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CLINICAL FEATURE
ORIGINAL RESEARCH

Lack of concordance amongst measurements of individual anaerobic threshold and maximal lactate steady state on a cycle ergometer

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Abstract

Introduction: The calculation of exertion intensity, in which a change is produced in the metabolic processes which provide the energy to maintain physical work, has been defined as the anaerobic threshold (AT). The direct calculation of maximal lactate steady state (MLSS) would require exertion intensities over a long period of time and with sufficient rest periods which would prove significantly difficult for daily practice. Many protocols have been used for the indirect calculation of MLSS. ***Objectives***: The aim of this study is to determine if the results of measurements with 12 different AT calculation methods and calculation software [Keul, Simon, Stegmann, Bunc, Dickhuth (TKM and WLa), D_{max}, Freiburg, Geiger-Hille, Log-Log, Lactate Minimum] can be used interchangeably, including the method of the fixed threshold of Mader/OBLA's 4 mmol/l and then to compare them with the direct measurement of MLSS. ***Methods***: There were two parts to this research. Phase 1: results from 162 exertion tests chosen at random from the 1560 tests. Phase 2: sixteen athletes (n = 16) carried out different tests on five consecutive days. ***Results***: There was very high concordance among all the methods [intraclass correlation coefficient (ICC) > 0.90], except Log-Log in relation to the Stegamnn, D_{max}, Dickhuth-WLa and Geiger-Hille. The Dickhuth-TKM showed a high tendency towards concordance, with D_{max} (2.2 W) and Dickhuth-WLa (0.1 W). The Dickhuth-TKM method presented a high tendency to concordance with Dickhuth-WLa (0.5 W), Freiburg (7.4 W), MLSS (2.0 W), Bunc (8.9 W), D_{max} (0.1 W). The calculation of MLSS power showed a high tendency to concordance, with Dickhuth-TKM (2 W), D_{max} (2.1 W), Dickhuth-WLa (1.5 W). ***Conclusion***: The fixed threshold of 4 mmol/l or OBLA produces slightly different and higher results than those obtained with all the methods analyzed, including MLSS, meaning an overestimation of power in the individual anaerobic threshold. The Dickhuth-TKM, D_{max} and Dickhuth-WLa methods defined a high concordance on a cycle ergometer. Dickhuth-TKM, D_{max}, Dickhuth-WLa described a high concordance with the power calculated to know the MLSS.

Keywords

IAT, MLSS, OBLA, Lactate, Cycle ergometer

History

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Introduction

The calculation of exertion intensity, in which a change is produced in the metabolic processes which provide the energy to maintain physical work, has been defined as the anaerobic threshold (AT).[1] The calculation must be exact and is of great interest for training control.[2–8] The AT is also thought to be of significant interest for the control of daily physical activity [9–11] as well as for the rehabilitation of patients with various disorders.[12–17] The intensity of the exercise, which indicates the transition from low to high intensity in an exertion of long duration, presumably represents the most constant workload which can be carried out with oxidative metabolism.[11] In low exertion intensity exercises, the concentration of blood lactate [LA] maintains constant values, as long as the intensity remains constant, because of the elimination of lactate exceeding its muscular production.[18–25] In high intensity exercises, [LA] increases progressively because the production of muscle lactate exceeds its elimination.[17] In this range of different exertion intensities there is one in which the [LA] remains stable, so consequently the maximal lactate steady state (MLSS) would be the maximum exertion intensity in which

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a balance exists between the appearance and disappearance of lactate in the blood.[21–23,26–34]

The direct calculation of MLSS requires performing various tests at a constant exertion intensity and with sufficient duration, in which the reality of the steady state is assessed and which allows for the differentiation of the maximum exertion intensity in which the steady state is produced.[11,19,29] Therefore, computation of MLSS would require exertion intensities over a long period of time and with sufficient rest periods which would prove significantly difficult for daily practice and, logically, for the control and monitoring of any sportsperson.[11,20,29,30,34,35] The situation is even more complex if we do not know the AT of the athlete in question. We would be forced to carry out the tests at a number of different intensities which, with the previously mentioned duration, would make the process excessively time-consuming.

