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Failure to obtain a unique threshold on the blood lactate concentration curve during exercise

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Abstract The purpose of this study was to compare various methods and criteria used to identify the anaerobic threshold (AT), and to correlate the AT obtained with each other and with running performance. Furthermore, a number of additional points throughout the entire range of lactate concentrations [La$^-$] were obtained and correlated with performance. A group of 19 runners [mean age 33.7 (SD 9.6) years, height 173 (SD 6.3) cm, body mass 68.3 (SD 5.4) kg, maximal O_2 uptake ($\dot{V}O_{2\,max}$) 55.2 (SD 5.9) ml · kg^{-1} · min^{-1}] performed a maximal multistage treadmill test (1 km · h^{-1} every 3.5 min) with blood sampling at the end of each stage while running. All AT points selected (visual [La$^-$], 4 mmol · l^{-1} [La$^-$], 1 mmol · l^{-1} above baseline, log-log breakpoint, and 45° tangent to the exponential regression) were highly correlated one with another and with performance ($r > 0.90$) even when there were many differences among the AT ($P < 0.05$). The additional points (ranging from 3 to 8 mmol · l^{-1} [La$^-$], 1 to 6 mmol · l^{-1} [La$^-$] above the baseline, and 30 to 70° tangent to the exponential curve of [La$^-$]) were also highly correlated with performance ($r > 0.90$). These results failed to demonstrate a distinct AT because many points of the curve provided similar information. Intercorrelations and correlations between AT and performance were, however, reduced when AT were expressed as the percentage of maximal treadmill speed obtained at AT or percentage of $\dot{V}O_{2\,max}$. This would indicate that different attributes of aerobic performance (i.e. maximal aerobic power, running economy and endurance) are measured when manipulating units. Thus, coaches should be aware of these results when they prescribe an intensity for training and concentrate more on the physiological consequences of a chosen [La$^-$] rather than on a "threshold".

Key words Lactate threshold · Onset of blood lactate accumulation · Running performance

Introduction

It has been suggested that the onset of metabolic acidosis within working muscles at a certain intensity of incremental exercise implies a unique threshold (Wasserman et al. 1973) where anaerobic metabolism begins to supplement aerobic metabolism. This transition, however, has been thoroughly disputed (Yeh et al. 1983; Brooks 1985; Hughson et al. 1987). In spite of the dispute, the anaerobic threshold (AT) is commonly used and many studies have indicated that AT can be used to predict accurately endurance running performance, characterize endurance athletes, determine a relative training intensity and evaluate training effects (Davis et al. 1979; Farrel et al. 1979; Sjödin and Jacobs 1981; Yoshida et al. 1987; Weltman 1995).

A problem arises because according to the AT concept, AT should only appear once; on the contrary, the wide range of techniques used and criteria found in the literature have sometimes produced differing AT. Some of these criteria included:

1. The conventional determination of abrupt sustained increases in blood lactate concentration ([La$^-$]; Davis et al. 1976)
2. The intercept of two linear regressions computed for the lower and higher regions of the log-log transformation of the [La$^-$] and oxygen uptake ($\dot{V}O_2$) coordinates (Beaver et al. 1985)
3. The slope index or the 45° tangent to an exponential regression curve (Hughson et al. 1987) as an alternative to AT
4. The point estimation with a selected tangent of 45° or 51° to a 3rd degree polynomial regression fitting of the [La$^-$] curve (Keul et al. 1979)

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5. A fixed [La$^-$] at 4 mmol · l^{-1} or 2 mmol · l^{-1} (Sjödin and Jacobs 1981)
6. A [La$^-$] of 1 mmol · l^{-1} above the resting level (Yoshida et al. 1987), or 1 mmol · l^{-1} above the exercise baseline (Coyle et al. 1983).

The purpose of this study was to compare various techniques that have been previously designed to assess AT and to correlate the AT obtained with each other as well as with running performance. In addition to AT, a wide range of different points throughout the entire [La$^-$] curve were obtained and correlated with performance. Regardless of the conceptual problems associated with the AT, it seemed crucial to examine how well the various approaches were related to performance. From a practical point of view, the latter was important to identify the best predictor of running performance.

In this paper, the expression AT has been based on its common use as seen in the literature and describes an estimation of a breakpoint on the blood [La$^-$] curve as a function of exercise intensity. The term *anaerobic*, although its use has been disputed (Brooks 1985; Hughson et al. 1987; Katz and Sahlin 1990; Stainsby and Brooks 1990), will not be thoroughly discussed. The term *threshold* is directly questioned by the results of this study.

Methods

Subjects

A group of 19 male volunteer runners gave their written consent to participate in this study after having completed a 15-km road race and after being informed of all risks and stress symptoms associated with the experiments. The procedures followed were in accordance with the Helsinki Declaration of 1975. The subjects had the following characteristics: mean age 33.7 (SD 9.6) years, height 173 (SD 6.3) cm, bodymass 68.3 (SD 5.4) kg, maximal O$_2$ uptake, ($\dot{V}O_{2\,max}$) 55.2 (SD 5.9) ml · kg^{-1} · min^{-1}, 15-km running speed 13.76 (SD 2.5) km · h^{-1}. The competition running conditions were similar throughout the 15-km race (temperature 18°C, relative humidity 43%) which gave the main performance criterion. For most of the subjects (n = 13), a marathon performance (42.195 km) was also obtained from the Montreal Marathon (temperature 20°C, relative humidity 75%). In addition, performances available from 10-km (n = 11) and 20-km races (n = 16) within a period of 3 months before or after the laboratory experiments were recorded and provided useful information. It is recognized that possible alterations in physical fitness within a period of 3 months may have affected the relationship between performance and AT.

