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Significance of the Velocity at $\dot{V}O_{2max}$ and Time to Exhaustion at this Velocity

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Summary

In 1923, Hill and Lupton pointed out that for Hill himself, 'the rate of oxygen intake due to exercise increases as speed increases, reaching a maximum for the speeds beyond about 256 m/min. At this particular speed, for which no further increases in O_2 intake can occur, the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres have attained their maximum activity. At higher speeds the requirement of the body for oxygen is far higher but cannot be satisfied, and the oxygen debt continuously increases'.

In 1975, this minimal velocity which elicits maximal oxygen uptake ($\dot{V}O_{2max}$) was called 'critical speed' and was used to measure the maximal aerobic capacity (max E_{ox}), i.e. the total oxygen consumed at $\dot{V}O_{2max}$. This should not be confused with the term 'critical power' which is closest to the power output at the 'lactate threshold'.

In 1984, the term 'velocity at $\dot{V}O_{2max}$' and the abbreviation '$v\dot{V}O_{2max}$' was intro-

duced. It was reported that $v\dot{V}O_{2max}$ is a useful variable that combines $\dot{V}O_{2max}$ and economy into a single factor which can identify aerobic differences between various runners or categories of runners. $v\dot{V}O_{2max}$ explained individual differences in performance that $\dot{V}O_{2max}$ or running economy alone did not. Following that, the concept of a maximal aerobic running velocity (V_{amax} in m/sec) was formulated. This was a running velocity at which $\dot{V}O_{2max}$ occurred and was calculated as the ratio between $\dot{V}O_{2max}$ (ml/kg/min) minus oxygen consumption at rest, and the energy cost of running (ml/kg/sec).

There are many ways to determine the velocity associated with $\dot{V}O_{2max}$ making it difficult to compare maintenance times. In fact, the time to exhaustion (t_{lim}) at $v\dot{V}O_{2max}$ is reproducible in an individual, however, there is a great variability among individuals with a low coefficient of variation for $v\dot{V}O_{2max}$. For an average value of about 6 minutes, the coefficient of variation is about 25%. It seems that the lactate threshold which is correlated with the t_{lim} at $v\dot{V}O_{2max}$ can explain this difference among individuals, the role of the anaerobic contribution being significant.

An inverse relationship has been found between t_{lim} at $v\dot{V}O_{2max}$ and $\dot{V}O_{2max}$, and a positive one between $v\dot{V}O_{2max}$ and the velocity at the lactate threshold expressed as a fraction of $v\dot{V}O_{2max}$. These results are similar for different sports (e.g. running, cycling, kayaking, swimming). It seems that the real time spent at $\dot{V}O_{2max}$ is significantly different from an exhaustive run at a velocity close to $v\dot{V}O_{2max}$ (105% $v\dot{V}O_{2max}$). However, the minimal velocity which elicits $\dot{V}O_{2max}$, and the t_{lim} at this velocity appear to convey valuable information when analysing a runner's performance over 1500m to a marathon.

In 1923, Hill (a 35-year old, 73kg 'practised runner') and Lupton (a 21-year old, 65kg 'well built athletic person') served as guinea-pigs, running at different velocities, to measure their own maximum oxygen uptake [$\dot{V}O_{2max}$] (57.2 ml/kg/min at 16 km/h and 54.4 ml/kg/min respectively; velocity not specified for Lupton). Hill and Lupton[1] pointed out that: 'the maximal value actually attained is only the maximum oxygen intake for that type of exercise (running), and may not correspond in the least to the oxygen requirement of the body'. At 16 km/h he felt that 'he would manifestly have been unable to continue at this speed for more than 10 minutes, if that long'.

In such severe exercise, lactic acid is continuously accumulating in the muscles, $\dot{V}O_{2max}$ (depending upon the capacity of heart and lungs) being inadequate to maintain the recovery at a level high enough to cope with the production of lactic acid. Hence, in such cases, the fact that the intake of oxygen has reached a constant value within 2.5 minutes represents nothing more than the fact that its maximum level has been attained; it does not imply that the body has reached a state of dynamic equilibrium in which break-down is balanced by recovery.

For Hill himself, 'the rate of oxygen intake due to exercise, increases as speed increases, reaching a maximum for the speeds beyond about 256 m/min. At this particular speed, for which no further increases in O_2 intake can occur, the heart, lungs, circulation, and the diffusion of oxygen to the active muscle-fibres have attained their maximum activity. At higher speeds the requirement of the body for oxygen is far higher but cannot be satisfied, and the oxygen debt continuously increases'. He also states: 'Considering the case of running, there is clearly some critical speed for each individual at which there is a genuine dynamic equilibrium, breakdown being balanced by restoration, above which, however, the maximum oxygen intake is inadequate, lactic acid accumulating, a continuously increasing oxygen debt being incurred, fatigue and exhaustion setting in'.

Hill and Lupton identified the major problems of applied physiology in this century which are: the meanings of $\dot{V}O_{2max}$; the velocity associated with $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$), the critical velocity defined later by Moritani et al.[2] as close to the lactate threshold velocity; and the oxygen deficit as an estimate of the anaerobic capacity as stated by Medbo et al.[3]

Volkov et al.[4] used the minimal velocity which elicits $\dot{V}O_{2max}$, described as the 'critical speed' to measure the maximal aerobic capacity (max E_{ox}) i.e. the total oxygen consumed at $\dot{V}O_{2max}$ asking the participant to maintain their 'critical speed' as long as possible. This term may be confused with the 'critical power' of Moritani et al.[2] and Lechevalier et al.[5] However, the time to exhaustion at the velocity associated with $\dot{V}O_{2max}$ that Hill estimated could be sustained for 10 minutes has since been overlooked because no studies have measured it, except the study by Volkov et al.[4] and those which measured critical power.[5,6] Recently, some papers have focused on this concept of v$\dot{V}O_{2max}$ and on its time to exhaustion (t_{lim}).

The aim of this review is 3-fold. First, to look at the definitions of the velocity associated with $\dot{V}O_{2max}$ and at their influence on the different protocols and values for v$\dot{V}O_{2max}$. Secondly, to examine the t_{lim} at v$\dot{V}O_{2max}$; (i) in the model approaches of the time-velocity relationship and (ii) in the experimental measurements of t_{lim} at v$\dot{V}O_{2max}$. Finally, to look at the use of v$\dot{V}O_{2max}$ and its time limit for training.

1. Definitions and Description of the Velocity at Maximal Oxygen Consumption (v$\dot{V}O_{2max}$)

Although $\dot{V}O_{2max}$ has been generally accepted as the physiological variable that best described the capacities of the cardiovascular and respiratory systems, v$\dot{V}O_{2max}$ was assessed only 50 years later to give a practical assessment of aerobic demands and capability during running performance. The reason for this gap could be the training habits among elite runners who did not use physiological parameters. Moreover, in the 1980s, aerobic training and running created a social demand, encouraged grants to evaluate fitness ($\dot{V}O_{2max}$ for example) and provided training advice. However, the procedure for measuring $\dot{V}O_{2max}$ is extremely time consuming, and requires trained personnel and special equipment which must be used under controlled conditions.[7]

1.1 Measurement of v$\dot{V}O_{2max}$ on the Field (Using a Constant Oxygen Cost of Running)

The first field test to examine v$\dot{V}O_{2max}$ had specific objectives, one of which was to replace Cooper's all-out 12-minute test[8] with an alternative method of $\dot{V}O_{2max}$ prediction in an effort to simplify procedures and reduce costs. Balke[9] suggested that the distance covered during 15 minutes of running or walking was a valid indicator of $\dot{V}O_{2max}$. Cooper,[8] whose study intensified efforts to establish the concurrent validity of distance runs, reported a correlation of 0.90 between $\dot{V}O_{2max}$ and the distance covered during a 12-minute run or walk. The Cooper test was the most widely used at the time but it required great motivation and a knowledge of pacing.[10] While the earlier studies[8,9] of distance run tests yielded high validity coefficients, it should be noted that, in some of these studies, the participants used were military personnel who were more likely to be highly motivated.[7]

The Cooper test was based on the linear relationship that linked the increase in running velocity to the rise in oxygen consumption ($\dot{V}O_2$) which, when conducted to the point of exhaustion, could be used to determine $\dot{V}O_{2max}$. The accuracy of the prediction, or indeed its inaccuracies, depended on the inter-individual variation of the energy cost of running.

