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Methods to Determine Aerobic Endurance

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Contents

Abstract

Physiological testing of elite athletes requires the correct identification and assessment of sports-specific underlying factors. It is now recognised that performance in long-distance events is determined by maximal oxygen uptake ($\dot{V}O_{2max}$), energy cost of exercise and the maximal fractional utilisation of $\dot{V}O_{2max}$ in any realised performance or as a corollary a set percentage of $\dot{V}O_{2max}$ that could be endured as long as possible. This later ability is defined as endurance, and more precisely aerobic endurance, since $\dot{V}O_{2max}$ sets the upper limit of aerobic pathway. It should be distinguished from endurance ability or endurance performance, which are synonymous with performance in long-distance events. The present review examines methods available in the literature to assess aerobic endurance. They are numerous and can be classified into two categories, namely direct and indirect methods. Direct methods bring together all indices that allow either a complete or a partial representation of the power-duration relationship, while indirect methods revolve around the determination of the so-called anaerobic threshold (AT). With regard to direct methods, performance in a series of tests provides a more complete and presumably more valid description of the power-duration relationship than performance in a single test, even if both approaches are well correlated with each other. However, the question remains open to determine which systems model should be employed among the several available in the literature, and how to use them in the prescription of training intensities. As for indirect methods, there is quantitative accumulation of data supporting the utilisation of the AT to assess aerobic endurance and to prescribe training intensities. However, it appears that: (i) there is no unique intensity corresponding to the AT, since criteria available in the literature provide inconsistent results; and (ii) the non-invasive determination of the AT using ventilatory and heart rate data instead of blood lactate concentration ($[La^-]_b$) is not valid. Added to the fact that the AT may not represent the optimal training intensity for elite athletes, it raises doubt on the usefulness of this theory without questioning, however, the usefulness of the whole $[La^-]_b$-power curve to assess aerobic endurance and predict performance in long-distance events.

Maximal oxygen uptake ($\dot{V}O_{2max}$) has long been used as a determinant of performance in middle- and long-distance events.[1] As such, its measurement has become routine in the physiological testing of elite athletes.[2] However, when the range of $\dot{V}O_{2max}$ is narrow, as is the case in highly trained athletes, the correlation between $\dot{V}O_{2max}$ and performance is relatively poor.[3,4] In fact, two athletes with similar $\dot{V}O_{2max}$ do not necessarily perform equally.[3,5] Alternatively, an athlete with a $\dot{V}O_{2max}$ lower than other athletes could compensate by being able to use a higher percentage of $\dot{V}O_{2max}$ ($\%\dot{V}O_{2max}$) to achieve the same oxygen uptake ($\dot{V}O_2$) [ml/min/kg] during the race.[4,6]

Since the classic work of di Prampero et al.,[7,8] it is recognised that other parameters are crucial in the prediction of long-distance performance, namely the energy cost of exercise and the ability to sustain a high $\%\dot{V}O_{2max}$ throughout the entire effort duration. This latter ability is defined by some authors as endurance.[9-12] In order to make the distinction with endurance performance, which is often used synonymously with performance ability in long-distance events, and since $\dot{V}O_{2max}$ sets the upper limit of the aerobic pathway, we propose to call it aerobic endurance. However, this definition of endurance is not unanimously accepted. The cornerstone of this theoretical framework is that endurance is always expressed relative to an upper limit. Otherwise, it is not possible to separate endurance from other factors of performance (i.e. the upper limit of the considered pathway and the energy cost of exercise). This theoretical framework proposes the existence of other types of endurance, namely muscular endurance, which can be defined as the ability to sustain a high fraction of maximum voluntary contraction for a prolonged period of time,[13] or even anaerobic endurance.

As outlined by Péronnet and Thibault,[12] the physiological basis of aerobic endurance is not clearly understood. Outstanding aerobic endurance (i.e. the capacity to sustain a very high fraction of $\dot{V}O_{2max}$ for a given duration) can be associated with a combination of several factors, including a high percentage of type I muscle fibres, the capacity to store large amounts of muscle and/or liver glycogen, the capacity to spare carbohydrate to reserve by using more fatty acids as energy substrates, and the capacity to efficiently dissipate heat.[14-16]

Since aerobic endurance is independent of $\dot{V}O_{2max}$ (i.e. two athletes with a similar $\dot{V}O_{2max}$ are not necessarily able to sustain the same $\%\dot{V}O_{2max}$

for the same duration),[6,12,17] aerobic endurance should be assessed with specific tools. Gradually the anaerobic threshold (AT: expressed in $\%\dot{V}O_{2max}$) has become a standard, because it is closely linked to the $\%\dot{V}O_{2max}$ that can be maintained in long-distance events.[4,6,18,19] However, it does not represent the unique means to assess aerobic endurance. Methods available in the literature are numerous and might generate some confusion for sports scientists, coaches and athletes.

The main purpose of this review, therefore, is to examine methods that have been proposed to assess aerobic endurance, presented as direct and indirect methods. Direct methods correspond to the definition we have adopted, that is, a relative intensity that could be maintained or endured as long as possible or its corollary, the highest relative intensity for a set duration or distance. On the other hand, indirect methods such as the 'anaerobic threshold' are not a maximal duration measure *per se* nor a maximal relative intensity for a set duration, but they are supposed to reflect aerobic endurance. A secondary aim of the manuscript is to examine practical applications of these methods.

1. Direct Measures of Aerobic Endurance

1.1 Aerobic Endurance Index Computed from the Performance in a Single Test

There are essentially three types of tests allowing one to assess aerobic endurance from a single bout at a set intensity: constant-work (CWT), constant-duration (CDT) and constant-power (CPT) tests.[20]

In CWT, sometimes referred to as time trials,[21] an individual completes a set amount of work or a set distance (real or simulated) as quickly as possible.[20] CDT are similar to CWT, but the individual completes as much work or covers as much distance as possible in a set time.[20] Finally, CPT consist of maintaining a constant power output to the point of exhaustion, defined by the inability to maintain power, speed or cadence.[20] The performance measure in a CPT is time to exhaustion or limit time (t_{lim}), as introduced by Monod and Scherrer.[22] However, whatever the type of test used to assess aerobic endurance, the results are finally expressed with a relative intensity corresponding to a t_{lim}.

1.1.1 Performance in a Single Test at Submaximal Intensity (Less than Maximal Oxygen Uptake ($\dot{V}O_{2max}$))

Performance in these tests has been used by researchers to assess aerobic endurance, since it is well correlated with other markers of this aptitude. In fact, Coyle et al.[23] demonstrated in an homogenous group of cyclists that t_{lim} at 88% of $\dot{V}O_{2max}$ was significantly related to the athlete's muscle capillary density and the lactate threshold (LT) [$r = 0.96$, $p < 0.05$]; the LT has been shown to be related to aerobic endurance when expressed as a $\%\dot{V}O_{2max}$ (see section 2.3). Moreover, individuals with the longer t_{lim} possessed a greater percentage of type I muscle fibres.[23] Coyle et al.[21] confirmed these observations with elite cyclists; they reported a high correlation between the performance in a CWT of 40km on the road and the performance in a CDT of 1 hour in the laboratory ($r = -0.88$, $p < 0.001$). Again, the individuals with the higher power during the laboratory tests had a higher percentage of type I muscle fibres and a higher muscle capillary density. More recently, Billat et al.[24] reported that t_{lim} at 90% of $\dot{V}O_{2max}$ was significantly related to the $\%\dot{V}O_{2max}$ corresponding to the LT ($r = 0.65$, $p < 0.05$), and was a good predictor, together with the exercise economy, of 3000m running performance ($r = 0.82$, $p < 0.05$).

Although a good relationship between the performance in CPT, CWT or CDT and aerobic endurance has been consistently found, some methodological considerations must be taken into account to ensure good measurement accuracy.

If a CPT is used to assess aerobic endurance, the power output should be set as a $\%\dot{V}O_{2max}$ rather than at a set absolute intensity (in km/h, W or ml/min/kg), otherwise it is not possible to separate aerobic endurance from other factors of performance in the interpretation of t_{lim}. In fact, when $\dot{V}O_{2max}$