Laboratory measurements

All measurements were performed in the morning within a period of 2 weeks after the 15-km race. The subjects were asked to decrease the amount of their training one day before the tests and keep to regular eating habits with overnight fasting. The subjects warmed up using their preferred submaximal running speed on a calibrated treadmill, which allowed them to familiarize themselves with the equipment. After the warm-up, a Rudolf non-rebreathing valve was fitted to each subject for the exercise test.The initial speed of the horizontal treadmill was set according to the subject's fitness level and ranged from 9 to 11 km · h^{-1}. Even though an exercise duration of 3 min has seemed sufficient to reveal the curve of [La$^-$] (Wasserman et al. 1973; Urhausen et al. 1993; Beneke 1995), the speed was increased by 1 km · h^{-1} every 3.5 min until exhaustion. The speed achieved during this protocol was recorded at a maximal decimal point (this occurred when the stage was not completed, i.e. running 20 km · h^{-1} for 1 min giving a score of 19.3 km · h^{-1}). Expired minute ventilation, oxygen consumption and carbon dioxide production were continuously measured throughout exercise by a Sensor Medics Horizon MMC System. The metabolic cart was calibrated with standard reference gases prior to each treadmill test.

Arterialized fingertip blood samples for the determination of [La$^-$] were obtained at rest and during exercise. The fingertip was cleaned with alcohol, dried, and pricked with an autolet mechanism. The samples during exercise were obtained without any problems while the subject was running, after the 3rd minute of each speed increment to avoid interference with lactate kinetics which can occur during intermittent exercise. Some subjects exceeded the 30-s time-limit-period for blood sampling (by about 5 to 8 s), and the running speed was increased as soon as blood sampling was completed. Using a micropipet, a blood sample of 50 µl was drawn and immediately deproteinized with 0.6 mol · l^{-1} cold perchloric acid. This solution was centrifuged for 5 min at 1500 rpm and the supernatant was stored at −80°C to be analysed enzymatically for [La$^-$] (Behring Diagnostics) after two weeks.

Threshold estimation

Conventional [La$^-$] threshold

The conventional lactate threshold ([La$^-$]$_{convent}$) was determined subjectively by the authors from the plots of blood [La$^-$] as a function of running speed and using the abrupt sustained increase in blood [La$^-$] as the criterion for the beginning of metabolic acidosis (Davis et al. 1976). Any disagreement among the authors was resolved by discussion.

The log-log model

For the [La$^-$]$_{log}$ (defined by a log-log model), a turning point was determined subjectively from plots of the log transformed coordinates. The two data sets, below and above this point, were then each fitted by a linear regression:

$$\log y = \mathrm{a} + \mathrm{b} \log x \tag{1}$$

where y stands for [La$^-$], x for running speed and a and b are constants. Eventually, a mathematical solution for $[La^-]_{log}$, according to Beaver et al. (1985), was assessed by the intersection of the two lines:

$$[La^-]_{x,\log} = (\mathrm{a}_1 - \mathrm{a}_2)/(\mathrm{b}_2 - \mathrm{b}_1) \tag{2}$$

where the suffix x gives the speed at $[La^-]_{log}$, a$_1$ and a$_2$ are the intercepts, and b$_1$ and b$_2$ are the slopes of the linear segments below and above the turning point.

The slope index model with an individual tangent

For the individual tangent ($[La^-]_{TI}$), the [La$^-$] data were fitted by a continuous nonlinear regression as has been suggested by Hughson et al. (1987):

$$y = \mathrm{a} + \mathrm{b}\exp(cx) \tag{3}$$

where y stands for [La$^-$], x for speed and a, b and c are constants. To locate a point on the typical exponential curve given by Eq. 3, it is necessary to use a tangent. For instance, in this equation, the slope is given by:

$$dy/dx = \mathrm{bc}\exp(cx) \tag{4}$$

Furthermore, the choice of a tangent at a certain angle z can be expressed as $dy/dx = \tan z$, and the location of this tangent is given by:

$$[La^-]_{x,TI} = [\ln(\tan z/bc)]/c \tag{5}$$

where the suffix x gives the speed at the point of contact of the tangent, z is the angle defined by the slope of a linear regression using the right upper part of the [La$^-$] curve for each individual, and b and c the parameters of Eq. 3. Thus, Eq. 5 provides the $[La^-]_{TI}$.

The slope index model with a fixed tangent

Instead of defining the angle of the individual's slope as described above, some researchers have chosen arbitrarily a tangent of 45° (Hughson et al. 1987). Hence, the estimation of the 45° slope index ($[La^-]_{T45}$) given by:

$$[La^-]_{x,T45} = [\ln(\tan 45^\circ/bc)]/c \tag{6}$$

where the suffix x indicates the speed at the point of contact of the tangent, and b and c the parameters of Eq. 3.

Additional points were also obtained using Eq. 6 and tangents at 30, 40, 50, 60 and 70° throughout the entire range of the [La$^-$] curve.

The fixed lactate concentration

The onset of blood lactate accumulation during progressive exercise at a concentration of 4 mmol · l^{-1} is commonly used to define the threshold. In the present study, this point $[La^-]_{4\,mmol}$ was estimated from Eq. 3, and the substitution of the dependent variable Y by a value of 4 mmol · l^{-1}:

$$[La^-]_{x,\,4\,mmol} = (\ln(4\,mmol \cdot l^{-1} - a) - \ln b)/c \tag{7}$$

where the suffix x indicates the speed at which an [La$^-$] of 4 mmol · l^{-1} was observed and a, b, and c the parameters of Eq. 3.