Léger and Boucher[10] showed the reliability of an indirect continuous running multistage field test to predict $\dot{V}O_{2max}$: the Université de Montréal Track Test. The speed was increased from 8.5 km/h at the rate of 1 km/h every 2 minutes until the participant could no longer maintain the pace. The so-called 'maximal aerobic speed' (MAS) was used to predict $\dot{V}O_{2max}$. This method was based on Shephard's linear equation[10] for the energy cost of running corrected for the wind effect by Pugh's formula[11] which yields the quadratic equation:

$$\dot{V}O_{2max} \text{ track (ml/kg/min)} = 0.0324\ (MAS_{track})^2 + 2.143\ MAS_{track} + 14.49 \quad \text{(Eq. 1)}$$

Four years later, Léger and Mercier[12] re-investigated the gross energy cost of horizontal treadmill and track running and demonstrated the following linear equation:

$$\dot{V}O_2 \text{ (ml/kg/min)} = 3.5 \cdot \text{speed (km/h)} \quad \text{(Eq. 2)}$$

or

$$\dot{V}O_2 \text{ (MET)} = \text{speed (km/h)} \quad \text{(Eq. 3)}$$

Thus, the test score that might be expressed as MAS in km/h or as maximal aerobic power (MAP) in METs (1 MET, or $\dot{V}O_2$ at rest = 3.5ml oxygen/kg/min) was very close, between 8 and 25 km/h, to the cubic equation for adults of average weight and height:

$$\dot{V}O_2 \text{ (ml/kg/min)} = 2.209 + 3.163 \text{ speed (km/h)} + 0.000525542 \text{ speed}^3 \quad \text{(Eq. 4)}$$

Many authors have emphasised the validity of these tests for assessing $\dot{V}O_{2max}$.[10,13,14] In a recent study,[14] 17 physical education students underwent a continuous multistage test[10] and $\dot{V}O_{2max}$ measurement on a treadmill. The $\dot{V}O_{2max}$ values estimated using the track test (56.8 ± 5.8 ml/kg/min) were not significantly different from those values measured in the treadmill test with the slope set at a gradient of 3% (56.8 ± 7.1 ml/kg/min). The maximal nature of the tests was checked by monitoring (i) the heart rate which was close to the theoretical maximal heart rate (HR_{max}) using equation 5[14] and (ii) blood lactate (>9 mmol/L).

$$HR_{max} \text{ (bpm)} = 209 - 0.587 \cdot \text{age (years)} \quad \text{(Eq. 5)}$$

The mean findings of the MAS observed in the track test (15.8 ± 1.9 km/h) and in the treadmill test (15.9 ± 2.6 km/h) were not significantly different.[14] Furthermore, the MAS measured by the use of a continuous running multistage field test, could predict middle-distance performance runs of elite male and female middle-distance running (r = 0.96, n = 12):[13]

$$MAS \text{ (m/sec)} = 0.97 \text{ v1500 (m/sec)} - 0.47 \quad \text{(Eq. 6)}$$

where v1500 is the velocity over 1500m.

These results were in accordance with studies performed by Mercier and Léger[15] among larger and more heterogeneous groups. Indeed, Mercier and Léger examined how the gender and sports speciality, as well as the distance completed by him/her, affected the predictive regression between the MAS and running performances. Men (n = 251) and women (n = 60) MAS were 17.9 ± 1.9 km/h and 16.3 ± 1.4 km/h respectively. Correlation coefficients (r) and standard errors of the estimate were very good and ranged from 0.6 to 20 km with maximal values for the 3000 and 5000m (r = 0.98, n = 69) Moreover, this study showed that for the same MAS, women gave better performances in long-distance running (between 10km and marathon distance) than men, who were better over shorter distances (from 200 to 2000m). Otherwise, gender did not affect the predictive regression between MAS and running performances over distances of between 3000 to 5000m.[15]

1.2 Determination of $v\dot{V}O_{2max}$ from $\dot{V}O_2$ – Velocity Linear Relationship

The measurement of $\dot{V}O_2$ is necessary to accurately determine the running economy and $\dot{V}O_{2max}$. $\dot{V}O_{2max}$ is defined as the point in the relationship between steady-state $\dot{V}O_2$ and running velocity where $\dot{V}O_2$ reaches a peak value[16] or a plateau ($\dot{V}O_{2max}$) where the increase in $\dot{V}O_2$ is less than 2.1 ml/kg/min for an increase in speed equal to 1 km/h.[17] Moreover, $\dot{V}O_{2max}$ must be associated with a blood lactate equal to 8 to 12 mmol/L and a respiratory exchange ratio equal to 1.1. Heart rate must be at least equal to 90% of the theoretical maximal heart rate in beats/min:[18] 220 – age (years).

In 1975, Volkov et al.[4] defined a 'critical power' at which $\dot{V}O_{2max}$ can be recorded, 'reflecting not only the capacity of an athlete to the maximum increase of the aerobic process but also the fact that this maximum increase in the rate of aerobic energy liberation may be realised in the growth of mechanical power output'.

Daniels et al.[19] introduced the term 'velocity at $\dot{V}O_{2max}$' and the abbreviation '$v\dot{V}O_{2max}$' and reported that $v\dot{V}O_{2max}$ is a useful variable that combines $\dot{V}O_{2max}$ and economy (previously defined by Conley and Krahenbuhl[20]) into a single factor which identifies aerobic differences between various runners or categories of runners. $v\dot{V}O_{2max}$ explained individual differences in performance that $\dot{V}O_{2max}$ or running economy alone did not. Daniels et al.[19] found, in elite female runners showing various combinations of $\dot{V}O_{2max}$ and running economy ($\dot{V}O_2$ submaximal), that $v\dot{V}O_{2max}$ was close to the average velocity performed over 3000m (maintained about 9 minutes). Morgan et al.[21] showed that variations in 10km run times attributable to $v\dot{V}O_{2max}$ were greater than those associated with either $\dot{V}O_{2max}$ or running economy.

Daniels et al.[19] calculated $v\dot{V}O_{2max}$ by extrapolating from the regression curve relating running velocity and $\dot{V}O_2$ to $\dot{V}O_{2max}$, with the velocity of running that corresponds to $\dot{V}O_{2max}$ being identified (fig. 1). $\dot{V}O_2$ submaximal was calculated from four 6-minute runs at velocities of 230, 248, 268 m/min with a 4- to 7-minute recovery between submaximal runs. They measured $\dot{V}O_{2max}$ separately with an incremental test based on the 5000m race pace adding a 1% grade to the treadmill each minute until the test was ended by the participant indicating that they could not run 30 seconds longer. The highest $\dot{V}O_2$ reached during the maximal test was considered to be $\dot{V}O_{2max}$.

1.3 Calculation of $v\dot{V}O_{2max}$ from the Individual Oxygen Cost of Running

di Prampero[22] defined V_{amax} as the MAS that a runner can maintain during a race under aerobic conditions and depends on both the maximal metabolic power available and the net energy cost of the run (C). At each speed, C was calculated from the ratio of the steady-state $\dot{V}O_2$ (ml/kg/min) above the pre-exercise resting level (determined with the participant standing on the treadmill) divided by the running speed (m/min). V_{amax} is then calculated by the following equation:[22]

$$V_{amax} = F\dot{V}O_{2max} / C \quad \text{(Eq. 7)}$$

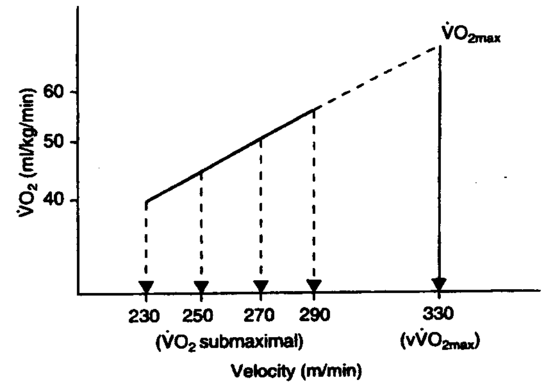

Fig. 1. Mean maximal oxygen uptake ($\dot{V}O_{2max}$) and the relationship between oxygen uptake ($\dot{V}O_2$) and treadmill-running velocity for 30 female runners. Also shown is the velocity which mathematically corresponds to $\dot{V}O_{2max}$ [$v\dot{V}O_{2max}$] (reproduced from Daniels et al.[19] with permission).

where F is the maximal fraction of $\dot{V}O_{2max}$ that can be sustained throughout the duration of the effort in question. For di Prampero[22] 'it is well known, in fact, that $\dot{V}O_{2max}$ cannot be sustained for more than 25 minutes' (according to Lacour and Flandrois[23]).

di Prampero et al.[24] calculated C for 6 minutes at 4 different speeds, (corresponding approximately to 85, 100, 120 and 130% of the average speed the runners sustained during a marathon) from the ratio of the steady-state $\dot{V}O_2$ (ml/kg/min) above the pre-exercise resting level (determined with the participant standing on the treadmill), divided by the running speed (m/min). $\dot{V}O_2$ attained at the highest speed was considered as the participant's $\dot{V}O_{2max}$. The velocity over marathon was 81.3% of $v\dot{V}O_{2max}$, so the 4 speeds used by di Prampero were 0.85, 1, 1.2 and 1.3 × 0.813 $v\dot{V}O_{2max}$: 69.2, 81.3, 97.6, 105.7% $v\dot{V}O_{2max}$., the 2 latter velocities being close to $v\dot{V}O_{2max}$. Between successive runs, 15 to 20 minutes of rest was allowed.

Lacour et al.[25,26] adapted the method originally suggested by di Prampero,[22] by subtracting a standard $\dot{V}O_2$ at rest (5 ml/kg/min) from $\dot{V}O_{2max}$ before dividing by a standard oxygen cost of running The main difference between the Lacour and di Prampero formulae being in the numerator e.g.

