running velocities (expressed in % peak velocity) (N = 13). VO₂end was measured from Tss to the end of the exercise when a steady-state was detected, or over the last 30 s of the exercise.

The three individual submaximal VO₂-velocity regressions mostly incorporated data for the four lowest velocities (range: 4–5 data points; correlation-coefficient for the regressions: 0.97 ± 0.02), depending on the individual number of square-wave tests having a steady-state in VO₂. At 80 ± 0.7% peak velocity, the VO₂ measured at 4 min were 97 ± 2.5% VO₂end; they were 97 ± 2.4% VO₂end at 82.5 ± 0.6% peak velocity, 96 ± 3.3% VO₂end at 85 ± 0.5% peak velocity and 95 ± 2.5% VO₂end at 87.5 ± 0.4% peak velocity; these VO₂ values were significantly different from the VO₂end values (P < 0.05). At these four fractions of peak velocity, the VO₂ measured at 6 min were 98 ± 1.2, 99 ± 1.4, 98 ± 2.9, and 98 ± 1.7% VO₂end, respectively; these VO₂ values were also significantly different from the VO₂end values (P < 0.05). As a consequence, the slope and the y-intercept calculated with VO₂ad were significantly different from the slopes and y-intercepts calculated with VO₂6 and VO₂SS (P < 0.01), whereas these last slopes and y-intercepts only tended to be different (P < 0.06). The three relationships crossed at 80% VO₂max, an intensity close to the ventilatory threshold for the whole group. This is listed in Table 1, with the mean values of the calculated vVO₂max, vVO₂max4, vVO₂max6 were significantly higher than vVO₂maxSS and vVO₂maxSS (P < 0.05) and well correlated with them (r = 0.85 and 0.87, respectively, P < 0.05); vVO₂maxSS and
vVO_{2\text{max6}} were significantly but slightly different (P < 0.05) and were closely correlated (r = 0.98, P < 0.05).

Table 2 shows the mean velocities used to evaluate the metabolic responses at the three extrapolated vVO_{2\text{max}}, the corresponding average time to exhaustion (T_{LIM}), the VO_{2}(VO_{2\text{end}}) either measured from T_{ss} to the end of the exercise when a VO_{2} steady-state was detected or over the last 30 s of the exercise, mean RER and the average blood lactate concentrations measured at the end of the test, and the kinetics data. In some cases (N = 5), the same individual velocity had to be used to evaluate the metabolic responses at vVO_{2\text{max6}} and vVO_{2\text{maxSS}} when these two calculated values were very close. VO_{2\text{end}} was similar for all velocities and not significantly different neither from VO_{2\text{max}} (4337 mL.min^{-1} STPD) nor from VO_{2\text{peak}} (4373 mL.min^{-1} STPD), both measured during the incremental test. Blood lactate concentrations were also similar at vVO_{2\text{max6}} and vVO_{2\text{maxSS}} when these two calculated values were very close. T_{LIM}, and RER at vVO_{2\text{max6}} were different from the corresponding values at vVO_{2\text{max6}} and vVO_{2\text{maxSS}} (P < 0.05). The time required to reach 90% and 95% VO_{2\text{max}} during a square-wave test were also significantly longer at vVO_{2\text{maxSS}} than at vVO_{2\text{max4}} (P < 0.05); the time required to reach 95% VO_{2\text{max}} at vVO_{2\text{max6}} was also longer than at vVO_{2\text{max4}} but significantly shorter than at vVO_{2\text{maxSS}} (Fig. 4; P < 0.05).

**DISCUSSION**

The main finding of the present study is that the three vVO_{2\text{max}} extrapolated from separate submaximal VO_{2}-velocity relationships are significantly different. Square-wave tests performed at velocities close to these three vVO_{2\text{max}} show that they all gave values for VO_{2\text{max}} and similar end-exercise blood lactate concentrations. Nevertheless, these square-wave runs differ in the time required to reach a high fraction of VO_{2\text{max}} and in the time to fatigue.