Additional points using Eq. 7 and the [La$^-$] of 3, 5, 6, 7 and 8 mmol · l^{-1} over the entire range of the [La$^-$] curve were also obtained.

The lactate concentration of 1 mmol · l^{-1} above the baseline

It has been shown that a [La$^-$] of 1 mmol · l^{-1} above rest (Yoshida et al. 1987) as well as above the exercise baseline (Coyle et al. 1983) can be used as an objective AT criterion. In the present study, the [La$^-$] baseline corresponded to the mean of both the resting concentration and the exercise baseline (computed over the first few stages without any obvious [La$^-$] increment). This approach outweighed unexpected high [La$^-$] at the beginning of exercise. Thus, the 1 mmol · l^{-1} above [La$^-$] baseline ($[La^-]_{b+1\,mmol}$) estimation using Eq. 7 gave a preferable value since it combined rest with exercise baseline blood [La$^-$] concentrations.

Additional points using Eq. 7 and [La$^-$] concentrations of 2, 3, 4, 5, and 6 mmol · l^{-1} above the exercise baseline over the entire range of the [La$^-$] curve were also obtained.

Units of AT

The various AT were estimated in units of speed (kilometres per hour). Energy cost (i.e. $\dot{V}O_2$ millilitres per kilogram per minute during the last 30 s of each stage) and running speed were used to obtain the linear regression for each subject. This regression was then applied to convert speed units into $\dot{V}O_2$ units. The above units were expressed as percentages of maximal treadmill speed and $\dot{V}O_{2max}$ (%SPEED$_{max}$ and %$\dot{V}O_{2max}$). The additional points (i.e. values of 3, 5, 6, 7, 8 mmol · l^{-1} [La$^-$], the above baseline [La$^-$] of 2, 3, 4, 5, 6 mmol · l^{-1}, or the tangents at 30, 40, 50, 60, 70° to the exponential [La$^-$] curve) were only expressed and treated in speed units.

Statistical analyses

The Pearson correlation was used to investigate the relationship between the various AT as well as the relationship between these points and the average speed of running. A normal distribution of samples was confirmed by the Kolmogorov-Smirnov test. The differences between the various AT were examined by a one-way ANOVA for repeated measures and a posteriori contrasts were computed using the Tukey procedure.

Results

Comparisons among the various AT

The additional AT were different by definition. The repeated measures ANOVA applied to a normally distributed sample revealed significant differences among the AT values (Table 1). Placed in rank order, $[La^-]_{log}$ and $[La^-]_{TI}$ were consistently found to reveal the lowest and highest values (15% difference; see also Fig. 1) and this order was not affected by the unit chosen to express the threshold (2.15 km · h^{-1}, 12.9 %SPEED$_{max}$, 6.9 ml · kg^{-1} · min^{-1} or 12.5 %$\dot{V}O_{2max}$). However, this was not true when the comparison was focused on the inter-correlation of the AT (Table 2). Absolute units such as kilometres per hour or millilitres per kilogram per minute yielded high inter-correlations. Correlations were slightly lower for the millilitre per kilogram per minute units (r = 0.85–0.97) than the kilometres per hour units (r = 0.94–0.99). This relationship decreased when the AT were expressed in %SPEED$_{max}$ or %$\dot{V}O_2$ (Table 2).

Correlations between AT and running performance

Whatever the point throughout the entire range of the [La$^-$] curve, a high correlation was obtained with the performance criterion in the 15-km race (r > 0.92, Table 3). Correlations were also high with the running performance in 10, 20 and 42.2 km (Table 3). Compared with the other methods, no given method significantly affected the correlations between its corresponding AT and a given performance velocity. The magnitude of these correlations was, however, directly affected by the unit chosen (Table 4). Indeed, when the AT were expressed in absolute units, high correlations were obtained and the speed unit (kilometres per hour) appeared to be better than the $\dot{V}O_2$ unit (millilitres per kilogram per minute) (i.e. $r \cong 0.87$–0.95 vs $r \cong 0.66$–0.86 for the 15-km race and $r \cong 0.77$–0.94 vs $r \cong 0.42$–0.83 for the 10, 20 and 42.2 km). On the other hand, when the AT were expressed in relative units of %SPEED$_{max}$ or %$\dot{V}O_{2max}$, non-significant correlations were obtained, close to 0 or even negative (Table 4).

Table 1 Anaerobic thresholds estimated using various methods and expressed in different units. $\%SPEED_{max}$ percentage of maximal treadmill speed, $\%\dot{V}O_{2max}$ percentage of maximal O_2 uptake. Definitions of the abbreviations for anaerobic threshold are given in Methods

	$[La^-]_{log}$	$[La^-]_{b+1\ mmol}$	$[La^-]_{convent}$	$[La^-]_{T45}$	$[La^-]_{4\ mmol}$	$[La^-]_{TI}$
Speed ($km \cdot h^{-1}$)						
Mean	13.19	13.27	13.32	13.76	14.30	15.34
SD	2.08	2.19	1.92	2.42	2.42	2.24
Minimum	9.95	9.39	10.00	10.09	10.58	11.72
Maximum	17.23	17.12	17.00	18.33	18.35	19.74
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)						
Mean	43.87	44.01	44.17	45.64	47.42	50.84
SD	4.99	4.94	4.39	5.74	5.55	4.97
Minimum	35.79	35.72	37.17	34.90	37.24	41.07
Maximum	50.65	52.45	51.19	54.36	56.64	59.83
$\%SPEED_{max}$						
Mean	79.60	79.88	80.41	82.69	86.01	92.49
SD	6.36	4.35	4.46	4.11	4.31	2.69
Minimum	69.34	71.11	71.86	75.25	78.79	86.76
Maximum	93.88	86.62	88.05	91.64	93.31	95.48
$\%\dot{V}O_{2max}$						
Mean	79.54	79.40	79.96	82.32	85.62	91.91
SD	4.79	6.57	5.35	4.25	4.63	3.34
Minimum	72.26	66.76	69.35	73.88	76.51	85.01
Maximum	87.31	89.84	87.49	91.54	92.89	96.32