$\dot{V}O_{2max}$ – $\dot{V}O_2$ at rest for Lacour whereas $\dot{V}O_{2max}$ only, for di Prampero.

$$V_{amax} = (\dot{V}O_{2max} - 0.083) \cdot C^{-1} \quad \text{(Eq. 8)}$$

where C is the oxygen cost of running at a given velocity calculated as: $C = (\dot{V}O_2 - 0.083) \cdot v^{-1}$ and where $\dot{V}O_{2max}$ is expressed in ml/kg/sec and V_{amax} in m/sec. The 0.083 ml/kg/sec (5 ml/kg/min) value is the $\dot{V}O_2$ value corresponding to the intercept of the $\dot{V}O_{2max}$/velocity relationship established by Medbo et al.[3]

Lacour et al.[25] used an intermittent graded treadmill test with a slope of 3%. The running and rest period times were 4 and 1 minute respectively. The initial velocity (v) was 10.3 km/h (for male middle-distance runners) and increased by 1.54 km/h after each rest period, until the participant was exhausted. The test was, between 30 and 40 minutes. The calculated value of C was the mean of the last 2 bouts sustained for 4 minutes (at 5.42 and 5.84 m/sec, i.e. 89 and 96%) for most of the athletes (V_{amax} = 6.08 m/sec). These velocities were above the velocity at the lactate threshold and C calculated from these velocities might be lower than the real C (since there is an increase in the anaerobic energetic contribution).

Morgan et al.[27] used the same method as Lacour et al.[25,26] except that $\dot{V}O_{2max}$ was measured with a short test (7 minutes) using a slope (see below). Afterwards, they estimated the velocity at $\dot{V}O_{2max}$ by extrapolating it from the submaximal velocity-$\dot{V}O_2$ relationship. The protocol used by Morgan et al.[27] for determining $\dot{V}O_{2max}$ was modified from that of Daniels et al.[19] The mean treadmill t_{lim} to reach $\dot{V}O_{2max}$ was 7.55 (±1.12) minutes. Following completion of the $\dot{V}O_{2max}$ test, each participant's results were scrutinised to determine whether a plateau in $\dot{V}O_2$ had been achieved according to Taylor et al.[17] If the difference in $\dot{V}O_2$ between the last 2 completed power outputs was greater than 2.1 ml/kg/min, the participant rested for 10 minutes, and then performed a 4-minute 'supramaximal' test. This procedure consisted of a 2-minute warm-up at a submaximal power output, followed by a 2-minute run at a power output greater than that last completed during the initial test.

Noakes[28] has questioned the validity of $\dot{V}O_{2max}$ as a predictor of endurance performance since changes in running performance with training occur without equivalent changes of $\dot{V}O_{2max}$. Noakes's data suggest that a good predictor of endurance performance is peak treadmill velocity. He hypothesised that maximum speed may be related to the muscles' capacity for high cross-bridge cycling and respiratory adaptations. Rather than calculate the velocity associated with $\dot{V}O_{2max}$, cumulating the error inherent in both the energy cost of running and the $\dot{V}O_2$ at rest, Noakes and his colleagues have shown that the 'peak running velocity' reached at exhaustion during the maximal treadmill test and maintained for 1 minute, was a better predictor of running performance than $\dot{V}O_{2max}$.[29] This was confirmed by Morgan et al.[27]

In a later study, Noakes et al.[30] confirmed that peak treadmill running velocity predicted the performance for all distances between 10 and 90km. In Noakes' protocol,[28] participants began exercising at 10 km/h with an incremental increase of 1 km/h every minute until exhaustion. Peak treadmill running velocity was taken as the highest speed (km/h) maintained for a whole minute during the maximal test. When an athlete was unable to complete 60 seconds at a particular treadmill velocity, the velocity of the immediately preceding completed work stage was recorded as the peak treadmill running velocity. The $\dot{V}O_{2max}$ was taken as the highest rate of $\dot{V}O_2$ measured during any 60 seconds. This means that the peak treadmill running velocity can be reached at a higher velocity than that which elicits $\dot{V}O_{2max}$.

Kuipers et al.[31] had previously proposed the following equation to adjust the maximal velocity based on the length of time it was maintained:

$$V_{max}\,(km/h) = v + 0.5 \times (t/180) \quad \text{(Eq. 9)}$$

where v is the last velocity completed for 180 seconds; t the number of seconds the final not completed velocity was sustained; 0.5 is the value of the increase in velocity in km/h from the last stage that was maintained and 180 is the number of seconds in the stage. For example if the participant is able to sustain 22 km/h for just 1 minute (instead of 3 minutes) at the last stage of a test, the equation used by Kuipers et al.[31] calculates the V_{max} (km/h) as follows:

$$V_{max}\ (km/h) = 22 + [2 \times (60/180)] \qquad (Eq.\ 10)$$

where V_{max} is the velocity maintained during the last stage, 2 is the value of the increase in velocity in km/h from the last stage that was maintained and 180 is the number of seconds in the stage. Then, V_{max} (km/h) = 22 + 1/3 = 22.33

Lastly, Billat et al.[32,33] investigated the significance of the 'minimal' speed that elicits $\dot{V}O_{2max}$, which they have called the 'maximal aerobic speed' (MAS),[32] in reference to Léger and Boucher's initial work.[10] This point will be discussed in section 4. The aim of Billat et al.'s[32] protocol was to determine the minimal velocity which elicits $\dot{V}O_{2max}$. Exercise consisted of an initial speed set at 12 km/h (0% slope) which was increased by 2 km/h every 3 minutes up to 80% of the runner's best performance over 3000m, and by 1 km/h thereafter. The $v\dot{V}O_{2max}$ was the lowest running speed which elicited a $\dot{V}O_2$ equal to $\dot{V}O_{2max}$, or a $\dot{V}O_2$ peak when a plateau was not observed. The criteria used for $\dot{V}O_{2max}$ included: a plateau in $\dot{V}O_2$ (increased <2.1 ml/kg/min) despite an increase in running speed of 1 km/h,[17] a respiratory exchange ratio >1.1, lactataemia >8 mmol/L and heart rate >90% of the predicted maximum heart rate.[18]

The different protocols discussed above are summarised in table I and the influence of the protocols summarised in table II. However, the definition of Billat et al.[32] seems to be closest to the original Hill and Lupton definition.

In summary, we can consider the advantage of some methodologies according to the purpose of the individual investigators. From a practical point of view, Léger and Boucher's[10] protocol can be used on the track and the last velocity sustained of at least 2 minutes is considered as the velocity associated with $\dot{V}O_{2max}$. In order to ensure that a runner reaches $\dot{V}O_{2max}$ it would be useful to measure the last values of heart rate recorded in the last 2 stages. If these are separated by >5 beats/min, we advise checking whether the runner is able to run faster at a higher heart rate.

Table I. Methods of determination of the velocity associated with $v\dot{V}O_{2max}$

Reference	Protocol and environment	Definition and methodology
Léger & Boucher[10]	On track with continuous stages of 2 min and 1 km/h of velocity increase	MAS: maximal velocity sustained for 2 min (completion of the stage)
Daniels et al.[19]	Treadmill with slope for $\dot{V}O_{2max}$. $v\dot{V}O_{2max}$ is extrapolated from submaximal velocities up to the value of $\dot{V}O_{2max}$ previously determined	$v\dot{V}O_{2max}$
di Prampero[22]	On treadmill without slope; calculated from $\dot{V}O_{2max}$/net oxygen cost of running (slope of the velocity-$\dot{V}O_2$ relationship)	V_{amax}: ratio between energy yielded with $\dot{V}O_{2max}$ and oxygen cost of running
Noakes[28]	On treadmill without slope. Peak running velocity reached at exhaustion and maintained for 1 min	Peak running velocity is not associated with a maximal value of $\dot{V}O_2$
Morgan et al.[27]	Modified from Daniels et al.'s[19] protocol. Short test: 7 min at the 5000m pace and increase of the slope every 2 min (+2%) to find $\dot{V}O_{2max}$	$v\dot{V}O_{2max}$
Lacour et al.[25]	On treadmill without slope; calculated from: $\dot{V}O_{2max}$ – $\dot{V}O_{2max}$ rest/net oxygen cost of running	V_{amax}: ratio between energy yielded with net $\dot{V}O_{2max}$ for running and net oxygen cost of running; $\dot{V}O_2$ at rest is standard (5 ml/kg/min)
Billat et al.[32]	On treadmill without slope. Maximal aerobic speed is directly measured from the relationship between $\dot{V}O_2$ and velocity	MAS: i.e. minimal velocity associated with $\dot{V}O_{2max}$

Abbreviations: MAS = maximal aerobic speed; V_{amax} = maximal aerobic speed that can be maintained under aerobic conditions; $\dot{V}O_{2max}$ = maximal oxygen consumption; $v\dot{V}O_{2max}$ = velocity at $\dot{V}O_{2max}$.

Table II. Influence of protocols and methods on the velocity associated with $\dot{V}O_{2max}$.