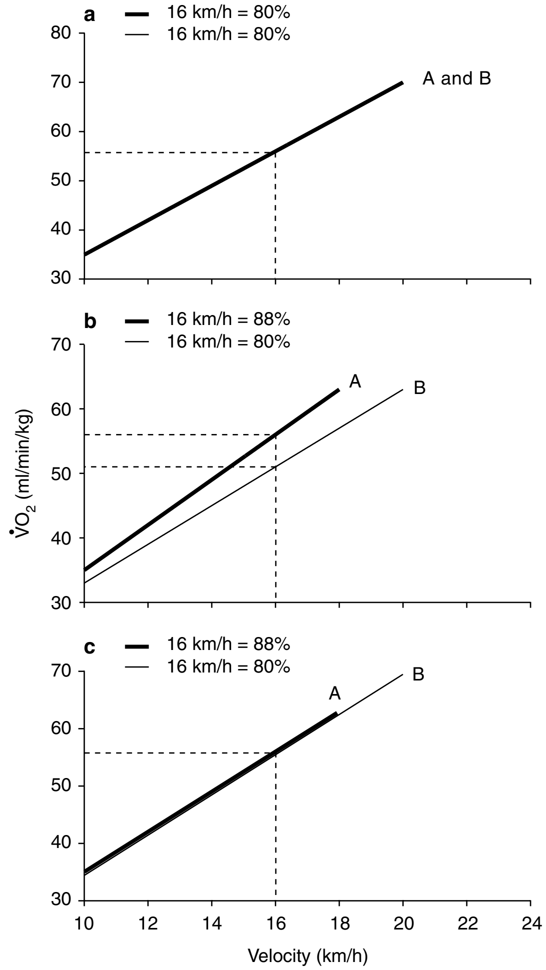

Fig. 1. Effect of measuring time to exhaustion at absolute (km/h) or relative intensity (percentage of $\dot{V}O_{2max}$): (**a**) $\dot{V}O_{2max}$ and exercise economy are identical between the study participants A and B; differences in time to exhaustion reflect aerobic endurance; (**b**) $\dot{V}O_{2max}$ is identical, but exercise economy is different; differences in time to exhaustion reflect both exercise economy and aerobic endurance; (**c**) exercise economy is identical, but $\dot{V}O_{2max}$ is different; differences in time to exhaustion reflect both $\dot{V}O_{2max}$ and aerobic endurance. **$\dot{V}O_2$** = oxygen uptake; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

and exercise economy are equal, the same absolute intensity corresponds to the same %$\dot{V}O_{2max}$ (figure 1) and differences in the t_{lim} are attributable to changes in aerobic endurance. However, when $\dot{V}O_{2max}$ or exercise economy are different, the same absolute intensity does not correspond to the same %$\dot{V}O_{2max}$ (figure 1), and differences in t_{lim} do not solely reflect differences in aerobic endurance, but also differences in $\dot{V}O_{2max}$ or exercise economy.

It appears that CPT is more or less reliable, particularly at low relative intensities. Hence, McLellan et al.[25] reported a coefficient of variation (CV) ranging from 2.8 to 31.4% for t_{lim} at 80% of $\dot{V}O_{2max}$ on a cycle ergometer. This variability is in agreement with previous observations made by Krebs and Powers,[26] who reported a CV ranging from 5.2 to 55.9% under similar conditions. The lack of reproducibility of these open-ended submaximal tests may be caused by psychological factors, such as motivation and monotony, but also by the accuracy with which the power output is determined or applied.[20] In fact, given the hyperbolic relationship between power and t_{lim}, a small change in the power output can result in a large change in its t_{lim} at or below $\dot{V}O_{2max}$.[20,27] It is noteworthy that Hopkins et al.[20] found CPT to have a high reliability when the change in t_{lim} is converted back into the change in mean power.

Reliability seems to be higher when the end of the test is set beforehand. Indeed, the CV of CDT is approximately 3%, both on a treadmill[28] and a cycle ergometer,[29,30] while it is often less than 2% for CWT (or time trials).[31-35] From these observations, and considering that field tests provide more specific and arguably more useful results than those obtained in the laboratory,[36,37] competition data gained over competitive events lasting several minutes or more represent a reliable means of assessing aerobic endurance.

1.1.2 Performance in a Single Constant-Power Test at the Velocity Associated with $\dot{V}O_{2max}$

Introduced by Daniels et al.[38] in the mid-eighties, the term 'velocity at $\dot{V}O_{2max}$' (v$\dot{V}O_{2max}$) is defined as the minimal velocity that elicits $\dot{V}O_{2max}$ during an incremental test.[39] T_{lim} at this velocity is also considered as a measure of aerobic endurance, since Billat et al.[24,40,41] have found in elite and sub-elite runners that it was significantly related to: (i) average velocity over a 1500m race (r = 0.72,

$p < 0.01$); (ii) the average velocity over a half-marathon race (21.1km; $r = 0.71$, $p < 0.05$); and (iii) the %$\dot{V}O_{2max}$ corresponding to the LT ($r = 0.74$, $p < 0.05$).

As shown in table I, average t_{lim} values for running range from 3.83 ± 1.11[42] to 7.60 ± 1.60 minutes[43] when measured on a treadmill, and from 5.12 ± 3.05[44] to 8.40 ± 2.10 minutes[45] when measured on the track. The mean t_{lim} of studies listed in table I is 5.92 ± 1.02 minutes.

Billat et al.[48] reported reproducible measures on the basis of similar results in eight long-distance runners who repeated the test twice at 1-week intervals (6.70 ± 1.88 and 6.73 ± 1.68 minutes, respectively; $r = 0.86$, $p < 0.01$). Although there was no significant difference between test and retest mean values, interindividual values showed large variations in agreement with the studies of McLellan et al.,[25] and Krebs and Powers.[26]

A difficulty in using v$\dot{V}O_{2max}$ to express intensity in percentage of v$\dot{V}O_{2max}$ resides in the exercise protocol used to determine $\dot{V}O_{2max}$; many methods are available in the literature to calculate v$\dot{V}O_{2max}$,[40,60-65] leading to velocities that can be significantly different.[39,52,66] For example, using a discontinuous multistage protocol with 5-minute stages and 5-minute or longer rest intervals that led to a plateau in the $\dot{V}O_{2max}$-velocity relationship, it has been found that only the continuous multistage protocol with 2-minute stages yields maximal

Table I. Summary of studies investigating time to exhaustion (t_{lim}) at the velocity associated with maximal oxygen uptake ($\dot{V}O_{2max}$)

Study	n	Ergometer	$\dot{V}O_{2max}$ (ml/min/kg)			t_{lim} (min)		
			mean	SD	CV	mean	SD	CV
Higgs[46]	20	Treadmill	41.32			4.60		
Volkov et al.[47]	4	Treadmill	60.80	3.20	5.26	5.40	3.25	60.19
Lavoie and Mercer[42]	5	Cycle ergometer	61.40	4.50	7.32	3.83	1.11	28.98
Adopo et al.[43]	10	Treadmill	69.80	6.30	9.03	7.60	1.60	21.05
Padilla et al.[45]	14	Track	65.30	5.00	7.66	7.00	2.20	31.43
	24	Track	71.90	4.20	5.84	8.40	2.10	25.00
Billat et al.[24]	13	Treadmill	74.90	3.10	4.14	5.35	1.45	27.10
Billat et al.[41]	12	Treadmill	69.40	3.70	5.33	6.57	1.73	26.40
Billat et al.[40]	38	Treadmill	71.40	5.50	7.70	6.00	1.78	29.72
Billat et al.[48]	8	Treadmill	69.50	4.20	6.04	6.70	1.88	28.11
	8	Treadmill	69.50	4.20	6.04	6.73	1.68	25.00
Billat et al.[49]	16	Treadmill	75.50	5.30	7.02	5.50	1.50	27.27
Billat et al.[50]	15	Treadmill	69.30	3.30	4.76	5.75	2.00	34.78
Billat et al.[51]	15	Treadmill	77.70	6.40	8.24	6.12	1.97	32.15
	15	Treadmill	68.40	4.70	6.87	6.22	2.82	45.31
	14	Treadmill	63.20	4.20	6.65	7.02	2.15	30.64
Hill and Rowell[52]	13	Treadmill	52.10	5.10	9.79	4.83	1.02	21.03
Villeneuve[53]	10	Cycle ergometer	59.60	6.00	10.07	6.43	0.87	13.52
	10	Treadmill	60.40	4.70	7.78	6.47	1.19	18.39
Gazeau et al.[54]	7	Treadmill	69.20	6.80	9.83	5.03	1.38	27.39
Billat et al.[55]	8	Treadmill	71.20	5.00	7.02	5.02	0.90	17.94
Renoux et al.[56]	14	Treadmill	68.90	4.60	6.68	4.48	1.28	28.62
Demarie et al.[44]	15	Track	56.30	4.40	7.82	5.12	3.05	59.57
Billat et al.[57]	7	Track	61.20	3.40	5.56	5.78	1.83	31.70
Morton and Billat[58]	10	Treadmill	59.30	5.20	8.77	6.08	1.77	29.04
Blondel et al.[59]	10	Track	61.80	6.20	10.03	5.95	1.83	30.76
Mean	**13**		**65.36**	**4.77**	**7.14**	**5.92**	**1.78**	**30.04**
SD	**7**		**7.96**	**1.04**	**1.66**	**1.02**	**0.61**	**10.91**

CV = coefficient of variation (%); **n** = number of participants; **SD** = standard deviation.

speeds similar to the criteria.[67] Otherwise, the maximal speed achieved at the end of the tests decreases from 0.5- to 1-, 1.5-, 2- and 3-minute stage protocols. A 1 km/h speed increment was used with these protocols. The acceleration (calculated as a combination of stage duration and speed increment) rather than the stage duration alone seems to be the key factor in continuous multistage protocols since Billat et al.[50] found no difference in 15 well trained long-distance runners, using either 2-minute stages with a 1 km/h increment or 1-minute stages with a 0.5 km/h increment (20.7 ± 1 and 20.8 ± 0.9 km/h, respectively; $p > 0.05$). It is worth noting that Villeneuve[53] also reported that t_{lim} at the maximal velocity attained at the end of multistage tests was longer in protocols using longer stage durations.