$P < 0.05$ is the difference of 0.645 $km \cdot h^{-1}$, 2.15 $ml \cdot kg^{-1} \cdot min^{-1}$, 3.78 $\%SPEED_{max}$ and 3.78 $\%\dot{V}O_{2max}$

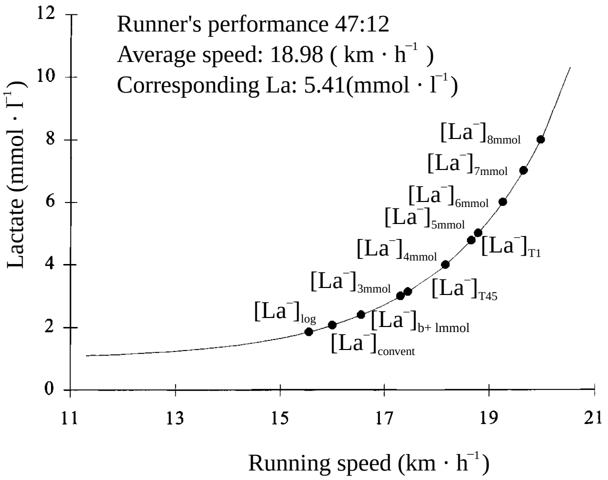

Fig. 1 The estimation of various anaerobic threshold points on the blood lactate concentration ($[La^-]$) curve of a runner using different methods. The additional points of 3, 5, 6, 7, and 8 $mmol \cdot l^{-1}$ of $[La^-]$ are also illustrated together with the performance data of the runner. Please refer to the methods for further details of definitions. The *curve* was drawn using Eq. 3

Discussion

Comparison of selected AT

If we suppose that there is a unique threshold, it must be located on the $[La^-]$ curve. This was difficult to distinguish from the points obtained over the entire range of the $[La^-]$ curve of the present study (Fig. 1). The points were highly correlated with the average speed of the various running performances (Table 3, 4). Yoshida et al. (1987) have come to similar conclusions with four AT points. Along the same lines, the four different AT (La^- breakpoint, 2, 2.5 and 4 $mmol \cdot l^{-1}$ $[La^-]$) used by Weltman et al. (1987) have yielded almost identical correlations with performance. The present study extended this notion and revealed high correlations with 5, 6, 7 and 8 $mmol \cdot l^{-1}$ of fixed $[La^-]$. Other researchers, using only one or two AT have also reported high correlations with performance (Lafontaine et al. 1981; Sjödin and Jacobs 1981; Kumagai et al. 1982; Lehmann et al. 1983; Tanaka and Matsuura 1984; Heck et al. 1985; Sjödin and Svedenhag 1985; Fay et al. 1989). This is in agreement with our results. However, our study failed to identify a unique AT. This is because the additional $[La^-]$ as well as the various AT were different even when they were well correlated with each other and with performance (Tables 1–4).

Although the AT concept requires a unique point related to the training status of the individual, no single method and no unique AT appear to exist. Apart from the AT concept, however, a selected $[La^-]$ relative to the runner's ability may dictate an appropriate intensity for training. The individual anaerobic threshold (IAT) and the maximal lactate steady state (MLSS) have seemed to be promising factors in endurance training (Urhausen et al. 1993), although there has been evidence that the IAT does not represent MLSS (Beneke 1995).

Determination of AT

To eliminate problems of subjectivity associated with the determination of AT, *objective* methods have gained popularity. This the case for [La$^-$]$_{4\ \mathrm{mmol}}$. The [La$^-$]$_{4\ \mathrm{mmol}}$ has been thought to present a different meaning for subjects who show different baseline or maximal [La$^-$] (Foster et al. 1986). The fact that a [La$^-$] of 2 mmol · l^{-1}, another fixed [La$^-$] criterion, is sometimes below the [La$^-$] baseline, further demonstrates the lack of individuality of such an approach. Moreover, the fixed [La$^-$] criteria, as well as some other methods, are not totally *objective* when the [La$^-$] curve is drawn by hand. The visual determination of the AT has tended to be replaced by fitting the [La$^-$] data to mathematical models. The [La$^-$] curve has been shown to fit the log-log model ([La$^-$]$_{\log}$) of Beaver et al. (1985) and the slope index model ([La$^-$]$_{T45}$) of Hughson et al. (1987). In the present

Table 2 Inter-correlations among the selected anaerobic thresholds using various methods and expressed in different units. Definitions of the abbreviations for anaerobic threshold are given in Methods. %$\dot{V}O_{2\max}$ percentage of maximal O_2 uptake, $\dot{V}O_2$ oxygen uptake, %SPEED$_{\max}$ percentage of maximal treadmill speed