The methodology used by Daniels et al. (17,18) and Morgan et al. (33) to extrapolate vVO_{2\text{max}} from the submaximal VO_{2}-velocity relationship was based on two assumptions. The first was that the VO_{2}-velocity relationship is essentially linear. The second was that the aerobic metabolism reacts like a linear first-order system, which leads to a VO_{2} steady-state in about 4 min, whatever the exercise intensity—below or above VT. Actually, the linearity of the VO_{2}-velocity relationship evaluated over the entire range of submaximal running velocities is disputed. Several authors consider this relationship to be linear from rest to VO_{2\text{max}} (31,19,14) with the y-intercept reflecting the significance of the VO_{2} measured at rest (5m L.min^{-1}kg^{-1}; 32). Others have reported a nonlinear VO_{2}-velocity relationship over the entire range of submaximal running speeds (1,18). Nevertheless, Daniels (16) concluded that “the concept of a linear relationship between velocity and the VO_{2} seems to hold up during submaximal running (1), where the range of running speeds is rather limited,” but pointed out that the...
slope and the y-intercept of such a linear regression depended on the chosen limited range of speeds. The higher these speeds, the steeper the slope and the lower the y-intercept (18). In the experiments where Daniels et al. (16,17) and Morgan et al. (33) determined $\text{vV}_2\text{max}$, they related the VO$_2$ measured at the 4th or 6th min of a square-wave treadmill test to the velocities of a limited range of high intensities (>60% VO$_2\text{max}$). The mean slope values (0.205–0.254 mL·m$^{-1}$·kg$^{-1}$) and the mean y-intercept values (−20.992 to −1.829 mL·m$^{-1}$·kg$^{-1}$) reported in their experiments are consistent with those found in our study for similar times of VO$_2$ measurement (Table 1). The negative y-intercept values found in all these studies also confirm that the VO$_2$-velocity relationship is not linear from rest to VO$_2\text{max}$. Although Daniels et al. (16,17) and Morgan et al. (33) computed the VO$_2$-velocity regression whatever the intensity (below or above VT), we have focused on supra-VT work rates, to assess the effect of the VO$_2$ slow component on the parameters of the VO$_2$-velocity regression. Previous experiments have found that the VO$_2$ slow component can delay the establishment of the steady-state in VO$_2$ (where achievable) well beyond the 6th min of a square-wave test (2,5,23,35,36) and that the later VO$_2$ is measured during a supra-VT test, the greater is the increase in VO$_2$ with work rate (3,5). Consequently, we postulated that the slope of the VO$_2$-velocity regression computed at the true steady-state should be significantly steeper, and the y-intercept lower, than the corresponding parameters of regressions computed during the rise in VO$_2$ (at the 4th or the 6th min of exercise). Our results (Fig. 3) confirm that the VO$_2$ measured up to the 6th min of a supra-VT test are significantly lower than the VO$_2$ at steady-state (<98% VO$_2$ at steady-state, in average). However, the interesting finding is that the parameters (slope and y-intercept) of the corresponding VO$_2$-velocity regressions are not significantly different when VO$_2$ is measured at the 6th minute or at steady-state during these constant-speed exercises (Table 1). This is presumably due to the fact that 6 min is long enough for the subjects’ VO$_2$ to reach over 98% of the asymptotic value for VO$_2$ (Fig. 3). As a consequence, $\text{vV}_2\text{max SS}$ and $\text{vV}_2\text{max 6}$ are closely correlated ($r = 0.98$), whereas $\text{vV}_2\text{max 4}$ is less so ($r ≤ 0.87$).