Beyond these methodological issues, the significance of the t_{lim} at $v\dot{V}O_{2max}$ needs consideration. In fact, it is not clear whether the large interindividual differences observed in populations with relative homogenous $\dot{V}O_{2max}$ values (see table I for CV) are caused by a higher aerobic endurance, or, as suggested by several researchers, by individual differences in anaerobic capacity.[59,68,69]

Finally, the analysis of individual cases reveals some athletes who, with similar $v\dot{V}O_{2max}$, perform differently over short- and long-duration events, some having better t_{lim} at high relative power, while others have more endurance at low relative power. Consequently, measuring aerobic endurance with a single test, whatever the intensity chosen, seems problematic.

1.1.3 The Square Wave Endurance Exercise Test of Gimenez et al.

Gimenez et al.[70-72] proposed a 45-minute square wave endurance exercise test (SWEET) to predict aerobic endurance. The first session consists of alternating 4-minute stages at 50% of maximum aerobic power (MAP) with 1-minute stages at 100% of MAP (base and peak intensities, respectively) over 45 minutes. The next sessions are identical to the first, except for the base of the SWEET, which is increased by 5% per session, until the participant is no longer able to complete the 45-minute test. Exercise is performed on a cycle ergometer and at least two sessions are required.[70] The total mechanical work (TMW, expressed in kJ/kg) from the beginning of the first session to the last completed work interval at 100% MAP, is considered by the authors as an index of aerobic endurance. Although the individual may perform more than one series where the intensity of recovery interval is increasing, the individual is exhausted only at the last series and the TMW is not based on a combination of exhaustion times.

The rationale for choosing a square wave test is based on the fact that a constant-load exercise does not correspond to the rapid accelerations that endurance athletes do voluntarily or are obliged to do in a short space of time. If this assumption is true for most middle-distance events (≤10000m), essentially for strategic reasons, it does not fit with the reality of long-distance events (marathons or longer), where a regular pace is a prerequisite for optimal performance. On the other hand, it is not possible to assume that the limiting factors which minimise the fatigue induced by pace breakdowns are the same as those used to maintain a high $\%\dot{V}O_{2max}$ for a long period of time. Furthermore, in order to be valid, an index of endurance must be independent of $\dot{V}O_{2max}$.[12] This is not the case for TMW, since with similar aerobic endurance, the athlete who has the greater $\dot{V}O_{2max}$ will also have the higher TMW. From a conceptual point of view at least, the relative power of the base intervals of the last completed session would appear a better aerobic endurance index. Moreover, given the square-wave form of the test, it is not clear whether TMW corresponds to the maximal work that can be performed in 45 minutes.

1.2 Aerobic Endurance Index Computed from the Performance in a Series of Tests

1.2.1 Fractional Utilisation of $\dot{V}O_{2max}$ as a Function of Performance Time

Preliminary efforts designed to describe the $\%\dot{V}O_{2max}$-duration relationship[73,74] revealed a curvilinear shape for short durations, and almost a linear shape for long durations (figure 2). However,

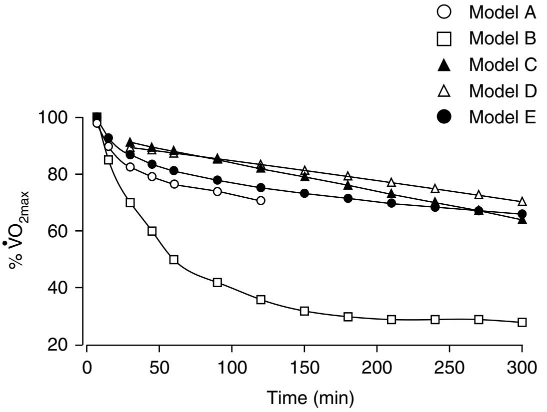

Fig. 2. Fractional utilisation of maximal oxygen uptake ($\dot{V}O_{2max}$) as a function of performance time: a comparison of models. **Model A** = Costill and Fox;[74] **Model B** = Åstrand and Rodhal;[73] **Model C** = Saltin;[75] **Model D** = Davies and Thompson;[76] **Model E** = Léger et al.[9]

these studies were based on limited data and included no regression equations. In addition, relative intensity was plotted against running distance while Léger et al.[9] have shown metabolic events to be a function of running time in heterogeneous populations. In other words, the physiological limitations are not the same for a 20km run in 60 minutes and another run in 120 minutes, while they would be similar for a 10 and 20km run in 60 minutes. Subsequent investigations have taken these limits into account.

Saltin[75] proposed a linear model that predicts the %$\dot{V}O_{2max}$ that can be sustained for exercise durations (t = time in minutes) of 30 to 300 minutes (equation 1):

$$\%\dot{V}O_{2max} = 94 - 0.1 \bullet t$$

This equation relates %$\dot{V}O_{2max}$ to running time, not to running distance. Consequently, an elite athlete who completes the marathon in 130 minutes can sustain approximately 81% $\dot{V}O_{2max}$, while a recreational athlete who runs the distance in 240 minutes can sustain only 70% of his/her $\dot{V}O_{2max}$. However, this does not mean that the elite athlete possesses higher aerobic endurance, since for the same duration, the relative intensity is the same.

Davies and Thompson[76] proposed a non-linear model derived from the data collected from four British ultramarathoners (including a world-record holder), to predict the %$\dot{V}O_{2max}$ that can be maintained for races of up to 24 hours (equation 2):

$$\%\dot{V}O_{2max} = 91.24 - 3.79 \bullet t - 0.08 \bullet t^2$$

where t represents the duration of the race, in hours. This model applies equally to running and cycling performance. However, because cycling is more efficient than running, the distance covered by a cyclist in standard conditions will be about 2.5 times the distance covered by a runner in the same time.[77]

Although of value, these equations have been developed with elite athletes only, and are not valid for exercise durations ranging from 1 to 29 minutes. To overcome these limitations, Léger et al.[9] re-examined the relationship between %$\dot{V}O_{2max}$ and performance time by analysing the performance of 311 moderately trained runners ($\dot{V}O_{2max}$ = 61.3 ± 6.1 ml/min/kg) at distances ranging from 0.2 to 42.2km. They proposed a double-logarithmic regression with four separate equations, where X represents time, in minutes, and Y the corresponding %$\dot{V}O_{2max}$ (see equations 3, 4, 5, and 6):

if $t < 4.6$ min: $\ln Y = 4.93 - 0.186 \bullet \ln X$

if $4.6 < t < 70.4$ min: $\ln Y = 4.79 - 0.096 \bullet \ln X$

if $70.4 < t < 173.7$ min: $\ln Y = 4.90 - 0.121 \bullet \ln X$

if $t > 173.7$ min: $\ln Y = 5.08 - 0.156 \bullet \ln X$

There is no physiological justification for the number of equations; the interest of this model is to improve the accuracy of the prediction ($r = -0.97$, standard error of the estimate = 5.5%), and to allow prediction of %$\dot{V}O_{2max}$ for very short durations ($t < 4.6$ min). However, it underestimates the aerobic endurance of elite athletes, since the curves of Saltin,[75] and Davies and Thompson[76] are more elevated (figure 2). Such a model reflects the average endurance of the average athlete and better estimates maximal training time at any relative intensity even though adjustments will probably be necessary.

Independently of these considerations, the main limitation of all these models is that they assume aerobic endurance is the same for all athletes, since it predicts an average $\%\dot{V}O_{2max}$ value for a set time; there is no provision for individual differences. On the other hand, they do not consider the slow component of $\dot{V}O_2$ kinetics,[78] which questions the assumption of a steady-state $\dot{V}O_2$ during heavy exercise.[79] Finally, if such average curves are useful to see if individual values are below or above average, it is imperative to know on which population sample the equations were derived from. In this respect, a curve drawn from world records could be interesting because it allows one to see how individual scores compare with the actual limits of human performance.

1.2.2 The Endurance Index of Péronnet and Thibault

Since the fractional utilisation of $\dot{V}O_{2max}$ decreases linearly when time (in minutes) is converted to a natural logarithm (figure 3), Péronnet and Thibault[12] proposed to use the slope of this relationship as an index of aerobic endurance. This endurance index (EI) is defined as the decrease of the fractional utilisation of $\dot{V}O_{2max}$ when running duration exceeds 7 minutes and when the natural logarithm of time is increased substantially. This can be written (equation 7):

$$EI = \frac{100 - \%\dot{V}O_{2max}}{\ln 7 - \ln t}$$

or after rearrangement (equation 8):

$$EI = \frac{\Delta\%\dot{V}O_{2max}}{\Delta\ln t}$$

The lower this slope (or EI), the higher the aerobic endurance. The major advantage of the EI is its accessibility, since it can be estimated easily from performance data ranging from 3000m to the marathon or longer distances. Moreover, it allows comparison between individuals with different $\dot{V}O_{2max}$ values or performance levels. However, using a slope to compare the aerobic endurance of several individuals requires the y-intercept to be the same for all athletes, or to choose a common ‘starting’ point for everyone. To achieve this, the authors assumed that $\dot{V}O_{2max}$ can be maintained for 7 minutes. But as shown in table I, there is large interindividual variability in t_{lim} at $v\dot{V}O_{2max}$ (CV = 30 ± 11%), and the mean value seems to be closer to 6 than to 7 minutes (5.92 ± 1.02 minutes). Consequently, the EI of Péronnet and Thibault[12] does not allow comparison between individuals with different performance levels or across competition events. Nonetheless, it remains a convenient tool for the modelling of aerobic endurance. The model is better to assess EI in long-lasting events (*vs* events close to 7-minutes duration); its validity is also improved when EI is computed from more than two performances.