	[La$^-$]$_{\mathrm{convent}}$	[La$^-$]$_{\log}$	[La$^-$]$_{TI}$	[La$^-$]$_{T45}$	[La$^-$]$_{4\ \mathrm{mmol}}$
Speed (km · h^{-1})					
[La$^-$]$_{\log}$	0.960***	–			
[La$^-$]$_{TI}$	0.960***	0.927***	–		
[La$^-$]$_{T45}$	0.958***	0.938***	0.987***	–	
[La$^-$]$_{4\ \mathrm{mmol}}$	0.964***	0.927***	0.978***	0.985***	–
[La$^-$]$_{b+1\ \mathrm{mmol}}$	0.970***	0.949***	0.977***	0.978***	0.989***
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})					
[La$^-$]$_{\log}$	0.907***	–			
[La$^-$]$_{TI}$	0.879***	0.851***	–		
[La$^-$]$_{T45}$	0.905***	0.859***	0.973***	–	
[La$^-$]$_{4\ \mathrm{mmol}}$	0.914***	0.849***	0.941***	0.966***	–
[La$^-$]$_{b+1\ \mathrm{mmol}}$	0.931***	0.875***	0.932***	0.957***	0.975***
%$\dot{V}O_{2\max}$					
[La$^-$]$_{\log}$	0.837***	–			
[La$^-$]$_{TI}$	0.677**	0.770***	–		
[La$^-$]$_{T45}$	0.427	0.618**	0.590**	–	
[La$^-$]$_{4\ \mathrm{mmol}}$	0.599*	0.617**	0.561*	0.802***	–
[La$^-$]$_{b+1\ \mathrm{mmol}}$	0.703**	0.769***	0.666**	0.698***	0.873***
%SPEED$_{\max}$					
[La$^-$]$_{\log}$	0.808***	–			
[La$^-$]$_{TI}$	0.692**	0.744***	–		
[La$^-$]$_{T45}$	0.565*	0.607**	0.673**	–	
[La$^-$]$_{4\ \mathrm{mmol}}$	0.693**	0.633**	0.637**	0.803***	–
[La$^-$]$_{b+1\ \mathrm{mmol}}$	0.798***	0.732***	0.723***	0.764***	0.895***

*** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$

Table 3 Correlation coefficients (r) between different points over the entire range of the blood lactate [La$^-$] curve and maximal oxygen uptake ($\dot{V}O_{2\max}$) and the average speed of various running performances. SPEED$_{\max}$ maximal treadmill speed. For definitions of abbreviations of the points examined on the blood [La$^-$] curve see Methods

	r					
	$\dot{V}O_{2\max}$ (ml · kg^{-1} · min^{-1}) ($n = 19$)	SPEED$_{\max}$ (km · h^{-1}) ($n = 19$)	15,000 m race (km · h^{-1}) ($n = 19$)	10,000 m race (km · h^{-1}) ($n = 11$)	20,000 m race (km · h^{-1}) ($n = 16$)	42,195 m race (km · h^{-1}) ($n = 16$)
$\dot{V}O_{2\max}$	1.000	0.866	0.864	0.743	0.886	0.856
SPEED$_{\max}$	0.866	1.000	0.960	0.932	0.919	0.961
[La$^-$]$_{3\ \mathrm{mmol}}$	0.756	0.928	0.930	0.929	0.889	0.907
[La$^-$]$_{5\ \mathrm{mmol}}$	0.819	0.968	0.949	0.934	0.911	0.917
[La$^-$]$_{6\ \mathrm{mmol}}$	0.826	0.973	0.949	0.932	0.910	0.915
[La$^-$]$_{7\ \mathrm{mmol}}$	0.831	0.976	0.948	0.930	0.908	0.913
[La$^-$]$_{8\ \mathrm{mmol}}$	0.834	0.977	0.946	0.928	0.905	0.911
[La$^-$]$_{b+2\ \mathrm{mmol}}$	0.813	0.962	0.942	0.922	0.907	0.907
[La$^-$]$_{b+3\ \mathrm{mmol}}$	0.825	0.968	0.944	0.922	0.908	0.905
[La$^-$]$_{b+4\ \mathrm{mmol}}$	0.831	0.972	0.944	0.922	0.907	0.904
[La$^-$]$_{b+5\ \mathrm{mmol}}$	0.834	0.975	0.943	0.921	0.905	0.903
[La$^-$]$_{b+6\ \mathrm{mmol}}$	0.836	0.976	0.942	0.921	0.903	0.902
[La$^-$]$_{T30}$	0.827	0.939	0.923	0.988	0.888	0.865
[La$^-$]$_{T40}$	0.837	0.957	0.934	0.900	0.899	0.880
[La$^-$]$_{T50}$	0.844	0.968	0.938	0.908	0.900	0.890
[La$^-$]$_{T60}$	0.845	0.974	0.936	0.913	0.896	0.839
[La$^-$]$_{T70}$	0.837	0.972	0.926	0.915	0.881	0.886