Reference	Parameters	Methods and protocols	$v\dot{V}O_{2max}$
Léger & Boucher[10]	Time (min) Speed (km/h)	From 8 km/h increase of speed of 2 km/h every 2 min The 2 last stages were for this runner: 20 km/h (2 min) and 22 km/h (for just 1 min)	MAS = 20 km/h
Daniels et al.[19]	Time (min) Pace (m/min) $\dot{V}O_2$ (ml/kg/min)	4 × 6 min at: 230 m/min = 13.8 km/h 248 = 14.9 km/h 268 = 16.1 km/h 293 = 17.6 km/h to measure RE. 1st min: pace 5000m – 30 m/min with 0% grade = 18.82 km/h 2nd min: pace 5000m with 0% grade = 19 km/h 3rd min: pace 5000m = 19 km/h + 1% grade then increase of 1% grade every minute to the last stage 7th min: pace 5000m 19 km/h + 5% grade	$\dot{V}O_{2max}$ = 71 ml/kg/min at pace 5000m with 2% grade $v\dot{V}O_{2max}$ = 20 km/h
di Prampero[22]	Time (min) Speed (km/h) $\dot{V}O_2$ (ml/kg/min)	4 × 6 min at: 85% $v_{Marathon}$ = 13.6 km/h 100% $v_{Marathon}$ = 16 km/h 120% $v_{Marathon}$ = 19.2 km/h 130% $v_{Marathon}$ = 20.2 km/h $\dot{V}O_{2max}$ is obtained at the last velocity	$V_{amax} = \dot{V}O_{2max}/C$ = 1.166/0.210 = 5.555 m/sec = 19.98 km/h $\dot{V}O_{2max}$ = 70 ml/kg/min = 1.666 ml/kg/sec
Noakes[28]	Time (min) Speed (km/h) $\dot{V}O_2$ (ml/kg/min)	5 min – 10 km/h and then an increase of 1 km/h every minute 2 last stages: 16th min: 21 km/h (71 ml/kg/min) 16.5th min: 21 km/h (71 ml/kg/min)	V_{peak} = 21 km/h sustained for 1 min $\dot{V}O_{2max}$ = 71 ml/kg/min at 20 km/h
Morgan et al.[27]	Time (min) Pace (m/min) $\dot{V}O_2$ (ml/kg/min)	1st min: pace 5000m (3:09 sec/km + 37 sec/km with 0% grade = 3:46 sec/km 2nd min: pace 5000m – 18.5 sec/km with 0% grade = 17.3 km/h 3rd min: pace 5000m with 0% grade = 19 km/h 4th min: pace 5000m – 19 km/h + 2% grade and then a 2% increase in slope every minute	$\dot{V}O_{2max}$ = 71 ml/kg/min at pace 5000m with 2% grade $v\dot{V}O_{2max}$ = 20 km/h
Lacour et al.[25]	Time (min) Pace (ml/min) $\dot{V}O_2$ (ml/kg/min)	4 min – 10.3 km/h (36 ml/kg/min) 1 min rest and then an increase of 1.5 km/h every 5 min (4 min run and 1 min of rest) The 2 last stages were for this runner: 34 min, 9.5 km/h (68.4 ml/kg/min) 39 min, 21.1 km/h (70 ml/kg/min)	$V_{amax} = \dot{V}O_{2max} - \dot{V}O_2$ rest/C = 1.166 (ml/kg/sec) 0.083 (ml/kg/sec)/0.210 (ml/m/kg) = 5.157 (m/sec) = 18.6 km/h
Billat et al.[32]	Time (min) Speed (km/h) $\dot{V}O_2$ (ml/kg/min)	3 min - 12 km/h (42 ml/kg/min) 6 min - 14 km/h (49 ml/kg/min) 9 min - 16 km/h (56 ml/kg/min) 12 min - 18 km/h (63 ml/kg/min) 14 min - 19 km/h (66.5 ml/kg/min) 16 min - 20 km/h (70 ml/kg/min) 18 min - 21 km/h (71 ml/kg/min)	MAS = 20 km/h $\dot{V}O_{2max}$ = 71 m/kg/min

Abbreviations: C = oxygen cost of running at a given velocity; MAS = maximal aerobic speed; RE = running economy; V_{amax} = maximal aerobic running velocity; $V_{Marathon}$ = velocity over marathon distance; V_{peak} = peak velocity; $\dot{V}O_2$ = oxygen consumption; $\dot{V}O_{2max}$ = maximal oxygen consumption; $v\dot{V}O_{2max}$ = velocity associated with $\dot{V}O_{2max}$.

When considering accuracy, calculations of velocity (di Prampero et al.,[22]) associated with $\dot{V}O_{2max}$ yield a precise measurement of the velocity at <0.5 km/h. However, this postulated a strict relationship between $\dot{V}O_{2max}$ and velocity. Moreover, Morgan et al.[27] used a slope to obtain $\dot{V}O_{2max}$ which could overestimate $\dot{V}O_{2max}$ with respect to flat track and then could change the experimental measurement of the velocity associated with $\dot{V}O_{2max}$.

More directly, we advise using a direct approach to the measurement of velocity associated with $\dot{V}O_{2max}$, being sure that this is the minimal velocity which elicits $\dot{V}O_{2max}$. However, this method presupposes that $\dot{V}O_2$ levels off at its maximal value, and that therefore one maximal $\dot{V}O_2$ exists for each exercise, considered as the $\dot{V}O_{2max}$. Moreover, increments must be small enough and the total test duration short enough to allow the accurate determination of $v\dot{V}O_{2max}$ without early exhaustion and surrender by the athlete. This method can determine $v\dot{V}O_{2max}$ to the nearest 0.5 km/h. This accuracy level seems to be in accordance with those of the overall experimental measurements.

2. Influence of the Different Protocols on $v\dot{V}O_{2max}$

Although definitions may not vary greatly between authors, the protocols of determining $\dot{V}O_{2max}$ and the speeds chosen to calculate the oxygen cost of running (under, or as is more likely, above the anaerobic threshold, in order to be close to $v\dot{V}O_{2max}$) can influence the value of $v\dot{V}O_{2max}$. Moreover, in $v\dot{V}O_{2max}$ formulae, some authors removed the $\dot{V}O_2$ at rest from $\dot{V}O_{2max}$ [22] and some did not[25] (table I). The velocities of the stages and increases in velocity used by different authors are factors responsible for the different values of $v\dot{V}O_{2max}$ found in the same runner. Table II gives an example of the influence of protocols and methods on $v\dot{V}O_{2max}$ for a runner having a $\dot{V}O_{2max}$ of 70 ml/kg/min, an oxygen cost of running of 210 ml/kg/km and a $\dot{V}O_2$ at rest of 3.5 ml/kg/min (1 MET). We can see that $v\dot{V}O_{2max}$ determined according to these different methods ranges from 18.6 km/h[25,26] to 21 km/h.[28]

In a large group of well-trained runners (n = 32), heterogeneous in terms of gender, age and specialisation, Lacour et al.[26] compared the velocity corresponding to $\dot{V}O_{2max}$, as calculated from treadmill measurement (V_{amax}) and the velocity obtained with Léger and Boucher's Université de Montréal Track Test.[10] These authors found that the velocity corresponding to the last stage of the test was slightly higher than V_{amax} (6.08 m/sec standard deviation = 0.41, *vs* 6.01 m/sec, standard deviation = 0.44 ($p < 0.03$) but that these 2 velocities were strongly correlated ($r = 0.92$, $p < 0.001$) and were also correlated with the best performance sustained over 1500m during the season. They concluded that the Track Test provides a value of V_{amax} as accurately as a treadmill measurement and that either could be used to measure the running velocity corresponding to $\dot{V}O_{2max}$.

Hill and Rowell[34] compared the different velocities obtained from 22 women track athletes in order to evaluate the effects of 5 definitions used to determine $v\dot{V}O_{2max}$. However, they used the same protocols, without appearing to consider that definitions and protocol are linked. Hill and Rowell calculated 5 $v\dot{V}O_{2max}$ according to several methodologies[22,25,27,30,32] Even if these 5 velocities were significantly different ($p < 0.001$), they were nonetheless correlated. Correlations among the various values ranged from 0.68 (Lacour[25] *vs* Noakes[28] $v\dot{V}O_{2max}$) to 0.90 (Noakes[28] *vs* Billat[32] $v\dot{V}O_{2max}$) and 1.00 (Lacour[25] *vs* di Prampero[22] $v\dot{V}O_{2max}$). The perfect correlation of 1 between Lacour[25] and di Prampero[22] is expected since they represent computed $v\dot{V}O_{2max}$ with similar formula from the same predictors ($\dot{V}O_{2max}$ and C) even if Lacour[25] removed $\dot{V}O_2$ at rest from $\dot{V}O_{2max}$, and di Prampero[22] accounted for the real $\dot{V}O_2$ at rest (and not standard, as Lacour et al.)[25] to calculate the net oxygen cost of running. The anaerobic contribution for sustaining these speeds depended on the methodology used to determine them, di Prampero[22] and Lacour[25] $v\dot{V}O_{2max}$ being more aerobic than the 3 others. Hill and Rowell[34] concluded that the methodology used must be chosen by considering both these differences and that the goal is to determine $v\dot{V}O_{2max}$.

Middle-distance performance could probably be best predicted by the Noakes peak treadmill running velocity rather than di Prampero's V_{amax} since the runners compete at a higher percentage of $\dot{V}O_{2max}$ and incur a greater energy cost for unit distance run.[35]

Inversely, Billat et al.,[36] compared $v\dot{V}O_{2max}$ using the same definition but different protocols for determining $v\dot{V}O_{2max}$ performed on a treadmill.