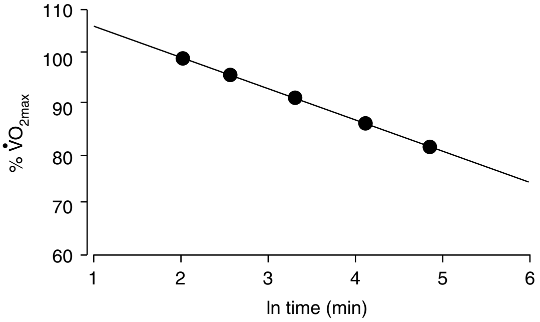

Fig. 3. Fractional utilisation of maximal oxygen uptake ($\dot{V}O_{2max}$) as a function of the natural logarithm (ln) of performance time.[12]

1.2.3 The Nomogram of Mercier et al.

Mercier et al.[80] developed a nomogram (figure 4) from empirical observations to predict aerobic endurance and running performances at different distances. This nomogram relies on the assumption of a constant energy cost of running, and supposes that the rate of decline of the fractional utilisation of $\dot{V}O_{2max}$ when time increases depends on the level of the athletes. The relative endurance index (REI) is a number without units, on a scale of –100 to +100. It is obtained by subtracting the value in column B in figure 4 from the value in column A, and corresponds to the points at which these columns are crossed by the line that describes the athlete's performances at two distances. The higher the REI, the higher the aerobic endurance. Once the line is traced, the nomogram enables one to predict performance at other distances, either by interpolation or by extrapolation. For example, Saïd Aouïta, the outstanding middle-distance run-

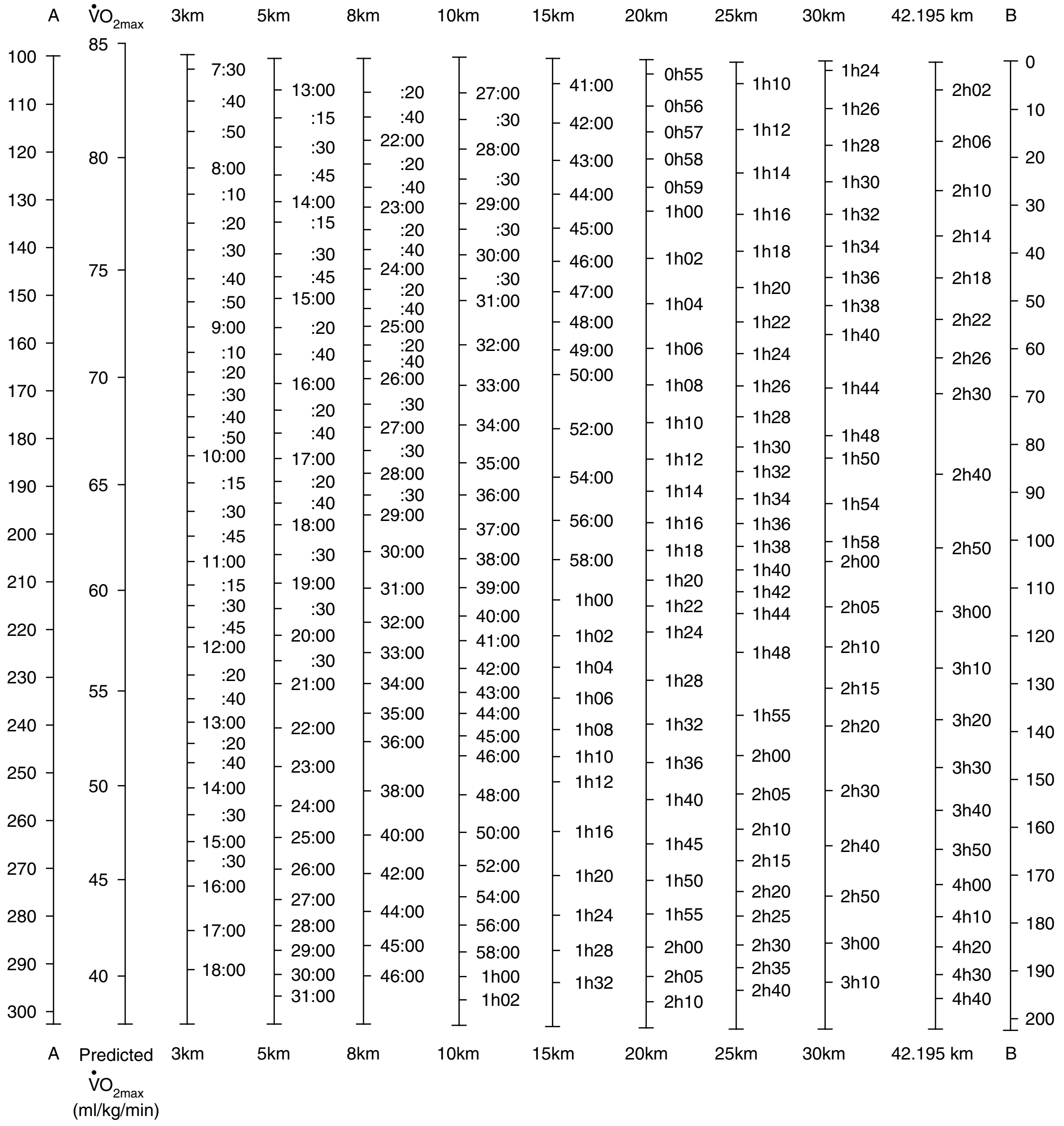

Fig. 4. The Mercier et al.[80] nomogram predicting running performances at distances of 3 to 42.2km. The line that describes the athlete's performance at two distances allows one to predict the performance at a third distance, as well as the index of endurance, obtained by subtracting the value in column B from the value in column A. The maximal oxygen uptake ($\dot{V}O_{2max}$) is predicted from a horizontal line passing by the 3km performance (reproduced from Mercier D, Léger L, Desjardins M. Nomogram to predict performance equivalence for distance runners. *Track Technique* 1986; 94: 3004-9,[80] with permission).

ner in the late eighties, ran 7:29.45 min:sec in the 3000m and 27:26 min:sec in the 10 000m. The nomogram predicts an endurance score of 76, and a performance time at the 5000m of approximately 12:59 min:sec. His personal best is 12:58.39. De Castella, who was one of the best marathoners during the same period, ran 13:34 min:sec in the 5000m and 28:10 min:sec in the 10 000m. The nomogram predicts an endurance score of 98, and a performance time in the marathon of approximately 2:08:15 h:min:sec. His personal best over the distance is 2:08:18 h:min:sec.

The nomogram also allows $\dot{V}O_{2max}$ to be estimated, with values being given on the scale that relates $\dot{V}O_{2max}$ to 3km running time. In addition to being relatively accurate in its predictions, the nomogram provides the opportunity to determine training priorities for a given chronometric objective, either by identifying the main physical aptitude to improve, or by setting chronometric objectives at lower distances. Like any model, however, the predictions are average scores with a prediction error that may be due to the fact that the best performances are affected not only by any one of the three components of performance in long-distance events,[7,8] but also by anaerobic capacities and motivation.

1.2.4 The Critical Power of Monod and Scherrer

It is assumed that the total amount of work that can be performed before exhaustion, either during small muscle[22] or whole-body exercise,[81] is given by (equation 9):

$$W_{lim} = P \bullet t_{lim} = AWC + CP \bullet t_{lim}$$

where W_{lim} is the total amount of work (J), P is the power output (W), AWC is the anaerobic work capacity (J) and CP is the critical power (W) [figure 5]. By rearrangement of this equation, we note that CP is the asymptotic value of the P-t_{lim} relationship (figure 6) [equation 10]:

$$t_{lim} = \frac{AWC}{P - CP}$$

Consequently, CP provides an estimate of the highest exercise intensity that can be maintained, at least theoretically, for a long period of time without fatigue.[22] In this respect, CP should reflect aerobic endurance.

It is worth noting that this systems model relies on several assumptions: (i) the energy cost is constant throughout the exercise intensities investigated; (ii) the anaerobic stores are completely utilised during each test; and (iii) $\dot{V}O_{2max}$ is attained at the very onset of work and is maintained at 100%.[82,83] If assumptions (i) and (ii) are reasonable, assumption (iii) can not be met given the existence of a time constant of the $\dot{V}O_2$ kinetics at the onset of exercise.[83] To overcome this flaw, Billat et al.[84] proposed to compute CP from the duration after $\dot{V}O_{2max}$ has been attained instead of the total duration of the CPT. Consequently, CP represents the power that allows $\dot{V}O_{2max}$ to be maintained for the longest time, and has been shown to be very close to $v\dot{V}O_{2max}$ (16.96 ± 0.92 and 17.22 ± 1.12 km/h, respectively; $r = 0.88$, $p < 0.05$).[84]

As seen in table II, most studies use four or five CPT separated by 24 hours recovery to determine CP. Power outputs are chosen such that fatigue occurs generally between 1 and 12 minutes. Nevertheless, it has been suggested that CP could be estimated with reasonable accuracy from two workloads,[85-87] provided their t_{lim} range from 1 to 10 minutes and differ by more than 5 minutes.[85] Moreover, Bishop and Jenkins[88] showed that CP estimated from three tests separated either by 3 hours or by

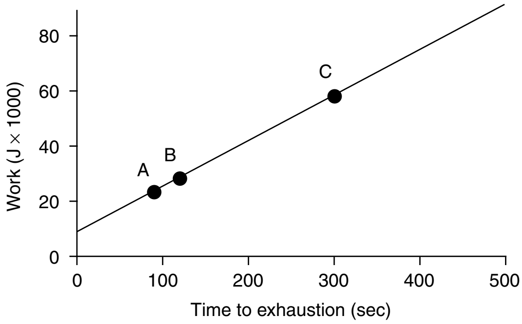

Fig. 5. Linear relationship between time to exhaustion and work. A, B and C are the coordinates of three trials performed at three constant powers. Slope b of the line Y = a + bX is defined as the critical power.