Although the initial definition of $\text{vV}_2\text{max}$ proposed by Daniels (16) used the extrapolation method, several other ways of determining this index have been published (7–9,19,25–29). However, Hill and Rowell (24) demonstrated that these various methods each give a different qualitative index. Billat, Hill, and their colleagues (10,11,25–27) evaluated the metabolic response to exercise at $\text{vV}_2\text{max}$ determined as the velocity at which VO$_2\text{max}$ is achieved in an incremental test. We therefore evaluated the methods of determining $\text{vV}_2\text{max}$ by the extrapolation method, as well evaluating the metabolic responses to exercise at the $\text{vV}_2\text{max}$ that were calculated. The metabolic responses

### Table 1. Values (means ± SD) for the three calculated velocities at VO$_2\text{max}$ ($\text{vV}_2\text{max}$) and the corresponding parameters of the submaximal VO$_2$-velocity regressions.

<table>
<thead>
<tr>
<th>($N = 13$)</th>
<th>$\text{vV}_2\text{max SS}$</th>
<th>$\text{vV}_2\text{max 6}$</th>
<th>$\text{vV}_2\text{max 4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (m·min$^{-1}$)</td>
<td>303 ± 14$^a$</td>
<td>307 ± 13$^a$</td>
<td>317 ± 11$^a$</td>
</tr>
<tr>
<td>VO$_2$-velocity Slope (mL·m$^{-1}$·kg$^{-1}$)</td>
<td>0.277 ± 0.106$^a$</td>
<td>0.251 ± 0.099$^d$</td>
<td>0.206 ± 0.089$^h$</td>
</tr>
<tr>
<td>Regression Y-intercept (mL·m$^{-1}$·kg$^{-1}$)</td>
<td>−23.07 ± 29.66$^e$</td>
<td>−16.36 ± 28.15$^f$</td>
<td>−4.99 ± 19.80$^m$</td>
</tr>
</tbody>
</table>

Mean values with the same subscript are significantly different from each other at the 0.05 level.

### Table 2. Metabolic responses at the three calculated $\text{vV}_2\text{max}$.

<table>
<thead>
<tr>
<th>($N = 13$)</th>
<th>$\text{vV}_2\text{max SS}$</th>
<th>$\text{vV}_2\text{max 6}$</th>
<th>$\text{vV}_2\text{max 4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity “close to $\text{vV}_2\text{max}$” (m·min$^{-1}$)</td>
<td>303 ± 14$^a$</td>
<td>307 ± 13$^a$</td>
<td>317 ± 11$^a$</td>
</tr>
<tr>
<td>(% true VO$_2$max)</td>
<td>99.8 ± 0.7</td>
<td>99.9 ± 0.7</td>
<td>100.2 ± 0.9</td>
</tr>
<tr>
<td>($s$)</td>
<td>619 ± 204$^{a}$</td>
<td>550 ± 158$^{a}$</td>
<td>370 ± 87$^{ac}$</td>
</tr>
<tr>
<td>VO$_2$end (mL·min$^{-1}$)</td>
<td>4246 ± 411</td>
<td>4266 ± 437</td>
<td>4262 ± 435</td>
</tr>
<tr>
<td>RER</td>
<td>1.02 ± 0.07$^d$</td>
<td>1.02 ± 0.08$^f$</td>
<td>1.05 ± 0.07$^{ac}$</td>
</tr>
<tr>
<td>Blood lactate (mmol·L$^{-1}$)</td>
<td>8.2 ± 1.7</td>
<td>8.4 ± 1.9</td>
<td>8.6 ± 1.5</td>
</tr>
<tr>
<td>Time at 95% VO$_2$max ($s$)</td>
<td>335 ± 38$^e$</td>
<td>286 ± 35$^f$</td>
<td>225 ± 38$^f$</td>
</tr>
</tbody>
</table>

Kinetic parameters

<table>
<thead>
<tr>
<th></th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>550 ± 146</td>
<td>560 ± 117</td>
<td>548 ± 94</td>
</tr>
<tr>
<td></td>
<td>3287 ± 275$^a$</td>
<td>3379 ± 380</td>
<td>3418 ± 365$^a$</td>
</tr>
<tr>
<td>$T_{lim}$ ($s$)</td>
<td>25 ± 4</td>
<td>25 ± 4</td>
<td>25 ± 3</td>
</tr>
<tr>
<td>$T_{ss}$ ($s$)</td>
<td>22 ± 5</td>
<td>23 ± 5</td>
<td>21 ± 6</td>
</tr>
</tbody>
</table>