They did not find a significant difference in $v\dot{V}O_{2max}$ in 15 well trained long-distance runners. The 1 km/h × 2 minute protocol was not significantly different from the 0.5 km/h × 1 minute protocol (20.7 ± 1 km/h *vs* 20.8 ± 0.9 km/h, respectively). What is important is the acceleration which was similar for both. When they compared the same protocol (1 km/h × 2 minutes) for 7 runners who performed alternately on a treadmill and an indoor track, they found a significant difference ($p = 0.003$: 21.1 ± 0.7 km/h *vs* 20.1 ± 0.7 km/h, respectively for treadmill and track test). $v\dot{V}O_{2max}$ was 1 ± 0.7 km/h faster than the values obtained from the field test according to the aerodynamic oxygen cost.[11]

The velocities used as reference to judge the aerobic ability and the running efficiency, are more or less aerobic, according to definitions and protocols (linked).

In summary, we can recall that from the less to the most anaerobic velocities as shown in table II are those of: Lacour et al.[26] (18.6 km/h), di Prampero (19.8 km/h), Morgan et al.,[27] Daniels et al.,[19] Billat et al. (20 km/h)[32] and Noakes et al. (21 km/h).[30] On the track, this runner would have his MAS at 20 km/h using Léger and Boucher's protocol.[10] The most important thing is to note these differences which may be considered slight in relation to the percentage of error associated with experimental $\dot{V}O_2$ measurement, but too important to accurately predict the performance in homogeneous high level long- and middle-distance runners.

3. Time to Exhaustion (t_{lim}) at $v\dot{V}O_{2max}$ in the Model of the Time-Velocity Relationship

t_{lim} at $v\dot{V}O_{2max}$ has not been systematically examined nor taken into account in the model of the time-velocity relationship (table III). The reason is perhaps the difficulty in accurately determining the minimal velocity which elicits $\dot{V}O_{2max}$. Out of 14 studies[37-50], only one (Gleser and Vogel[47]) has based the time-velocity relationship on the t_{lim} at $v\dot{V}O_{2max}$: in fact, they stipulated that 100% $\dot{V}O_{2max}$ could be sustained for 10 minutes, 90% $\dot{V}O_{2max}$ for 25 minutes, and 85% $\dot{V}O_{2max}$ for 1 hour in the high level endurance participant.

Only Gleser and Vogel[47] have based their time-velocity modelling on time limit at $v\dot{V}O_{2max}$ (see table III for comparison with the other models). Authors who actually measured t_{lim} at $v\dot{V}O_{2max}$ did not elaborate a time-velocity modelling. Their en-

Table III. Time to exhaustion (t_{lim}) at $v\dot{V}O_{2max}$ in the different models of the velocity-time relationship

Reference	Experimental measurement of t_{lim} in laboratory	Theoretical approach of t_{lim} from relationship between world record time over distance	Physiological background	Included: MAP, delay of adjustment of $\dot{V}O_2$, t_{lim} at $v\dot{V}O_{2max}$
Kennelly[37]	–	+	–	–
Hill[38]	–	+	+	–
Sargent[39]	–	+	+	–
Grosse-Lordemann & Müller[40]	+	–	–	–
Tornvall[41]	+	–	–	–
Scherrer et al.[42]	+	–	+	–
Wilkie[43,44]	–	+	+	+ (no t_{lim} at $v\dot{V}O_{2max}$)
Ettema[45]	–	+	–	–
Margaria[46]	–	+	+	–
Gleser & Vogel[47]	+	–	+	– (t_{lim} at $v\dot{V}O_{2max}$ = 10 min)
Ward-Smith[48]	–	+	+	+ (no t_{lim} at $v\dot{V}O_{2max}$)
di Prampero[49]	–	+	+	+ (no t_{lim} at $v\dot{V}O_{2max}$)
Péronnet & Thibault[50]	–	+	+	+ (t_{lim} at $v\dot{V}O_{2max}$ = 7 min)

Abbreviations and symbols: MAP = maximal aerobic power; $\dot{V}O_{2max}$ = maximal oxygen consumption; $v\dot{V}O_{2max}$ = velocity associated with $\dot{V}O_{2max}$; + indicates included in the model; – indicates not included in the model.

durance model was exponential, closer to the physiological reality than the hyperbolic[42,45,51] models for loads between 50 and 110% $\dot{V}O_{2max}$.[47] Endurance time (t), the maximal length of time an individual can work at a given work intensity, was found to be related to work intensity by the equation:

$$\log(t) = A \cdot L_r + B \qquad \text{(Eq. 11)}$$

where L_r is the work load (in kg/m) divided by $\dot{V}O_{2max}$ (L/min). The parameters A and B are sufficient to describe an individual's 'endurance capacity', i.e. the ability to sustain prolonged work at any relative work load.

The other physiological model which accounted for the t_{lim} at $\dot{V}O_2$ for the analysis of the 'running curve' (i.e. the relationship between running time and power output from 60m to marathon), is that of Péronnet and Thibault.[50] This model considered the slow adjustment of oxygen utilisation and of glycolysis at the onset of exercise and the progressive reduction of the average aerobic power sustained with an increase in running time for races lasting longer than 7 minutes, which is the estimated t_{lim} at $\dot{V}O_{2max}$.

$$P\ \text{plateau} = MAP + MAP \cdot S_1 \cdot \ln(tr)$$
$$= MAP \cdot (1 + S_1 \cdot \ln(t_r)) \qquad \text{(Eq. 12)}$$

where S_1 is a negative constant and tr a value of t_{lim} expressed in multiple of the t_{lim} at the maximal aerobic power (t_{MAP}). For t_{lim} equal to 7 minutes (420 seconds) t_r equals 1, ln (t_r) equals 0 and P plateau equals MAP. The product $MAP \cdot S_1$ is an endurance index (E). This is an objective measure of endurance, i.e. the so-called 'ability to sustain a high percentage of $\dot{V}O_{2max}$ for a long period of time'. Endurance is then expressed more precisely as 'the reduction of percentage $\dot{V}O_2$ which can be sustained over the racing time, when the running time is multiplied by e (2.71828), for runs greater than 7 minutes'.[50] However, experimental approaches of t_{lim} at $v\dot{V}O_{2max}$ show that this value has a great intervariability range which makes it difficult to use this endurance index to compare endurance ability among individuals.

4. Experimental Measurements of t_{lim} at $v\dot{V}O_{2max}$

4.1 The Range in Values of t_{lim} at $v\dot{V}O_{2max}$

Astrand and Rodahl[52] reported that in trained individuals, $\dot{V}O_{2max}$ can be sustained for a maximum of 20 minutes. However, when we look at studies that have measured this, we note that t_{lim} at $v\dot{V}O_{2max}$ is less than 12 minutes, the average value being close to 6 minutes.

Table IV shows the different studies which have measured or calculated the t_{lim} between 90 to 120% $v\dot{V}O_{2max}$ based on individuals best times over distances. The range of average values of t_{lim} at 100% $v\dot{V}O_{2max}$ reported in these studies is from 3 minutes[53] to 6.5 minutes.[32] Values obtained on the field are higher (8.7 minutes in Lacour et al.[25]). In fact, $v\dot{V}O_{2max}$ was close to the velocity over 3000m in male elite middle-distance runners.[25] It is logical that the time limit at $v\dot{V}O_{2max}$ be similar to the record time over 3000m. In sub-elite male long-distance runners, Billat et al.[67] measured a distance limit at $v\dot{V}O_{2max}$ of 2008.7 ± 496m. However, we have to distinguish the total run at $v\dot{V}O_{2max}$ from the time run at $\dot{V}O_{2max}$ only.

4.2 t_{lim} at $v\dot{V}O_{2max}$ and the Real Time Spent at $\dot{V}O_{2max}$

Volkov et al.[4] determined the length of t_{lim} sustauned at $\dot{V}O_{2max}$ that can be maintained, and calculated max E_{ox} from a continuous measurement of the level of $\dot{V}O_2$ during running at the 'critical speed' ($v\dot{V}O_{2max}$). The accurate sustained time at $\dot{V}O_{2max}$ was determined as the moment when the decrease in $\dot{V}O_2$ exceeded the limits of slight variation registered during 'the relative steady-state' (value not specified). Even if the participant is able to sustain the critical speed further, Volkov et al. only accounted for the time spent at $\dot{V}O_{2max}$. The max E_{ox} is calculated according to the formula:

$$\max E_{ox} = \dot{V}O_{2max} \cdot t_{lim} \qquad \text{(Eq. 13)}$$

and max E_{ox} is corrected by the delay adjustment of $\dot{V}O_2$ at the steady-state maximal value of $\dot{V}O_2$

Table IV. Time to exhaustion (t_{lim}) at the velocity associated with $\dot{V}O_{2max}$: some experimental approaches (chronological order)