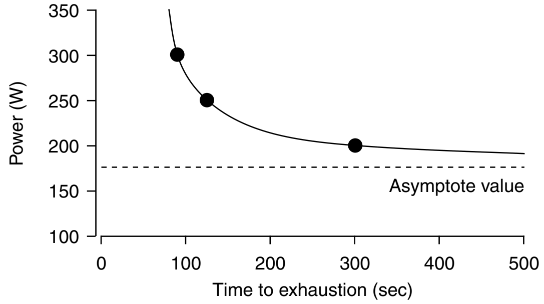

Fig. 6. Hyperbolic relationship between power and time to exhaustion. The coordinates are deduced from the relationship depicted in figure 5. The asymptote value is equivalent to the critical power of figure 5.

24 hours was not statistically different (170.0 ± 13.4 and 171.3 ± 13.5W, respectively; $p > 0.05$). Consequently, CP can be determined from two tests separated by 3 hours recovery, provided the participants are first familiarised with the tests[83] and the workloads are selected with care.[85,89]

The choice of a given range of duration is particularly important in estimating CP. As shown by Vandewalle et al.,[27] the relationship between W_{lim} and t_{lim} is not strictly linear, since the data corresponding to t_{lim} shorter than 3.5 minutes are under the regression line calculated from the values of t_{lim} ranging from 3.5 to 35 minutes. Consequently, CP is overestimated when supramaximal power outputs are used. This methodological bias was reported by Clingeleffer et al.,[89] who found that CP calculated from two trials of 90 and 240 seconds was significantly higher than the slope of the best-fit line of four trials leading to exhaustion in 90, 240, 600 and 1200 seconds (214 ± 32 and 164 ± 28W, respectively; $p < 0.05$). This was later confirmed by Bishop et al.,[108] who reported a significant difference when CP was estimated from coordinates of three tests ranging either from 1.13 to 3.21 minutes or from 3.21 to 8.08 minutes (197 ± 44 and 163 ± 23W, respectively; $p < 0.05$). Considering the inverse relationship between power and t_{lim}, a lower CP estimate is certainly more closely related to the concept of CP, since, at least theoretically, it corresponds to a power output that can be maintained almost indefinitely.[108] Thus, longer predictive trials should be preferred. The shortest duration should be more than 3 minutes, in order to overcome the inertia of the aerobic metabolism, while the longest duration should not be more than 30 minutes, in order to avoid the influence of glycogen stores, dehydration, or motivation on performance.[27,108]

In section 1.1.1, we have questioned the reliability of CPT. However, given the hyperbolic relationship between P and t_{lim}, CP is not particularly sensitive to the errors of t_{lim},[27] even when they are large.[106] This is probably the reason why most of the studies reported a good reliability of CP,[92,93] provided the participants were familiarised with the procedure.[88]

The linear W_{lim}-t_{lim} and non-linear P-t_{lim} relationships (Equations 9 and 10) do not represent the sole mathematical models allowing the estimation of CP. Dividing equation 9 by t yields an alternate linear formulation which is used by some researchers (equation 11):[82]

$$P = AWC \bullet t^{-1} + CP$$

In order to overcome the assumption of Equation 10, that power is infinite when time approaches zero, Morton[114] proposed an alternative non-linear model and added a third parameter called P_{max}, which represents the maximal instantaneous power (equation 12):

$$t_{lim} = \frac{AWC}{P - CP} - \frac{AWC}{P_{max} - CP}$$

Finally, Gaesser et al.[115] proposed an exponential model, which overcomes the assumption of infinite power at very short durations, but does not provide an estimation of AWC (equation 13):

$$P = CP + (P_{max} - CP) \bullet \exp^{-t/\tau}$$

where τ is an undefined time constant.

Studies designed to compare these five mathematical models reported a significant difference between CP estimates, whatever the ergometer.[95,97,101] The 3-parameters model of Morton[114] produced CP estimates that were significantly lower than the four other models, while the exponential model resulted in the highest estimates.[111,112,115] Considering these large differences, approximately 20% between the highest and the lowest estimates, the choice of equation appears important. The question remains: which model provides the most valid index of aerobic endurance?

A variety of correlates for CP have been investigated. If some studies reported significant correlations between CP and most of the so-called threshold measures, either ventilatory threshold (VT)[81,90,109,116,117] or LT,[96,103,118-121] others failed to do so or reported significant differences between the power or the velocity associated with

Table II. Summary of modalities for the determination of critical power

Study	n	Ergometer	Number of tests	Duration (min)	Recovery (h)	Range of intensity (or distance)
Moritani et al.[81]	8	Cycle ergometer	3	1-5	0.5	275-400W
	8	Cycle ergometer	3	2-5	0.5	175-300W
DeVries et al.[90]	6	Cycle ergometer	4	1-5	0.5	275-400W
	5	Cycle ergometer	4	1-5	0.5	225-350W
Hughson et al.[91]	6	Treadmill	6	2-12	48	5.3-6.2 m/sec
Nebelsick-Gullett et al.[92]	25	Cycle ergometer	3	<6	0.5	156-313W
Gaesser and Wilson[93]	14	Cycle ergometer	5	1-10	24	−30W < MAP < +60W
Housh et al.[85]	12	Cycle ergometer	2	1-10	24	172-360W
	12	Cycle ergometer	4	1-10	24	172-360W
Jenkins and Quigley[94]	8	Cycle ergometer	4	<15	24	360-520W
Poole et al.[95]	8	Cycle ergometer	5	1-10	24	200-400W
Housh et al.[96]	12	Cycle ergometer	2		0.5	314-392W
Jenkins and Quigley[97]	9	Cycle ergometer	3	<6	3	300-400W
Carnevale and Gaesser[98]	7	Cycle ergometer	4	1-10	24	300-390W
Housh et al.[99]	10	Treadmill	4	2-12	24	4-5.35 m/sec
Jenkins and Quigley[100]	18	Cycle ergometer	3	<15	3	270-390W
Overend et al.[101]	26	Cycle ergometer	4	2-15	0.7/24	
Pepper et al.[102]	10	Treadmill	4		24	3.6-6 m/sec
Wakayoshi et al.[103]	8	Swimming	2	2-4	24	200 and 400m
Smith and Hill[104]	26	Cycle ergometer	5		24	
Clingeleffer et al.[89]	7	Kayak	2	1.5-20	3	150-215W
Clingeleffer et al.[86]	8	Kayak	4	1.5-20	3	150-215W
Bishop and Jenkins[88]	9	Cycle ergometer	3	1-10	3	
Kolbe et al.[105]	17	Treadmill	6	2-12	1wk	4.7-6.9 m/sec
Kachouri et al.[106]	7	Track	2	3-12		95 and 105% MAS
Kranenburg and Smith[37]	9	Treadmill	3	3-13	1/24	
	9	Track	3		1/24	900-4000m
Florence and Weir[107]	12	Treadmill	4		0.33	3.6-6 m/sec
Bishop et al.[108]	10	Cycle ergometer	3	1-10	24	
Billat et al.[84]	6	Track	4	1-12	24	90-140% MAS
Smith et al.[109]	13	Cycle ergometer	4	1.5-10	24	
Neder et al.[110]	17	Cycle ergometer	4	1-20	24	80-120% $\dot{V}O_{2max}$
Bull et al.[111]	9	Cycle ergometer	5	1-10	24	−50W < MAP < +50W
Martin and Whyte[87]	8	Swimming	5		24	100-1500m
Housh et al.[112]	10	Treadmill	4	2-12		4-5.35 m/sec
Smith and Jones[113]	8	Treadmill	4	4-9		100-120% MAS
Blondel et al. [59]	10	Track	4	1-14	24	90-140% MAS

MAP = maximum aerobic power; **MAS** = maximum aerobic speed; **n** = number of participants; **$\dot{V}O_{2max}$** = maximal oxygen uptake.

CP and the considered threshold.[86,87,95,96,107,122] Differences in the duration of predictive trials can explain at least part of this discrepancy between studies. Recently Smith and Jones[113] provided a new insight into the relationship between CP and maximal lactate steady state (MLSS). Although conventional statistical approaches demonstrated that there was no significant difference between the two estimates (14.1 ± 1.1 and 13.8 ± 1.1 km/h, respectively; $p > 0.05$), the bias ± 95% limits of agreement[123] indicated that estimating one variable from another in individuals might result in significant error.[113] These results suggests that CP and the MLSS probably represent the same physiological phenomenon, but also that CP can not be considered as a non-invasive measure of MLSS.