$P < 0.001$ for all the r values

Table 4 Correlation between the estimated anaerobic thresholds expressed in different units and the average speed of various running performances. For definition of abbreviations see Methods. %$\dot{V}O_{2max}$ percentage of $\dot{V}O_{2max}$; %SPEED$_{max}$ percentage of maximal treadmill speed

	r					
	$\dot{V}O_{2max}$ (ml · kg^{-1} · min^{-1}) (n = 19)	SPEED$_{max}$ (km · h^{-1}) (n = 19)	15,000 m race (km · h^{-1}) (n = 19)	10,000 m race (km · h^{-1}) (n = 11)	20,000 m race (km · h^{-1}) (n = 16)	42,195 m race (km · h^{-1}) (n = 13)
Speed (km · h^{-1})						
$[La^-]_{convert}$	0.778***	0.929***	0.921***	0.893***	0.869***	0.863***
$[La^-]_{log}$	0.738***	0.866***	0.868***	0.849***	0.827***	0.770**
$[La^-]_{TI}$	0.819***	0.979***	0.933***	0.906***	0.897***	0.906***
$[La^-]_{T45}$	0.842***	0.963***	0.937***	0.904***	0.900***	0.886***
$[La^-]_{4\ mmol}$	0.805***	0.960***	0.948***	0.937***	0.910***	0.918***
$[La^-]_{b+1\ mmol}$	0.788***	0.951***	0.935***	0.923***	0.904***	0.914***
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})						
$[La^-]_{convert}$	0.795***	0.653**	0.718***	0.557	0.687**	0.520
$[La^-]_{log}$	0.723***	0.597**	0.655**	0.518	0.661**	0.417
$[La^-]_{TI}$	0.938***	0.838***	0.834***	0.695*	0.829***	0.711**
$[La^-]_{T45}$	0.906***	0.797***	0.811***	0.656*	0.814***	0.668*
$[La^-]_{4\ mmol}$	0.883***	0.813***	0.855***	0.743**	0.834***	0.729**
$[La^-]_{b+1\ mmol}$	0.851***	0.773***	0.812***	0.692**	0.797***	0.653*
%$\dot{V}O_{2max}$						
$[La^-]_{convert}$	−0.428	−0.413	−0.319	−0.194	−0.280	−0.302
$[La^-]_{log}$	−0.298	−0.317	−0.214	−0.170	−0.120	−0.314
$[La^-]_{TI}$	−0.437	−0.300	−0.312	−0.050	−0.357	−0.356
$[La^-]_{T45}$	0.135	0.144	0.176	0.186	0.158	−0.019
$[La^-]_{4\ mmol}$	−0.064	0.050	0.139	0.212	0.057	0.018
$[La^-]_{b+1\ mmol}$	−0.199	−0.102	−0.031	0.095	−0.028	−0.164
%SPEED$_{max}$						
$[La^-]_{convert}$	−0.297	−0.260	−0.172	−0.035	−0.220	−0.221
$[La^-]_{log}$	−0.148	−0.149	−0.068	−0.024	−0.042	−0.210
$[La^-]_{TI}$	−0.306	−0.192	−0.219	0.056	−0.300	−0.300
$[La^-]_{T45}$	0.404	0.403	0.429	0.415	0.319	0.128
$[La^-]_{4\ mmol}$	0.157	0.277	0.352	0.404	0.186	0.161
$[La^-]_{b+1\ mmol}$	0.026	0.161	0.217	0.325	0.109	−0.028

***$P < 0.001$, **$P < 0.01$, *$P < 0.05$

study as well as in other studies (Hughson et al. 1987; Tokmakidis and Léger 1992), the slope index model appeared to be slightly superior because of smaller residual errors. As a result of this observation, and since the slope index model is based on a mono-segmental curvilinear regression as opposed to a bi-segmental regression of the log-log model, Hughson et al. (1987) have claimed that there was no real threshold on the $[La^-]$ curve. The better fit of the slope index model should not be used as proof against the existence of a threshold. There has also been evidence that a modified log-log model presents a better fit than the slope index model (Myers et al. 1994). The good fit of the bi-segmental log-log model cannot confirm the existence of an AT either because a tri-segmental model can be even better.

The use of a fixed 45° tangent might not suit each individual and has been shown to be directly and arbitrarily affected by the size and the units of the x and y axes (Heck et al. 1985) – unless everyone uses the same scale and units. It was thus decided to take the tangent corresponding to the slope of the right upper part of the $[La^-]$ curve to suit the tangent method to each individual. This was because in its ascending portion the $[La^-]$ curve shifts to the right for the fit individual as compared to the unfit one. The lower portion extends to the right and stays more or less parallel to the horizontal without affecting the AT on the abscissa. No significant improvement was found when predicting performance using this individualized tangent ($[La^-]_{TI}$) compared to the fixed tangent ($[La^-]_{T45}$) of Hughson et al. (1987). In fact, similar results were obtained using tangents ranging from $[La^-]_{T30}$ to $[La^-]_{T70}$ or any additional point to a $[La^-]$ of 5, 6, 7 or 8 mmol · l^{-1} on the $[La^-]$ curve (Tables 3, 4).

Physiological implications of training using AT

According to the AT concept (Wasserman et al. 1973; Davis et al. 1976; Beaver et al. 1985), this point on the $[La^-]$ curve should correspond to the capacities and limitations of the cardio-pulmonary system as well as to the optimal supply of energy using cytosol and mitochondrial enzyme activities. In addition, this point should correspond to the balance between the rate of muscle lactate formation, transmembrane exchange, and removal for oxidation. The results of the present study do not focus on the dispute involving lactate kinetics and the aerobic conditions of the muscle cell (see Katz and Sahlin 1990; Stainsby and Brooks 1990). They do question, however, the hypothesis of a representative threshold at a certain point in exercise. The methods used yield different AT which cannot represent the desired intracellular balance of metabolic procedures during exercise.