Study	Year	Study participants	$\dot{V}O_{2max}$ (ml/kg/min)	Ergometer protocol and environment	$\%\dot{V}O_{2max}$ and t_{lim} (min)
Horvath & Michael[55]	1970	14 female college students	29.5 ± 3.7	Cycle ergometer	100%; 3 ± 2
Costill[54]	1970	3 elite long distance runners	75.6 ± 3.4	Treadmill 10km run to exhaustion	95 ± 3%; 30 ± 1
Costill et al.[55]	1973	16 male runners	66.6 ± 8.7	Treadmill 16km run to exhaustion	86.1 ± 3.9%; 56.3 ± 6.3
Higgs[56]	1973	20 active college women	41.3	Treadmill	100%; 4.63
Volkov et al.[5]	1975	4 recreational runners	60.8 ± 3.2	Treadmill	100%; 5.4 ± 3.25
McLellan & Skinner[57]	1985	16 international women rowers	50.7 ± 7.2	Cycle ergometer	95 ± 3.4%; 11
Léger et al.[58]	1986	311 runners: 251 men and 60 women	61.3 ± 6.1	Running distances ranging from 0.2-42.2km	100% (calculated); 7
Reybrouck et al.[59]	1986	11 healthy men	57.5 ± 7.1	Treadmill	91.3%; 22.9 ± 20.9
Lavoie & Mercer[60]	1987	5 international women rowers	61.4 ± 4.5	Cycle ergometer	100%; 3.83 ± 1.11
Camus et al.[61]	1988	7 male students	57.6 ± 9.0	Cycle ergometer	100%; 5.50
Lacour et al.[25]	1990	27 male middle distance runners	71.3 ± 4.5	Track, calculated from personal records (800-5000m)	100%; 8.7 min = v3000m
Ramsbottom et al.[62]	1992	16 recreational runners: 8 men 8 women	 60 ± 4.3 52.9 ± 3.4	Track (5000m)	Men 90%; 18.7 ± 1.27 Women 82%; 21.8 ± 1.98
Pepper et al.[63]	1992	10 adult men	15.5 ± 1.9 km/h	Treadmill	98%; 7.2 ± 2.8 111%; 3.4 ± 1.4
McLellan & Cheung et al.[64]	1992	14 adult men	54.4 ± 5	Cycle ergometer	90%; 15 120%; 2
Padilla et al.[65]	1992	38 middle distance runners: 24 men 14 women	71.9 ± 4.2 65.3 ± 5.0	Track, calculated from personal records (800-5000m)	100%; men 8.4 ± 2.1 Women 7 ± 2.2
Billat et al.[32]	1994	14 male middle distance runners	69.4 ± 3.7 $v\dot{V}O_{2max}$ = 21.3 ± 0.9 km/h	Treadmill	100%; 6.7 ± 1.88
Billat et al.[66]	1995	16 male middle distance runners	75.5 ± 5.3 $v\dot{V}O_{2max}$ = 22.3 ± 1.1 km/h	Treadmill	90%; 17.6 ± 4.5 100%; 5.5 ± 1.5 100%; 2.9 ± 0.7

Abbreviations: $\dot{V}O_{2max}$ = maximal oxygen consumption; $v\dot{V}O_{2max}$ = velocity associated with $\dot{V}O_{2max}$; v3000m = velocity over 3000m.

(28 seconds) and the consequent oxygen deficit (O_2d) by the formula:

$$E_{ox}^{cor} = \max E_{ox} - O_2d \qquad \text{(Eq. 14)}$$

where E_{ox}^{cor} is the corrected aerobic capacity. t_{lim} at $\dot{V}O_{2max}$ measured in 4 individuals ($\dot{V}O_{2max}$ = 60.8 ± 3.2 ml/kg/min) was equal to 5:23 ± 3:15 minutes and seconds, respectively, and E_{ox}^{cor} was equal to 274.7 ± 84.3 ml/kg (for an oxygen deficit equal to 36 ± 6.2 ml/kg which is low according to Medbo et al.[3]). However, in the experiment by Volkov and his coworkers[4] that evaluated max E_{ox}, the running speeds selected exceeded the different participants' speeds by a certain percentage, t_{lim} depending on this relative value of the speed. They concluded that in tests designed to assess the max E_{ox}, the running speed should be selected in such a way that it strictly corresponds to the critical velocity.

Volkov et al.[4] pointed out the main difficulties in measuring the t_{lim} at $\dot{V}O_{2max}$: the determination of $v\dot{V}O_{2max}$ (see above) and the measurement of the exact time run at $\dot{V}O_{2max}$. In some studies that tried to model the velocity-time relationship and/or to evaluate the critical speed according to the initial work of Monod and Scherrer,[51] the t_{lim} at the power or velocity which elicits $\dot{V}O_{2max}$ is measured (table III).

Another difficulty of this measurement (and use) of t_{lim} at $\dot{V}O_{2max}$ is the reproducibility of a measurement where time is an abstract goal for athletes. Distance limit is preferred for this reason.[7]

4.3 The Reproducibility Intraindividual of t_{lim} at $v\dot{V}O_{2max}$

Weltman and Regan[68] pointed out that the constant load maximal endurance performance was not as well established as for the tests which allowed a drop-off in work (a decrease in running or pedalling speed). McLellan et al.[69] found a substantial variability in cycling t_{lim} at 80% $\dot{V}O_{2max}$ over 5 trials performed by the same participant ($n = 15$), ranging from 2.8 to 31.4% with an average value of 17.3%.

Graham and McLellan[70] calculated a 10% variability for trained cyclists during exercise to exhaustion at 120% $\dot{V}O_{2max}$. The study by Billat et al.[32] focused on the reproducibility of running t_{lim} at MAS in 8 sub-elite long-distance runners who repeated a time limit at MAS protocol at 1-week intervals. No significant differences were obtained from the time limit at MAS carried out with the same warm-up protocol at 1-week intervals: 6:44 ± 1:41 *vs* 6:02 ± 1:53 minutes and seconds, respectively ($r = 0.86$, $p = 0.005$). However, the standard error of the estimate in the percentage of trial 1 was equal to 14%. McLellan et al.[69] concluded that the longer the performance test, the greater the variability.

4.4 Interindividual Variability of the t_{lim} at $v\dot{V}O_{2max}$

Although the t_{lim} at $v\dot{V}O_{2max}$ is reproducible in one individual provided the relative importance of the standard error of the estimate, there is however, great variability between individuals who have the same value of $v\dot{V}O_{2max}$. Indeed, for an average value of about 6 minutes, the coefficient of variation is about 25% (table IV). It would seem that the lactate threshold which correlates with the t_{lim} at $v\dot{V}O_{2max}$ also explains the difference between each individual and that the role of anaerobic contribution should be taken into account. In fact, Billat et al.[71] reported that the velocity of 12 sub-elite long-distance runners at the lactate threshold (expressed in percentage $v\dot{V}O_{2max}$) correlated with the t_{lim} at $v\dot{V}O_{2max}$ ($r = 0.58$, $n = 12$, $p < 0.05$).

A further study by Billat et al.[33] reported a significant correlation between the velocity of the blood lactate at maximal steady-state (in percentage $v\dot{V}O_{2max}$) and t_{lim} at $v\dot{V}O_{2max}$: ($r = 0.604$, $n = 10$, $p < 0.05$). Finally, a study conducted among 38 sub-elite long- and middle-distance runners revealed a significant correlation between velocity at the lactate threshold (LT) expressed in % $v\dot{V}O_{2max}$ and the t_{lim} at $v\dot{V}O_{2max}$ ($r = 0.38$, $n = 38$, $p < 0.05$).[72] Higgs[56] pointed out that 'the anaerobic capacity and motivation should have been the most important variables influencing performance time'. Higgs did not find any correlation between $\dot{V}O_{2max}$ and its time to exhaustion ($r = 0.066$ in 20 fairly active women). This brings up the question of the relationship between the t_{lim} at $v\dot{V}O_{2max}$ and $\dot{V}O_{2max}$.

4.5 The Inverse Relationship Between t_{lim} at $v\dot{V}O_{2max}$ and $\dot{V}O_{2max}$

In 38 elite male long-distance runners ($\dot{V}O_{2max}$ = 71.4 ± 5.5 ml/kg/min and $v\dot{V}O_{2max}$ = 21.8 ± 1.2 km/h), Billat et al.[72] showed that t_{lim} at $v\dot{V}O_{2max}$ was correlated negatively with $v\dot{V}O_{2max}$ ($r = -0.362$, $p < 0.05$) and $\dot{V}O_{2max}$ ($r = -0.347$, $p < 0.05$) (fig. 2). The runners who obtained the highest MAP outputs were those who shortened their t_{lim}. In fact, the 38 participants ran at the same relative speed calibrated in percentage of $v\dot{V}O_{2max}$, but if expressed as an absolute value, it did not represent the same energy uptake. These data demonstrated that running t_{lim} at $v\dot{V}O_{2max}$ in a homogeneous group of elite male long-distance runners was inversely related to $v\dot{V}O_{2max}$, and illustrated experimentally Monod and Scherrer's model[51] concerning the time limit-velocity relationship. This experimental