Considering that field tests using performance data may be more applicable for coaches than physiological variables obtained from laboratory tests, Kranenburg and Smith[37] compared CP determined from track running and treadmill tests in elite runners. They found no significant difference between the two estimates (293 ± 21 and 300 ± 20 m/min, respectively), and both were highly correlated with 9.8km race performance ($r = 0.92$; $p < 0.001$). Similar results were obtained by Wakayoshi et al.,[36] who found no differences between CP determined in a swimming flume (CP_{flume}) or in a swimming pool (CP_{pool}; 1.49 ± 0.03 and 1.54 ± 0.02 m/sec, respectively). But unlike Kranenburg and Smith,[37] CP_{pool} was more strongly related to 400m freestyle performance than CP_{flume} was ($r = 0.99$ and 0.89, respectively). Considering the higher accessibility and specificity of field testing, and since the results are similar with the laboratory, and sometimes more correlated with performance, determining CP on the track or in a swimming pool is undoubtedly of greater interest for runners and swimmers.

1.3 Practical Issues

Since CP represents the highest exercise intensity that can be maintained for a long period of time without fatigue,[22] it should be strongly related to aerobic endurance. Several studies suggest this is the case, since CP is significantly correlated with running performance over distances ranging from 1 to 42.2km,[37,105,107] with cycling performance over distances ranging from 17 to 40km,[109] and with the mean velocity of a 400m freestyle.[36,103] But contrary to the hypothesis of Monod and Scherrer,[22] exercise at CP can not be maintained indefinitely. Depending on the duration of the predictive trials or the mathematical modelling, t_{lim} at CP ranges from 30 to 60 minutes.[94,111,119,122,124,125] It is noteworthy that CP determined from the 1500 and 5000m world records in males using equation 9 corresponds to the mean velocity of the 10 000m world record (22.77 and 22.75 km/h, respectively), while it differs only by 3% with females (19.73 and 20.31 km/h, respectively).

Given the hyperbolic relationship between power and t_{lim}, a small variation in power induces a large difference in the estimated value of t_{lim}, especially for power outputs slightly lower than CP. Consequently, CP has a relatively low predictive value, and power should not be extrapolated for values of t_{lim} which are very short or very long.[27]

Contrary to indirect measures of aerobic endurance (see section 2.3), few attempts have been made to establish the influence of training on CP. Jenkins and Quigley[97,100] found that AWC and CP were, respectively, more affected by anaerobic and aerobic training. Unfortunately, there are no data available about the value of training at or around CP to improve performance at endurance events. However, it has to be recognised that as long as methodological considerations like the choice of the appropriate mathematical modelling are not elucidated, the interest of such studies is limited.

2. Indirect Measures of Predicting Endurance Performance

Indirect methods used to predict aerobic endurance are based on a significant relationship between the fractional utilisation of $\dot{V}O_{2max}$ for a given event and some biological variables, such as ventilatory parameters, blood lactate concentrations ($[La^-]_b$) or heart rate. Generally, this relationship is described in terms of a threshold. By definition, the term 'threshold' is the level at which changes in a physiological parameter occur in response to a stimulus. Below the threshold, the stimulus is insufficient to generate any response; conversely, above the threshold, the stimulus begins to evoke the expected response.[126]

Owles,[127] in 1932, was the first to report changes in $[La^-]_b$ in response to light exercise. He concluded that 'there was no lactate increase as a result of exercise up to a certain critical level'. Wasserman et al.[128] showed that this 'critical level' of $[La^-]_b$ was related to significant changes in selected ventilatory parameters during incremental exercise. They defined the AT as 'the level of work or O_2 consumption at which metabolic acidosis and the changes in gas exchange occur'.[128] Theoretically, an athlete who exercises below this threshold will be able to accommodate the lactate and hydrogen ions produced by the muscles; fatigue will therefore be limited only by substrate reserves. Consequently, the higher the threshold, the higher the aerobic endurance.[11]

It is worth noting that the AT is not a threshold for anaerobiosis. Not only is the contribution of anaerobic pathways minor during submaximal exercise (intensity less than $\dot{V}O_{2max}$),[129] but also the formation of lactate during exercise can be caused by a larger pyruvate formation than is needed and is not necessarily the result of anaerobic conditions.[130] In fact, lactate can be produced in oxidative as well as in glycolytic fibres of fully oxygenated muscle.[131] Although the use of the term 'anaerobic' is clearly incorrect, and probably the underlying theory,[62,132] the fact is that the so-called AT is well-correlated with the fractional utilisation of $\dot{V}O_{2max}$ for a given event. Therefore, it represents a convenient tool to assess aerobic endurance. Both invasive and non-invasive methods during incremental or steady-state exercise have been used by researchers to 'locate' the AT.

2.1 Incremental Tests

2.1.1 Lactate Threshold

The onset of plasma lactate accumulation,[18] the LT,[133] the onset of blood lactate accumulation,[134] the individual AT,[135] the lactate turning point[136] and the lactate slope index[137] are terms, among others (see table III), which have been used to define the exercise intensity at which there is a non-linear increase $[La^-]_b$.[138]

As shown in table IV, this increase or 'breakpoint' has been determined using a wide range of criteria. For instance, Sjödin and Jacobs[134] used a fixed concentration of 4 mmol/L, while Worms et al.[165] used 3 mmol/L. Hurley et al.[166] used 2.5 mmol/L, LaFontaine et al.[142] 2.2 mmol/L and Yoshida et al.[167] used 1 mmol/L above the resting level. Using a fixed lactate value as the threshold certainly increases objectivity but denies individuality since the non-linear increase in $[La^-]_b$ does not always occur at 4 mmol/L.[168]

Other researchers have used the tangent point of the lactate curve to locate the threshold. For Simon et al.[176] an angle of 51° was used, while Keul et al.[175] elected to use 45°. Furthermore, depending on the units used or the relative magnitude of the X and Y scales, the tangent point at a set angle could yield a different threshold value, thus questioning this type of approach. Bunc et al.[177] have used the intersection between the exponential regression of the lactate curve and the bisector of the tangents on the upper and lower parts of the regression. Whether the multistage protocol starts and finishes at low or high intensities would affect the tangents of the lower and upper parts of the regressions as well as the position of the crossing point between the two tangents thus making this particular approach somewhat arbitrary (figure 7).

This diversity in methods has led to confusion and misinterpretation. Indeed, while there should be only one threshold value, computed thresholds using various 'scientific' techniques on the same set of data could range between 79 and 92% of $\dot{V}O_{2max}$.[185] In any event, a rightward shift of the lactate curve, when expressed in $\%\dot{V}O_{2max}$, is a good marker of aerobic endurance and any single standardised point on that curve, whether it is termed a 'threshold' or not, will reflect aerobic endurance.

2.1.2 Ventilatory Threshold

Wasserman and McIlroy[153] used expired air and changes in ventilatory markers to establish a 'ventilatory threshold'. This non-invasive method relies on the assumption that the H^+ ions of lactic acid are buffered by blood bicarbonate, producing excess CO_2, which in turn increases expired minute ventilation ($\dot{V}E$). According to this theory, the initial rise in $[La^-]_b$ coincides with the onset of exercise-induced hyperventilation during incremental work. With regard to the $[La^-]_b$, several criteria or combinations of criteria have been proposed to detect this threshold (table IV).

Although many studies have reported that VT was strongly related to the LT,[118,172,179,186-189] there are considerable doubts about the validity of this statement. First and foremost, given the large range of invasive techniques (table IV), a significant correlation between the VT and one of the numerous lactic thresholds is not a sufficient criterion to establish its validity. Moreover, even if we hypothesise that all studies are using the same definition and the same criteria to detect the LT, there is strong evidence to suggest that these thresholds do not occur at the same power output.

Hugues et al.[182] have shown that the LT and VT could be manipulated independently of each other by changing the pedalling frequency (LT < VT at 90 rpm, but not at 50 rpm), or by modifying the substrate availability (LT > VT in glycogen depleted state, but not in normal glycogen state). Hagberg et al.,[190] while studying patients who lack muscle phosphorylase (MacArdle's disease), demonstrated that hyperventilation during incremental exercise could occur despite there being no increase in plasma $[H^+]$. Added to the fact that detection of the VT is highly subjective, given that different evaluators can choose different thresholds from the same data,[161,191] and that it is dependant on the duration of the stages in an incremental test,[192] these studies suggest that the non-invasive determination of the AT from ventilatory data during incremental exercise is not valid.