Running exercises with a steady-state VO$_2$ (SSVO$_2$ exercises)

<table>
<thead>
<tr>
<th></th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>410 ± 139</td>
<td>328 ± 95</td>
<td>442</td>
</tr>
<tr>
<td></td>
<td>152 ± 37</td>
<td>171 ± 22</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>139 ± 98</td>
<td>102 ± 87</td>
<td>84</td>
</tr>
<tr>
<td>$T_{ss}$ ($s$)</td>
<td>491 ± 235</td>
<td>394 ± 209</td>
<td>309</td>
</tr>
<tr>
<td>$N$</td>
<td>7</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>

Running exercises without a steady-state VO$_2$ (RVO$_2$ exercises)

<table>
<thead>
<tr>
<th></th>
<th>$A_0$</th>
<th>$A_1$</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>545 ± 227</td>
<td>446 ± 117</td>
<td>735 ± 620</td>
</tr>
<tr>
<td></td>
<td>126 ± 41</td>
<td>139 ± 55</td>
<td>113 ± 47</td>
</tr>
<tr>
<td></td>
<td>356 ± 358</td>
<td>265 ± 328</td>
<td>296 ± 303</td>
</tr>
<tr>
<td>$N$</td>
<td>6</td>
<td>7</td>
<td>12</td>
</tr>
</tbody>
</table>

$A_0$, $A_1$, and $A_2$ are expressed in mL·min$^{-1}$·STPD. $T_{d1}$, $T_{d2}$, $T_{ss}$, $T_{lim}$, and $T_{ss}$ are expressed in seconds. Mean values with the same subscript are significantly different from each other at the 0.05 level.
were not assessed at the exact calculated \( \text{vVO2}_{\text{max}} \), but the square-wave treadmill tests were conducted at very similar velocities: the absolute difference in velocity was always less than 0.25 km·h\(^{-1}\) and was 0.12 ± 0.07 km·h\(^{-1}\) on average (Table 2). Our results show that the three \( \text{vVO2}_{\text{max}} \) did not differ by the blood lactate concentration measured at the end of the exercise. \( \text{VO2}_{\text{max}} \) was also reached during or at the end of the exercise, whatever the \( \text{vVO2}_{\text{max}} \). However, the main difference between the three metabolic responses concerns the rate of \( \text{VO2} \) (Table 2; Fig. 4). The time required to reach a desired fraction of \( \text{VO2}_{\text{max}} \) during the square-wave treadmill test varied inversely with the calculated \( \text{vVO2}_{\text{max}} \). This suggests that the three velocities influenced the cellular processes controlling the increase in \( \text{VO2} \) differently (i.e., the phosphate pool turnover).