Furthermore, the blood [La$^-$] breakpoint has been considered as a useful tool in predicting endurance performance and designing training programmes (Weltman 1995). Our data indicated that the 4, 5, 6, 7, 8 mmol $\cdot$ l^{-1} [La$^-$] or any additional point on the [La$^-$] curve can serve as a performance index. This does not mean that the 7 or 8 mmol $\cdot$ l^{-1} [La$^-$] can be used in training despite its high correlation with performance. Therefore, the problem is not focused on the AT itself but on the significance of such a point; the knowledge of the physiological consequences of a chosen [La$^-$] is what counts and not the [La$^-$] itself. When examining how [La$^-$] determination can be used in training, the MLSS seems appropriate but it is hard to detect. The 4 mmol $\cdot$ l^{-1} [La$^-$] can also be used but not for everyone. Individuality must be respected and 3 or even the 5 mmol $\cdot$ l^{-1} [La$^-$] in some cases would be more suitable. If the coach knows the physiological meaning of the [La$^-$] and the associated consequences of intracellular acidosis, he can use this knowledge to conduct his training programmes better. He may also use a higher [La$^-$] if his goal is to have appropriate adaptation to a high intensity. Coaches should be aware of these results and choose their own specific [La$^-$] or concentrate on the shifting of the [La$^-$] curve to the right after training by using mathematical models.

The physiological mechanisms behind the AT concept

To our knowledge, there is no sufficient explanation for a single mechanism or a combination of mechanisms for the [La$^-$] threshold. Several factors which occur within the working muscle cell during progressive exercise including oxygen availability, substrate utilization, muscle temperature, motor unit recruitment order, catecholaminergic stimulation, and humoral or neurogenic engagement have been involved in the discussion concerning the AT concept (Tokmakids 1990). In addition, the blood [La$^-$] curve does not necessarily reflect the intracellular environment. Blood [La$^-$] is a balance between production and utilization. The fact that no unique AT was detected from our data does not prove that there is no threshold within the muscle cell.

If we take into consideration that lactate uptake is systematic, then the blood [La$^-$] may correspond to lactate production. This in turn could indicate that the adenosine triphosphate hydrolysis or the metabolic acidosis associated with exercise intensity represents the capacity of an individual (i.e. high performers' produce more energy and/or resist more in metabolic acidosis at a certain intensity of exercise). Thus, the training status which affects the intracellular processes of an individual may be displayed on the [La$^-$] curve or with many *AT* as in the case of the present study. The [La$^-$] breakpoint provides a practical solution. It has been found that the continuous process of metabolic acidosis (Dennis et al. 1992) or [La$^-$] increase (Yeh et al. 1983; Hughson et al. 1987) can better represent and describe the metabolic-physiological phenomena.

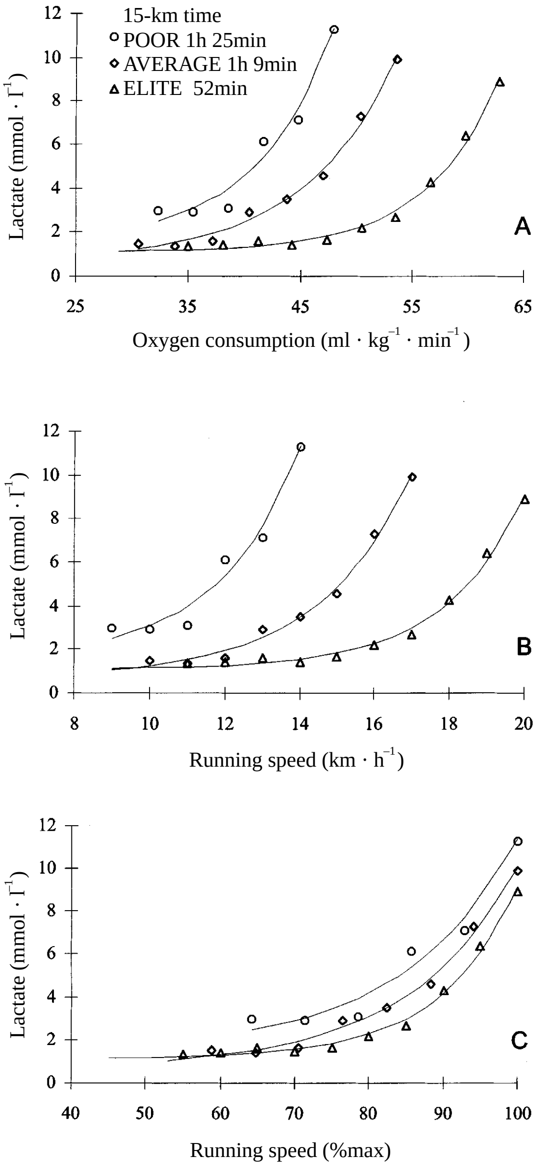

Fig. 2 The blood lactate concentration curves of three runners poor, average and elite, selected according to their 15-km performance time, come closer when they are plotted against oxygen consumption (**A**) compared to running speed (**B**) a difference attributable to running economy. The differences disappear when the speed units in (**B**) are expressed relative to the maximal treadmill speed (**C**). The individual 15-km running speeds were: poor 10.5, average 12.9, and elite 17.1 km $\cdot$ h^{-1}. *Curves* were drawn using Eq. 3

Consequences of expressing AT in various units

The AT may be expressed in units that represent a combination of aerobic power ($\dot{V}O_{2max}$), running economy and/or endurance. Endurance is defined as the ability of a runner to use and maintain for a long period of time as much of his aerobic capacity as he can (Tokmakidis et al. 1987). When this happens, the [La$^-$] curve shifts to the right. Keeping the range of the abscissa the same (Fig. 2), one can observe that the differences among the [La$^-$] curves of the three runners are reduced when speed units are transformed into $\dot{V}O_2$ units (see Fig. 2a, b). Differences in these curves are attributable to running economy. When AT is expressed in kilometres per hour, it represents a combination of $\dot{V}O_{2max}$, running economy and endurance and thus, large differences are disclosed among the three runners (Fig. 2b). When AT is normalized according to the maximal treadmill velocity and is expressed as %SPEED$_{max}$, the running economy and perhaps endurance are removed. This in turn, reduces the differences among the runners (Fig. 2c) and eliminates the correlation between AT and running performance (Table 4, see %$\dot{V}O_{2max}$ and %SPEED$_{max}$).