Table III. Nomenclature used to describe anaerobic threshold (adapted from Tokmakidis,[126] with permission)

Study	Nomenclature
Invasive methods	
Owles[127]	Critical metabolic level
Williams et al.[139]	Lactate excess
Farrell et al.[18]	Onset of plasma lactate accumulation
Kinderman et al.[140]	Aerobic/anaerobic threshold
Ivy et al.[133]	Lactate threshold
Skinner and McLellan[141]	Aerobic threshold Anaerobic threshold
Sjödin and Jacobs[134]	Onset of blood lactate accumulation
LaFontaine et al.[142]	Maximal steady state
Stegmann et al.[135]	Individual anaerobic threshold
Jones and Ehrsam[143]	Owles point
Davis et al.[136]	Lactate turning point Lactate breaking point
Wasserman et al.[144]	Pyruvate threshold
Van Harn and Brooks[145]	Epi/norepinephrine threshold
Mader and Heck[146]	Transitional state
Simon et al.[147]	Plasma lactate threshold
Beaver et al.[148]	Bicarbonate threshold
Smith et al.[149]	Plasma ammonia threshold
Hughson et al.[137]	Lactate slope index
Tegtbur et al.[150]	Lactate minimum speed
Beneke[151]	Maximal lactate steady state
Non-invasive methods	
Holmann[152]	Point of optimum ventilatory efficiency
Wasserman and McIlroy[153]	Threshold of anaerobic metabolism
Wasserman et al.[128]	Anaerobic threshold
Reinhard et al.[154]	Threshold of decompensated metabolism acidosis
Skinner and McLellan[141]	Aerobic threshold
Sheen and Juchmes[155]	Hyperventilation threshold
Jones and Ehrsam[143]	Proportional limit
Conconi et al.[156]	Deflection velocity
Powers et al.[157]	Ventilatory threshold
Simon et al.[158]	Respiratory compensation threshold
Boulay et al.[159]	Ventilatory anaerobic threshold
McLellan and Skinner[160]	First and second ventilatory threshold
Gladden et al.[161]	Gas exchange threshold
Palka and Rogozinski[162]	Respiratory anaerobic threshold
Chicharro et al.[163]	Salivary threshold
Jones and Doust[164]	Breathing frequency breakpoint

Table IV. Criteria used to define the different thresholds (adapted from Tokmakidis,[126] with permission)

Reference	Threshold	Criteria
Invasive methods		
Holmann[152]	OEPL	Non-linear increase of [La]
Farrell et al.[18]	OPLA	Rupture of the [La] curve
Foxdal et al.[169]	OPLA	[La] of 4.0 mmol/L
Sjödin and Jacobs[134]	OBLA	[La] of 4.0 mmol/L
Kinderman et al.[140]	LT	[La] of 2.0 mmol/L
Reinhard et al.[154]	LT	2 standard deviations above resting [La]
Ivy et al.[133]	LT	Before onset of [La] breakpoint
Hughson and Green[170]	LT	0.5 mmol/L above resting [La]
Hagberg and Coyle[171]	LT	1 mmol/L above 40-60% $\dot{V}O_{2max}$
Hurley et al.[166]	LT	[La] of 2.5 mmol/L
Sucec et al.[172]	LT	Abrupt and sustained [La] increase
Worms et al.[165]	LT	[La] of 3.0 mmol/L
Yoshida et al.[167]	LT	1 mmol/L above resting [La]
Coyle et al.[173]	LT	1.0 mmol/L above baseline [La]
Cheng et al.[174]	LT	Distance max from [La] curve to the line formed by its two endpoints
Skinner and McLellan[141]	AT	First increase of [La] (2 mmol/L)
	AnT	Second increase of [La] (4 mmol/L)
Keul et al.[175]	IAT	[La] tangent at 45°
Simon et al.[176]	IAT	[La] tangent at 51°
Stegmann et al.[135]	IAT	[La] tangent with [La] recovery curve where [La] is equal to the value at the end of exercise
Bunc et al.[177]	IAT	See section 2.1.1 in text
LaFontaine et al.[142]	MSS	[La] of 2.2 mmol/L
Palmer et al.[178]	MLSS	Change of <1.0 mmol/L in [La] during SSE
Tegtbur et al.[150]	LMS	Minimum [La] during MET after HIE
Non-invasive methods		
Holmann[152]	POW	$\dot{V}E$ tangent at 45°
Wasserman and McIlroy[153]	AnT	Abrupt increase in RER
Wasserman et al.[128]	AnT	Increase in $\dot{V}E$ and $\dot{V}CO_2$
Davis et al.[179]	AnT	Abrupt increase in FEO_2
Davis et al.[180]	AnT	Increase in $\dot{V}E/\dot{V}O_2$ but not in $\dot{V}E/\dot{V}CO_2$
Moritani and DeVries[181]	AnT	IEMG breakpoint
Conconi et al.[156]	AnT	Deflection point of HR
Skinner and McLellan[141]	AT	First and second $\dot{V}E$ breakpoint
Reinhard et al.[154]	TDMA	Minimum $\dot{V}E/\dot{V}O_2$
Hugues et al.[182]	VT	$\dot{V}E$ breakpoint
James et al.[183]	AnT	Disproportionate increase in BF
Chicharro et al.[163]	AnT	First increase in Cl^- or Na^+ in saliva
Jones and Doust[164]	VT	$\dot{V}CO_2$ breakpoint
	BFB	Disproportionate increase in BF
Snyder et al.[184]	MLSS	$\%HR_{max}$ during SSE
Palmer et al.[178]	MLSS	RPE of 12

AnT = anaerobic threshold; **AT** = aerobic threshold; **BF** = breathing frequency; **BFB** = breathing frequency breakpoint; **FEO_2** = expired fraction of oxygen; **HIE** = high-intensity exercise; **HR** = heart rate; **$\%HR_{max}$** = percentage of maximal heart rate; **IAT** = individual anaerobic threshold; **IEMG** = integrated electromyogram; **[La]** = lactate concentration; **LMS** = lactate minimum speed; **LT**= lactate threshold; **max** = maximum; **MET** = multistage exercise test; **MLSS** = maximal lactate steady state; **MSS** = maximal steady state; **OBLA** = onset of blood lactate accumulation; **OEPL** = oxygen endurance performance limit; **OPLA** = onset of plasma lactate accumulation; **POW** = point of optimum ventilatory efficiency; **RER** = respiratory exchange ratio; **RPE** = rated perceived exertion; **SSE** = steady-state exercise; **TDMA** = threshold of decompensated metabolic acidosis; **$\dot{V}CO_2$** = volume of carbon dioxide eliminated per minute; **$\dot{V}E$** = minute ventilation; **$\dot{V}O_2$** = oxygen uptake; **$\dot{V}O_{2max}$** = maximal oxygen uptake; **VT** = ventilatory threshold.

2.1.3 Heart Rate Threshold

Wyndham et al.[193] showed that the heart rate–power relationship during incremental exercise is sigmoidal, with a linear component in the middle and a plateau at work loads close to the maximal. Conconi et al.[156] have observed that the point at which the heart rate–power relationship deviates from linearity (deflection point) occurs in the same range of power to the point at which there is an exponential increase in $[La^-]_b$. They also proposed that a non-invasive field test could be used to detect this deflection point. Despite the fact that the Conconi test is used by some athletes and coaches, there is considerable criticism of the method in the scientific literature.[194-204]

The main difficulty concerns the concept of a deflection point itself, since several studies failed to detect it systematically in all participants, either during running or cycling.[143,194-199] A number of authors have therefore questioned the physiological existence of the deflection point, and have suggested that it is an artefact dependent on the protocol.[200] Indeed, the original method published in 1982 was based on a testing procedure which enforces a plateau in heart rate.[126,205] The short-distance (200m) running speed increment yields more heart rate values at high speed, since time of the stages decreases when speed increases.

To control this methodological bias, Conconi et al.[206] have modified their procedure by adopting an incremental exercise test based on a fixed time protocol, instead of a fixed distance. Bourgois and Vrijens[207] used this protocol and took into account the new recommendations of Conconi et al.[206] to assess the deflection point in rowers. They were effectively able to detect a heart rate deflection point in all participants. Nonetheless, the debate is not closed, since it still has to be determined if the deflection point can be used as a non-invasive measure of the AT.

From the initial work of Conconi et al.,[156] there is a very strong relationship between the two variables, heart rate deflection and the LT (r = 0.99). Although some authors have since provided support,[208-210] numerous other studies have failed to establish a relationship.[195,197,199,201-205] The studies of Jones and Doust,[199] and Bourgois and Vrijens[207] are particularly interesting, in that they scrupulously respect the original[156] and the modified[206] protocol of Conconi and colleagues. Both studies concluded that this test is not valid for the non-invasive estimation of the AT, since the velocity[199] and the power[207] associated with the deflection point overestimates the velocity or power associated with the lactate turnpoint by 13 to 28%. Furthermore, they both demonstrated that continuous exercise close to the deflection point leads to significant accumulation of blood lactate (8.1 ± 1.8 and 10.4 ± 3.10 mmol/L, respectively), and rapid development of fatigue (time to exhaustion = 15.9 ± 6.7 and 17.5 ± 11.1 min, respectively).

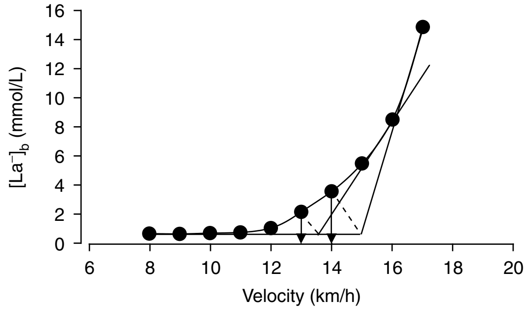

Fig. 7. Effect of tracing the tangent from different points on the determination of anaerobic threshold (AT) according to the algorithm of Bunc et al.[177] AT is defined as the intersection between the exponential regression of the lactate curve and the bisector of the tangents on the upper and lower parts of the regression. **$[La^-]_b$** = blood lactate concentration.