The present study was done to assess the effect of the \( \text{VO2} \) slow component on the \( \text{VO2} \)-velocity relationship and the \( \text{vVO2}_{\text{max}} \) values extrapolated from this relationship. The present findings have several practical implications. According to Daniels (16), \( \text{vVO2}_{\text{max}} \) may be useful for explaining the similar performances among competitive distance runners whose desirable attributes of \( \text{VO2}_{\text{max}} \) and running economy are different. Because \( \text{vVO2}_{\text{max}} \) is a valid index of distance running performance (33), our study shows that the \( \text{vVO2}_{\text{max}} \) values extrapolated from this relationship describe very similar qualitative indices of performance when \( \text{VO2} \) is measured beyond the 6th minute of constant velocity running within the heavy intensity domain. An attempt has also been made recently to assess the contributions of aerobic and anaerobic metabolism during an exhaustive run at \( \text{vVO2}_{\text{max}} \) (25). The energy demand (\( \text{O2} \) demand when it is expressed in \( \text{O2} \) equivalents) extrapolated from the submaximal \( \text{VO2} \)-velocity relationship was used to determine the accumulated \( \text{O2} \) deficit (an estimate of the anaerobic energy requirement). However, our findings suggest that the estimated \( \text{O2} \) demand at a given running velocity depends on the type of submaximal exercise used to calculate the \( \text{VO2} \)-velocity relationship. When work rates from the heavy intensity domain are introduced into the \( \text{VO2} \)-velocity regression, the estimated \( \text{O2} \) demand depends on the period during which \( \text{VO2} \) is measured. Therefore, introducing work rates from the moderate intensity domain or from the heavy intensity domain into the \( \text{VO2} \)-velocity regression leads to different \( \text{O2} \) demand because these two intensity domains are associated with different \( \text{VO2} \) kinetics responses. In fact, recent experiments on the validity of the accumulated \( \text{O2} \) deficit method have reported the effect of introducing submaximal work rates associated with a \( \text{VO2} \) slow component into the computation of the \( \text{VO2} \)-work rate regression. Green and Dawson (20) reported that “at submaximal power outputs which are not associated with a \( \text{O2} \) slow component, measurements made at any point within 3 and 15 min yield similar values. In contrast, at higher intensities the period of measurement does affect the \( \text{VO2} \) recorded, the slope of the \( \text{VO2} \)-power regression, and the \( \text{O2} \) demand predicted for a supra-\( \text{VO2peak} \) power output.” The findings for the \( \text{VO2} \)-velocity regression are also similar (1). Therefore, Green et al. (21) concluded that the submaximal \( \text{VO2} \)-work rate regression is an inaccurate way to estimate the \( \text{O2} \) demand of high power outputs, and further experiments are needed to identify the most appropriate protocol. Taken together, the findings by Green and his colleagues and the findings of the present study indicate that the \( \text{O2} \) demand at \( \text{vVO2}_{\text{max}} \) (when extrapolated from a submaximal \( \text{VO2} \)-velocity relationship) can be higher than \( \text{VO2}_{\text{max}} \), and so, \( \text{vVO2}_{\text{max}} \) is not necessarily the lowest velocity which elicits \( \text{VO2}_{\text{max}} \); it depends on the duration and the intensity of the submaximal bouts used to compute the regression. Nevertheless, some authors have argued that \( \text{vVO2}_{\text{max}} \) is the minimal velocity which elicits \( \text{VO2}_{\text{max}} \) (6,10,11), although their \( \text{vVO2}_{\text{max}} \) seems to be much higher than the three \( \text{vVO2}_{\text{max}} \) we determined: these authors used the velocity at which \( \text{VO2}_{\text{max}} \) was first elicited in an incremental test, and the duration of the stages for that test was not longer than 3 min. On a practical point of view, \( \text{vVO2}_{\text{maxSS}} \) seems to be the lowest velocity associated with \( \text{VO2}_{\text{max}} \); whatever the submaximal \( \text{VO2} \)-velocity relationship, but it is possible that velocities just below \( \text{vVO2}_{\text{maxSS}} \) can also elicit \( \text{VO2}_{\text{max}} \).

In summary, the present study shows that the \( \text{vVO2}_{\text{max}} \) values, extrapolated from the submaximal \( \text{VO2} \)-velocity relationship in the heavy intensity domain, is independent of the period during which \( \text{VO2} \) is measured, as long as this time is longer than 6 min. These results can therefore serve as guidelines for determining \( \text{vVO2}_{\text{max}} \). Further experiments on the nature of the \( \text{VO2} \) slow component will help evaluate the precise contributions of aerobic and anaerobic metabolism at each \( \text{vVO2}_{\text{max}} \).

Figure 4 —Mean times (±SEM) required to reach a desired fraction of \( \text{VO2}_{\text{max}} \) during square-wave tests run at velocities close to the calculated \( \text{vVO2}_{\text{max}} \). *Significantly different (\( P < 0.05 \)).
REFERENCES