Since Hollmann, in the year 1959, defined the "point of optimal respiratory efficiency",[36] many progressive graded protocols have been used for the indirect calculation of MLSS, thereby defining the AT. Different methods exist for this calculation depending on the physiological parameter used: analysis of exhaled gases,[17,36,37] the [LA] in peripheral blood,[7,24,29,38–42] the concentration of lactate in saliva,[43] heart rate (HR) [26,44–51] and the rate of perceived exertion (RPE), as measured on the Borg scale.[52–56] One of the most commonly used methods is the measurement of [LA], because of its economy, reliability and ease, both in the laboratory and on the training and playing ground.[2,8,9,11,18–20,57]

At first, AT was defined as a fixed threshold at 4 mmol/l [58] or Onset of Blood Lactate Accumulation (OBLA).[7] Over time, many authors have continued to use the concept of the fixed threshold at 4 mmol/l, both for monitoring training and as a comparative value in research.[59–61]

The aim of this study is to determine if the results of measurements with 12 different AT calculation methods and calculation software [Keul, Simon, Stegmann, Bunc, Dickhuth (TKM and WLa), D_{max}, Freiburg, Geiger-Hille, Log-Log, Lactate Minimum (LM)] can be used interchangeably. We include those measurements obtained with the method of the fixed threshold of Mader/OBLA's 4 mmol/l and then compare them with the direct measurement of MLSS in Phase 2 of this study. Our proposed research is unique as a search of the current literature does not yield any existing studies which analyze such a large number of methods, in comparison to the MLSS.

Our first hypothesis is that different calculation methods yield different results and the second hypothesis is that the fixed thresholds produce an overestimation of exercise capacity, which does not match the MLSS.

Material and methods

There were two parts to this research: a retrospective, transversal, experimental phase using the results of tests carried out over 4 years, followed by another prospective, transversal, experimental phase.

Participants

Phase 1

Results were analyzed from 162 exertion tests (n = 162) chosen at random from the 1560 tests performed in the same medical consultation room with the same aforementioned protocol. The tests were performed over 4 years, executed by the same accredited health staff, with [LA] values measured by the same analyzer unit and carried out with the same equipment (Table 1). The 162 exertion were chosen as they met certain criteria: they all had been performed using the same cycle ergometer (as opposed to those which used a previous cycle ergometer), all the lactate values had been analyzed with the same type of lactate analyzer. In this phase, we did not possess the ability to measure the MLSS, nor the method of minimum lactate.

Phase 2

Sixteen athletes (n = 16) participated in Phase 2. All participated in various endurance sports with the common factor being the use of the bicycle as their main training method. Of the 16 participants, nine were elite category high-performance cyclists, two others were touring cyclists and five were amateur tri-athletes (Table 1).

The inclusion criteria for Phase 1 were that the athletes were familiar with the test and had completed at least five steps of the stress test. In Phase 2, the athletes also had to maintain a training level of at least 200 km per week by bike as well as be able to complete the distribution of the proposed test and accept the prescribed diet and training plan. The exclusion criteria were as follows: the participants had not completed a prior test; they did not manage to complete five steps and the presence of any medical problem (injuries or illnesses) or food intolerance in the month prior to the test. In addition, in Phase 2, inability to

Table 1. Participant characteristics. Descriptive data (minimum, maximum, mean and SD).