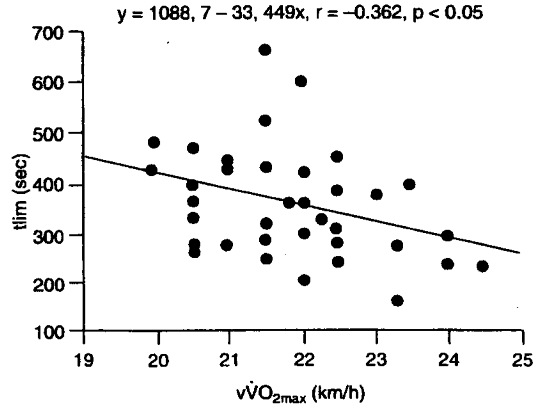

Fig. 2. The inverse relationship between the velocity which mathematically corresponds to maximal oxygen uptake ($v\dot{V}O_{2max}$) and time to exhaustion (t_{lim}) at $v\dot{V}O_{2max}$ (n = 38).

finding was in accordance with Monod and Scherrer's model:

$$t_{lim} = \frac{a}{P - b} \quad \text{(Eq. 15)}$$

In this study, P is the power output at $\dot{V}O_{2max}$ i.e. $v\dot{V}O_{2max}$ and t_{lim} is the time to exhaustion at $v\dot{V}O_{2max}$ (t_{lim}). Moreover, 'a' is the anaerobic running capacity and 'b' is estimated by the fraction of $v\dot{V}O_{2max}$ at the lactate threshold ($F \cdot v\dot{V}O_{2max}$) since the critical speed can be compared to the LT value.[5] Given that $b = F \cdot v\dot{V}O_{2max}$ it can be inferred that:

$$t_{lim} = \frac{a}{v\dot{V}O_{2max} - Fv\dot{V}O_{2max}} \quad \text{(Eq. 16)}$$

where $Fv\dot{V}O_{2max}$ is the fraction of $v\dot{V}O_{2max}$ at the lactate threshold.

In this model, the highest value of t_{lim} at $v\dot{V}O_2$ is obtained with a high value of 'a' and a low value of 'P – b' which here, is the difference between $v\dot{V}O_{2max}$ and the critical speed. In our experimental approach, according to Monod and Scherrer's model, participants who have the highest time limit values are those who have the lowest $v\dot{V}O_{2max}$ – velocity associated with LT (vLT) difference (or the highest vLT value expressed as a fraction of $v\dot{V}O_{2max}$) and therefore the lowest $v\dot{V}O_{2max}$ (km/h). This model shows that at MAP, t_{lim} is inversely proportional to the difference between MAP (P) and the power output at the lactate threshold (b). The greater the difference, the shorter the t_{lim} at MAP. It also depends, however, on the absolute value of MAP; the same difference between MAP and lactate threshold (expressed in % MAP) represents not only an increase in adenosine triphosphate turnover for highest value of absolute power output, but an increase in oxygen deficit. This is perhaps one of the discriminant factors that would explain the difference in t_{lim} at $v\dot{V}O_{2max}$ among the homogeneous spread of long-distance runners. Further studies will be necessary to elucidate the relationship between the t_{lim} at $v\dot{V}O_{2max}$ and anaerobic capacity.

The inverse relationship between $\dot{V}O_{2max}$ and t_{lim} at $\dot{V}O_{2max}$ was confirmed by another study which compared the t_{lim} at the power output (or velocity) at $\dot{V}O_{2max}$ for different values of $\dot{V}O_{2max}$, depending on the type of exercise and not only on the aerobic capacity.[73] The t_{lim} at $v\dot{V}O_{2max}$ was measured in 41 elite (national level) sportsmen: 9 cyclists, 9 kayakers, 9 swimmers and 14 runners using specific ergometers. In this study, t_{lim} at $v\dot{V}O_{2max}$ was also inversely related to $\dot{V}O_{2max}$ for the entire group of elite sportsmen ($r = -0.320$, $p < 0.05$, $n = 41$). The inverse relationship between $\dot{V}O_{2max}$ and t_{lim} at $v\dot{V}O_{2max}$ needs to be explained: it would seem that t_{lim} depends on $\dot{V}O_{2max}$ regardless of the type of exercise undertaken.

Except for these studies,[5,72,74] no other study has examined or discussed such a relationship between $\dot{V}O_{2max}$ and its t_{lim} so it is impossible to compare results. The anaerobic counterpart might be the cause of an inverse relationship as discussed above. Faina et al.[74] have shown in 23 elite athletes (8 cyclists, 7 kayakers and 8 swimmers) the positive relationship between the accumulated oxygen deficit calculated according to Medbo et al.[3] and the t_{lim} at $\dot{V}O_{2max}$ ($r = 0.57$). The mean percentage value of energy expenditure covered by anaerobic metabolism was $13.8 \pm 7.1\%$ (ranging from 6.2 to 23.5%) with significant differences between swimmers and kayakers (18.1% *vs* 8.9%).

The oxygen deficit concerned the total t_{lim} at the power output at $\dot{V}O_{2max}$. Volkov et al.[4] have already pointed out the difference between total t_{lim} at the power output which elicits $\dot{V}O_{2max}$ and the real time spent at $\dot{V}O_{2max}$. The question was to examine the possibility of t_{lim} at $\dot{V}O_{2max}$ if the individual ran at only 90% of $v\dot{V}O_{2max}$ could reach $\dot{V}O_{2max}$ because of the $\dot{V}O_2$ drift.

4.6 t_{lim} at $\dot{V}O_{2max}$ During Running Above the Lactate Threshold

In 1972, Whipp and Wasserman[75] described a slow component of $\dot{V}O_2$ response during cycling exercises above the lactate threshold. They observed that even at the higher work rates, a steady-state of $\dot{V}O_2$ was not attained during the sixth minute of exercise. It was stressed that a certain range of supra-lactate threshold work rates does exist in which a delayed steady-state may be reached. However, a steady-state is unattainable at higher work rates because $\dot{V}O_2$ continues to increase until the maximum $\dot{V}O_2$ has been reached.

Whipp[76] believes that if the slow component rises more rapidly toward $\dot{V}O_{2max}$, the time period in which the work rate is tolerated will be shorter. Therefore, in a recent study (Billat et al., unpublished data) we focused upon $\dot{V}O_2$ drift in 2 all-out runs at 90 and 100% of $v\dot{V}O_{2max}$ to see wether it was a possible cause of delay in the apparition of fatigue. We examined: (i) whether it was possible to reach $\dot{V}O_{2max}$ during an all-out run at 90% $v\dot{V}O_{2max}$, the $v\dot{V}O_{2max}$ having already been determined during an incremental test, and (ii) whether the $\dot{V}O_2$ drift measured in all-out runs at 90 and 100% $v\dot{V}O_{2max}$ was related to t_{lim} indeed, at 90 and 100% of $v\dot{V}O_{2max}$. 14 elite male long-distance runners underwent an incremental test on a treadmill, set with a slope of 0% gradient to determine their $\dot{V}O_{2max}$ (71.1 ± 2.4 ml/kg/min) and the $v\dot{V}O_{2max}$ (22.3 ± 1.0 km/h). The lactate threshold (defined as a starting point of accelerated lactate accumulation around 4 mmol/L) was at 72 ± 3.9% $\dot{V}O_{2max}$ (with a range between 66.2% to 80.8% $\dot{V}O_{2max}$). Exhaustive treadmill runs were then performed at 90% and 100% $v\dot{V}O_{2max}$ with 1 week of light training in between. t_{lim} 90 and t_{lim} 100 were 17:40 ± 4:30 and 5:25 ± 1:31 minutes and seconds, respectively.

$\dot{V}O_{2max}$ during the constant velocity test at $v\dot{V}O_{2max}$ (70.4 ± 3.5 ml/kg/min) did not differ from the incremental value (71.1 ± 2.4 ml/kg/min). The $\dot{V}O_2$ drifts observed between the second and fifth minute of the all-out tests at 90% and 100% $v\dot{V}O_{2max}$ were not significantly different (226.5 ± 144.4 ml/min *vs* 216.7 ± 188.5 ml/min, p = 0.68). However, no further $\dot{V}O_2$ drift was calculated between the sixth and ninth minutes of the all-out run at 90% of $v\dot{V}O_{2max}$. The runner, therefore, did not reach $\dot{V}O_{2max}$ (the final $\dot{V}O_2$ in the final minute of the all out run at 90% of $v\dot{V}O_{2max}$ was equal to 87% of $\dot{V}O_{2max}$). Furthermore, there was no relationship either between the performances (i.e. t_{lim} 90 and t_{lim} 100) and the $\dot{V}O_2$ drift that occurred between the second and fifth minute. Moreover, there was no relationship between the $\dot{V}O_2$ drift between the second and fifth minute, the blood lactate accumulation during the all-out run at 90 and 100% $v\dot{V}O_{2max}$, nor with the end pH value at 90 and 100% $v\dot{V}O_{2max}$. Moreover, t_{lim} 90 was not correlated with t_{lim} 100 (r = 0.42, p = 0.1) meaning that the runners who gave a better performance at 90% $v\dot{V}O_{2max}$ were not necessarily those who took longer to reach exhaustion at 100% $v\dot{V}O_{2max}$. However, t_{lim} 90 was significantly correlated with the lactate threshold expressed in percentage $v\dot{V}O_{2max}$ (r = 535, p = 0.04) and $\dot{V}O_2$ drift observed between the second and fifth minute was not correlated with the lactate threshold (Billat et al., unpublished data).