High correlations between the methods selected and performance were decreased when expressing AT in relative units such as %SPEED$_{max}$ or %$\dot{V}O_{2max}$ (correlations near to 0, see Table 4). The absolute speed units have been shown to yield better correlations than absolute $\dot{V}O_2$ units (Farrell et al. 1979; Palgi et al. 1984; Rotstein et al. 1984; Fay et al. 1989; Tokmakidis and Léger 1992). This is because each of these variable-unit combinations represent different components of running performance. It has been reported that some units of measurement represent more than one single basic component: $\dot{V}O_{2max}$, endurance, running economy, or energy cost of running per unit distance (Sjödin and Jacobs 1985; di Prampero et al. 1986; Peronnet et al. 1987). It would seem, therefore, that a combination of simple components yields better correlations with performance than any single component alone (Table 5).

Absolute speed units yield higher correlations than relative units because they depend both on maximal and endurance values. When AT was normalized for maximal speed or $\dot{V}O_2$ values, the net results were not well correlated with performance (Table 5). In fact, the AT point included that of $\dot{V}O_{2max}$ and indicated high correlations between AT (in kilometres per hour or millilitres per kilogram per minute) and $\dot{V}O_{2max}$ (Tables 4, 5). Thus, absolute AT was not independent of $\dot{V}O_{2max}$ as it has been considered (Davis et al. 1979). This becomes obvious when one takes into account the rightward shifting of the [La$^-$] curve which occurs during training. The rightward displacement of any AT point is partly due to the increase of the maximal speed or $\dot{V}O_{2max}$ values. Most of the time, when there is an increase in $\dot{V}O_{2max}$, there is also an increase in AT. The net AT displacement should be obtained by subtracting the displacement caused by the rise of $\dot{V}O_{2max}$. This could be attained when following intra-individual changes during training. The AT should be expressed as %$\dot{V}O_{2max}$ to

Table 5 Correlation coefficients between the anaerobic thresholds (AT) and running performance reported in the present study and in the literature indicating how different components of the unit of running performance affect correlation. $\dot{V}O_2$ Oxygen, uptake, %$\dot{V}O_{2max}$ percentage of maximal oxygen uptake, %SPEED$_{max}$ percentage of maximal speed. *YES* indicates the included and *NO* the excluded component of the AT unit that affects the correlation. Question mark (?) indicates uncertainty

AT - Units	Aerobic power	Running economy	Endurance[a]	Correlation (*r*)
Present study				15.00 km
Speed (km · h^{-1})	YES	YES	YES	0.95
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	YES	NO	?	0.86
%$\dot{V}O_{2max}$	NO	YES	?	0.35
%SPEED$_{max}$	NO	?	?	0.14
Farrel et al. (1979)				15.00 km
Speed (km · h^{-1}	YES	YES	YES	0.97
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1}	YES	NO	?	0.91
Kumagai et al. (1982)				16.09 km
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	YES	NO	?	0.83
%$\dot{V}O_{2max}$	NO	YES	?	0.11
Palgi et al. (1984)				2.00 km
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	YES	NO	?	0.77
%$\dot{V}O_{2max}$	NO	YES	?	0.49
Rotstein et al. (1986)				1.20 km
Speed (km · h^{-1})	YES	YES	YES	0.74
% $\dot{V}O_{2\ max}$	NO	YES	?	0.14
Weltman et al. (1987)				3.20 km
Speed (km · h^{-1})	YES	YES	YES	0.88
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	YES	NO	?	0.79
Fay et al. (1989)				15.00 km
Speed (km · h^{-1})	YES	YES	YES	0.93
$\dot{V}O_2$ (ml · kg^{-1} · min^{-1})	YES	NO	?	0.90

[a] Endurance needs two performances to be measured (see Tokmakidis et al. 1987)

compare different individuals with different $\dot{V}O_{2max}$. Such a computation, however, increases the relative homogeneity of the data and reduces the correlations. This could also be an explanation for the lower correlations observed with relative units (Tables 4, 5).

Conclusion

The present study questions the occurrence of a unique threshold point over the range of the [La$^-$] curve. The various AT methods yielded different AT that were well correlated with performance. None of these methods appear unique. The 4 mmol · l^{-1} [La$^-$], for example, did not yield a higher correlation with performance than the 5, 6, 7 or even 8 mmol · l^{-1} and this occured in other *ATs* as well (see Tables 3, 4). In addition, this study emphasized the significance of the various units in expressing AT values. The relative importance of AT compared to $\dot{V}O_{2max}$ might not be as critical when AT is expressed as $\%\dot{V}O_{2max}$. Although the results of the present study do not justify the efforts exerted in the search for an AT, the properties of the [La$^-$] curve should not be overlooked. The blood [La$^-$] response to exercise has been a useful tool for exercise prescription (see Lafontaine et al. 1981; Yoshida et al. 1987; Urhausen et al. 1993; Beneke 1995; Weltman 1995) and represents the training status of the individual. Athletics trainers should concentrate more on the physiological consequences of a chosen [La$^-$] rather than on an *AT* when they prescribe the intensity for an exercise training programme.

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