2.2 Constant-Duration Tests

The kinetics of muscle lactate concentration and $[La^-]_b$ are not superimposable, both during and after exercise, and even at very low intensities.[131,211,212] This phenomenon has been theorised by Brooks,[213] who suggested that $[La^-]_b$ reflects, at any given time, the difference between lactate production, mainly by the muscle but also by the liver, intestine and skin, and lactate utilisation, mainly by the liver but also by the heart and skeletal muscles.[214] During CPT, $[La^-]_b$ over time is strongly dependent on the exercise intensity.[155]

During low-intensity exercise, there is an initial rise, a brief plateau, and finally a decrease of $[La^-]_b$. During high-intensity exercise, $[La^-]_b$ shows a sustained increase up to and sometimes beyond the end of exercise. Logically, there exists an exercise intensity at which $[La^-]_b$ increases progressively to a steady state. By definition, the MLSS is the maximal exercise intensity where an equilibrium between the rate of appearance and the rate of disappearance of lactate in the blood is still maintained.[213]

In most studies, the MLSS is located between 70 and 80% of $\dot{V}O_{2max}$.[215-224] However, some authors have observed a MLSS at 65% of $\dot{V}O_{2max}$,[225] while others reported intensities equal to or above 85% of $\dot{V}O_{2max}$.[226,227] Beneke[151] has reported a lower workload and $[La^-]_b$ at MLSS when compared with the 4 mmol/L threshold or the individual anaerobic threshold (255 ± 17, 287 ± 20 and 287 ± 25W, 3.0 ± 0.6, 4.0 ± 0 and 4.2 ± 0.8 mmol/L, respectively; $p < 0.001$), suggesting that, in rowing, these two AT do not represent the MLSS.

The determination of the MLSS usually requires 4 or 5 CDT of up to 30 minutes duration, performed at exercise intensities between 50 and 90% of $\dot{V}O_{2max}$.[151,155,166,215,228,229] The intention is to establish the highest exercise intensity where $[La^-]_b$ increases by no more than 1.0 mmol/L between 10 to 30 minutes.[184] McLellan and Jacobs[230] proposed a slightly different algorithm to determine MLSS. Participants performed an incremental test and three CDT of 60 minutes. The exercise intensity of the first CDT is the power or velocity corresponding to a $[La^-]_b$ of 4 mmol/L during the incremental test. The workload of the two remaining CDT is adjusted by increments of ±2.5% in order to identify the highest exercise intensity for which $[La^-]_b$ variations between 10 and 60 minutes are lower than 0.75 mmol/L.

To improve the accessibility of this method, Billat et al.[221] suggested that MLSS could be estimated from only two bouts of 20 minutes performed at 65 and 80% of $\dot{V}O_{2max}$ (with each bout separated by 40 minutes of complete rest). The differential values of $[La^-]_b$ between the 20th and the 5th minute of each bout can be plotted against velocity. The MLSS, obtained by interpolation is the velocity for which the differential value is equal to zero.

This method is simple, accessible and has the advantage of not significantly disrupting an athlete's training schedule, since it is submaximal and non-exhaustive. However, its validity can be questioned. The method relies on the assumption that the $[La^-]_b$-power relationship is linear. Hughson et al.[137] and Oyono-Enguelle et al.[220] have shown that the $[La^-]_b$-power relationship describes an exponential curve. Consequently, it is not certain that the velocity measured by the approach of Billat et al.[221] corresponds to the MLSS. According to Billat,[138] this methodological consideration (i.e. non-linearity of the $[La^-]_b$-power relationship) can be controlled by choosing two velocities close to each other. Then the arc of the exponential relationship between $[La^-]_b$ and power tends to a straight line, which minimises the error of estimation inherent to the interpolation procedure. However, this involves a high risk of distortion, since a slight error of measurement in $[La^-]_b$ can adversely influence the estimation of the MLSS.

Based on the work of Davis and Gass,[231] Tegtbur et al.[150] have developed the lactate minimum test (LMT) in order to estimate the MLSS in a single testing session. The LMT is a treadmill multistage test performed immediately after supramaximal exercise leading to high blood lactate values. After a small rest period to allow for equilibrium between muscle and $[La^-]_b$, the multistage test begins. At intensities below MLSS, the lactate removal rate exceeds the production rate and $[La^-]_b$ decreases. However, when the exercise intensity is beyond the MLSS, the lactate production rate exceeds the rate of removal and $[La^-]_b$ increases. The lower $[La^-]_b$ value is associated with the MLSS and the corresponding speed is referred to as the lactate minimum speed (LMS). The procedure has been criticised because of difficulties in its standardisation.[232,233] $[La^-]_b$ after initial supramaximal loads has to be sufficiently high without imposing undue fatigue before the multistage test (8 mmol/L is suggested by Carter et al.[233]). Moreover, rest duration between these two bouts of exercise and stage duration during the incremental test have to be long enough to ensure blood lactate equilibrium while avoiding full recovery to resting values which would make it impossible to identify the passage from removal phase to production phase corresponding to MLSS. Initial intensity and incrementation as well as stage duration also appear to affect LMS estimates.[233] With an additional pre-test, MacIntosh et al.[234] appear to have solved some of these problems. Their study showed similar mean values between MLSS and LMS assessed with the LMT but there were a few obvious individual differences.

2.3 Practical Issues

The scientific literature of the two last decades abounds with studies showing that the AT is significantly related to various types of performances [235,236] and is a better predictor of performance in long-distance events than $\dot{V}O_{2max}$.[18,167,171,194] Although there is a quantitative accumulation of experimental data supporting this point of view, some methodological considerations raise doubts about validity. As is the case for all biological indices, the units used to describe the AT are important. When expressed in m/min, km/h or ml/min/kg, the AT does not measure solely aerobic endurance, but also $\dot{V}O_{2max}$ and the mechanical efficiency. Indeed, the higher the $\dot{V}O_{2max}$, the higher the AT in ml/min/kg, and the higher the mechanical efficiency, the higher the AT in m/min, for the same capacity to accumulate lactate. If AT is to be an indicator of aerobic endurance alone, it has to be expressed as $\%\dot{V}O_{2max}$. Then, when expressed in $\%\dot{V}O_{2max}$, the AT is no better a predictor of performance than $\dot{V}O_{2max}$ alone.[126,237-239]

Holmann et al.[240] suggested that the improvement in performance in long-distance events is better when the training intensity is prescribed from the AT instead of from the maximal heart rate or the $\dot{V}O_{2max}$. Effectively, numerous studies have reported that training at an intensity near the AT induces a rightward shift of the lactate curve and a concomitant increase in AT, either in $\dot{V}O_{2max}$ or in $\%\dot{V}O_{2max}$.[180,241-245] A meta-analysis including 85 experimental groups from 34 studies has concluded that training at an intensity near the AT is an adequate stimulus for improving the AT for sedentary individuals.[246] However, a higher intensity is necessary to increase the AT with conditioned individuals.[246] Since the minimal stimulus required to improve the $\dot{V}O_{2max}$[247] or the AT[246] depends on the initial level of fitness of individuals, it is not possible to conclude that training at the intensity corresponding to the AT represents the optimal means to improve one's performance in endurance events.

Recently, Tokmakidis et al.[185] have compared various methods and criteria used to identify the AT. It appears that there is no unique intensity corresponding to the AT, since their results ranged from 79.40 (1 mmol/L above baseline $[La^-]_b$[173]) to 91.91% of $\dot{V}O_{2max}$ (slope index with a fixed tangent[137]). Independently of the method or criteria used for their identification, all these AT indices provided the same information; they reflected the displacements of the $[La^-]_b$ curve on the x-axis. This explains why, despite the large variability observed by Tokmakidis et al.,[185] all the AT are highly correlated with one another and with performance ($r > 0.90$).

In conclusion, the AT may not be the optimal training intensity for endurance athletes. However, given that the AT does change with training, it may be a useful tool in monitoring changes in response to a training programme. Jones and Ehrsam[143] have suggested that the terminology associated with the AT should be abandoned, and that scientists and coaches should focus on an arbitrary point on the $[La^-]_b$ curve (at a given $\%\dot{V}O_{2max}$) to follow its displacements. This would free the AT from a somewhat troubled past and allow recognition of the properties of the $[La^-]_b$ curve in the prediction of performance in long-distance events.

3. Conclusion

Aerobic endurance represents the ability to sustain a high $\%\dot{V}O_{2max}$ for a long period of time.[9-12] Since it represents one of the parameters of performance in long-distance events[7,8] and is independent of $\dot{V}O_{2max}$,[12] aerobic endurance must be assessed with specific tools. This review has shown that the methods of determination are numerous. Although indirect methods like the AT are very commonly used in the physiological testing of elite athletes, their superiority against direct methods in terms of validity and reliability is not established. Future research should focus on the comparison between these methods to determine which of them correlates the most with performance in long-distance events. Efforts should be made to integrate them into a multi-regression approach in order to determine the relative importance of aerobic endurance and other parameters in the prediction of performance in long-distance events according to the duration of the event, gender and the level of practice. Finally, health benefits of physical activity are often measured with reference to $\dot{V}O_{2max}$,[248] but little is known about the specific effect of aerobic endurance improvement on cardiovascular disease risk factors, while it represents one parameter of aerobic fitness.

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