The data showed that the t_{lim} at 90% $v\dot{V}O_{2max}$ in a group of elite male long-distance runners did not lead to $\dot{V}O_{2max}$. Furthermore, there was no correlation between the ability to sustain 100% $v\dot{V}O_{2max}$ and the $\dot{V}O_2$ drift observed between the second and fifth minute. Consequently, with high level middle-distance runners, $\dot{V}O_2$ drift registered at a fixed relative workload appeared to be independent of the relative lactate threshold and endurance at this level of power output. The data also show that, within a homogeneous group of elite male long-distance runners, the t_{lim} at 90%$v\dot{V}O_{2max}$ does not lead to $\dot{V}O_{2max}$ (Billat et al., unpublished data), contrary to previous results. However, 90% $v\dot{V}O_{2max}$ is similar to the higher work rate used by Casaburi et al.,[77] i.e. the velocity at the anaerobic threshold + 75% of the difference between the anaerobic threshold and $v\dot{V}O_{2max}$. The absence of drift at this high intensity may have been due to the high fitness levels of our participants, as well as the 10-minute exercise at 60% $v\dot{V}O_{2max}$ that preceded the test.[77,78] It was perhaps also due to the difference in types of muscular contraction regimen: cycling *vs* level running where there is less isometric contraction. This question addresses the mechanisms for $\dot{V}O_2$ slow components during heavy exercise. Fast-twitch fibres have a high glycolytic capacity and this may increase at higher speeds and/or work rates, resulting in a reduction in muscular efficiency.[79]

Whipp[76] considered that a likely, and major, contributor to the slow component of $\dot{V}O_2$ was the high energy cost of contraction in the type II fibres; these are recruited proportionally more at high work rates. However, Zoladz et al.[80] recently reported that there was no systematic effect on the magnitude or onset of the extra $\dot{V}O_2$ found in relation to the rate of pedalling. This would suggest that there was no relation to the pattern of motor unit recruitment.

Dick and Cavanagh[81] demonstrated in the same manner that, for running, the upward drift in $\dot{V}O_2$ which occurs after 40 minutes on a downhill gradient of 10% (eliciting 44% of $\dot{V}O_{2max}$) was not related to the increase in integrated electromyography. This showed an increase in motor unit recruitment caused within by an ongoing combination of muscle, connective tissue damages, and local fatigue due to the eccentrically acting muscles. Further studies are needed to elucidate possible differences in $\dot{V}O_2$ between running and cycling which imply different muscle contraction regimens.

Another explanation of the great intervariability of t_{lim} might be the limitation of pulmonary function. In fact, hypoxaemia induced by exercise previously shown in endurance trained athletes ($\dot{V}O_{2max}$ >60 ml/kg/min by Dempsey et al.[82] among others[83,84]) was observed after all-out tests at 90% and 100% of $v\dot{V}O_{2max}$. With the all-out runs at 90% and 100% of $v\dot{V}O_{2max}$, there was a significant drop in arterial oxyhaemoglobin saturation and partial arterial oxygen pressure at the end of both tests. However, only t_{lim} 90, was correlated with hypoxaemia (r = −0.757).[66]

5. Gender and Age Effects of t_{lim} at $v\dot{V}O_{2max}$

A recent study[85] investigated the influence of gender on the possible contribution of t_{lim} at v_{amax} in performance speeds. Men and women elite middle-distance runners had similar performances (International Amateur Athletic Federation scores). In this study, 14 women and 15 men (mean age 25.2 ± 3.6 and 25.1 ± 4.2 years; $\dot{V}O_{2max}$ = 63.2 ± 4.2 and 77.7 ± 6.4 ml/kg/min; v_{amax} = 17.3 ± 0.7 and 20.8 ± 1.1 km/h, respectively) performed 3 exercise tests on a treadmill (3% slope) over a 2-week period. The following tests were carried out:

- An incremental test to determine $\dot{V}O_{2max}$, $v\dot{V}O_{2max}$ and the velocity at the onset of blood lactate accumulation.
- An exhaustive constant velocity test to determine t_{lim} at v_{amax}.
- Another exhaustive constant velocity test at 110% $v\dot{V}O_{2max}$ to determine the accumulated oxygen deficit.

There were no significant differences observed in t_{lim} at $v\dot{V}O_{2max}$ between the female and male runners (421 ± 129 *vs* 367 ± 118 seconds respectively). There was also no gender effect on:

- The onset of blood lactate accumulation relative to $v\dot{V}O_{2max}$ (88.4 ± 2.7 *vs* 90.4 ± 3% of $v\dot{V}O_{2max}$).
- Accumulated oxygen deficit (40.1 ± 14.9 *vs* 48.9 ± 21.3 mlO_2/kg).
- Running economy at the same absolute speed i.e. 14 km/h (53.4 ± 2.6 *vs* 52.7 ± 4.1 mlO_2/min/kg).
- Gross oxygen cost of running at the same relative velocity [75% $v\dot{V}O_{2max}$] (0.214 ± 0.001 *vs* 0.214 ± 0.002 mlO_2/kg/m).

However, gender was found to have an effect on the relationship between performance and bioenergetic parameters and performance. For the male participants, velocity over 1500m was predicted by v_{amax}, the onset of blood lactate accumulation, t_{lim} at 110% of $v\dot{V}O_{2max}$, and gross oxygen cost of running ($r^2 = 0.98$). For the female participants, there was no significant correlation observed between bioenergetic parameters and v1500m. The inverse relationship previously found between $v\dot{V}O_{2max}$ and t_{lim} at v_{amax} in 38 male long-distance runners[72] was confirmed for the 29 runners in this study, and for the subset of male runners only; this relationship was not observed among the group of female runners. The difference in performance over 1500m between the 2 genders was explained only by the difference of relative $\dot{V}O_{2max}$. This difference of relative $\dot{V}O_{2max}$ remained when the relative $\dot{V}O_{2max}$ was calculated with lean body mass only.

Gerbeaux et al.[86] demonstrated that t_{lim} at MAS determined on the track by Léger and Boucher's protocol,[10] was not significantly different between boys and girls, was the same as those measured in adults and significantly increased for both sexes between the ages of 10 and 15 years. After 15 years of age, t_{lim} at MAS decreased slightly for the boys and more significantly for the girls. However, the decrease of t_{lim} at MAS was greater for boys than for girls aged between 10 and 20 years. The authors concluded on practical application concerning the child's 'training programs for girls and boys which could only differ in the chosen power output'.

Recently, Berthoin et al.[87] used the MAS to set training intensities for aerobic training and to measure the effects of 2 different training programmes on MAS and on the running t_{lim} at MAS for 121 students aged 14 to 17 years. The MAS was measured using the Université de Montréal Track Test. The students followed a 12-week training programme of 1-weekly training sessions. Students had 3 hours per week of physical education. For the experimental groups, one of these hours was used for the training programme.

Two training programmes were proposed (intense or moderate) which differed in the ratio between continuous exercise (85% of MAS) and intermittent exercise (between 90% and 120% of MAS), a third group constituted the control group. For the moderate training programme, the ratio between continuous and intermittent exercise was greater than for the intensive training programme. Each training programme included 3 types of exercises. First, continuous exercise (20 to 25 minutes) at 85% of the MAS; secondly, long intermittent exercise including 2 series of 3 repetitions and 5 minutes of passive recovery between the series. Finally, short intermittent exercises including 3 series of 10 repetitions of 10 seconds at 120% of the MAS. The passive recovery was 10 seconds between the repetitions and 3 minutes between the series. The students MAS and t_{lim} at MAS were 13.7 ± 1.6 km/h and 380.5 ± 91.8 seconds for the men and 11.3 ± 1.2 km/h and 347.2 ± 91.1 seconds for the women, respectively. Only the participants of the intense training group improved their MAS: +5.7% for the men ($p < 0.001$) and +5.4% for the women ($p < 0.001$). In neither case, t_{lim} at MAS improved significantly with training. The authors concluded that MAS was a pertinent criterion to set training intensities for aerobic training and that a weekly training session over 12 weeks was sufficient to moderately improve the MAS of initially untrained students.

6. Conclusions

Since $v\dot{V}O_{2max}$ contains both $\dot{V}O_{2max}$ and running economy in one term,[22] $v\dot{V}O_{2max}$ should be used to monitor athletes' training. Since $v\dot{V}O_{2max}$ is theoretically the minimal velocity needed to elicit $\dot{V}O_{2max}$, it should describe the ideal training intensity for middle- and long-distance training (1500m to marathon). $v\dot{V}O_{2max}$ was very similar to the velocity that can be sustained by elite long-distance runners over 3000m.[19] Lacour et al.[25,26] confirmed that V_{amax} according to di Prampero[22] corresponded to the velocity sustained over 3000m performed on track events by elite middle-distance runners. We have to further examine the influence of training on the reciprocal variation of $v\dot{V}O_{2max}$ and t_{lim} at $\dot{V}O_{2max}$. It would be useful to examine the effect of overloaded training at $v\dot{V}O_{2max}$ on $v\dot{V}O_{2max}$ and on the delay to exhaustion at $\dot{V}O_{2max}$.

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