	Participant characteristics							
	Phase 1 (n = 162)				Phase 2 (n = 16)			
Variable	Minimum	Maximum	Mean	SD	Minimum	Maximum	Mean	SD
Age (years)	16.0	47.0	24.8	6.2	19.0	38.0	26.8	6.8
Height (cm)	172.0	192.0	173.8	11.0	165.0	190.5	176.0	6.2
Body mass (kg)	45.8	97.5	70.9	8.7	58.0	83.0	70.5	6.5
VO_2max (ml/kg/min)	47.6	64.7	54.6	5.1	52.5	69.2	58.9	4.9
BMI (au)	16.7	30.0	23.2	2.0	20.0	24.9	22.7	1.6
Fat (%)	4.2	23.1	12.9	3.0	7.4	16.1	11.2	2.7
Sum 6 (mm)	13.8	146.4	56.8	17.2	38.0	86.1	53.6	15.7
FFM (kg)	38.3	82.1	61.6	6.9	53.2	74.6	62.5	5.6

Fat (%), fat percentage; FFM (kg), fat free mass; BMI, body mass index (arbitrary units); Sum 6 (mm), 6 folds summation.

attend over the proposed 5 days of the test (Monday to Friday) was also criterion for exclusion.

The participants were informed of the experimental processes as well as the proposed tests and gave their written consent. The experimental process to which the athletes were subjected fulfills the guidelines established in the Declaration of Helsinki (1964) and its procedures are in compliance with the Data Protection Act [Ley Orgánica 15/1999 de Protección de Datos de Carácter Personal (LOPD)], having obtained the relevant permission from the Ethics Committee of the University of the Basque Country (EHU-UPV). The anthropometric data of the participants from both phases appears in Table 1.

General procedure

This study compares 12 methods of individual anaerobic threshold (IAT) calculation, and furthermore, compares them with the results obtained in the MLSS test. In Phase 1, results obtained over 4 years were compared in accordance with the aforementioned criteria. Each sportsperson carried out a Staggered Progressive Incremental Maximal test (SPIM) on a cycle ergometer. In Phase 2 of the study, the participants carried out different tests on five consecutive days, from Monday to Friday, at the same time, following a specific schedule (Table 2). On Monday they conducted the usual ergometer protocol; on Tuesday before the usual ergometer protocol they conducted two sprints at high intensity. On Wednesdays, Thursdays and Fridays they performed the constant test.

Physiological tests

Phase 1

Over a 4 year period the data were collated from the tests carried out by each sportsperson during a SPIM test on a cycle ergometer employing the following protocol: initial power starting at 50 W with a 3-min duration of steps, then increasing power by 50 W from step to step, without pauses between them. A blood sample was secured from the ear lobe for blood [LA] measurement in the last 15 s of each step.[62] The same protocol has been used in accordance with a previously published protocol using this type of test.[63] Furthermore, our research group recently published a study,[64] using the same protocol with a top Himalayan climber. This article has been published in the top scientific journal in the field of altitude phenomenon.[23] Furthermore, the use of protocols with different steps to this 50 W/3 min protocol (30 W/5 min; 25 W/2 min; 50 W/2 min) presented no differences in the calculation of AT.[29] All tests were carried out by the same health care staff under standardized laboratory environmental conditions. In this phase, the possible methods (Table 3) were analyzed in line with the followed protocol, but it was not possible to analyze the lactate minimum (LM) methods.[24]

Table 2. Schedule of Phase 2 of the research, carried out by each participant.

Research schedule				
Monday	Tuesday	Wednesday	Thursday	Friday
Test SPIM	2nd sprint + SIM	1st constant test	2nd constant test	3rd constant test

Phase 2

The second part of the study consisted of an initial phase in which the necessary staggered tests were carried out for the calculation of the different IATs. Two tests were required since the initial SPIM protocol [62] did not allow for the calculation of the LM method. The method was calculated by drawing a polynomial curve of grade 2, in which the lowest point of the curve was measured. In the followings days, the tests at constant intensity were carried out (minimum 3), for the direct measurement of MLSS, in line with the Beneke protocol, in which exertions are carried out at a constant intensity for 30 min [19] (Table 3). The Ws of the first of these were fixed depending on the mean value from the different IAT calculations. On the following days, minimum 2, they were calculated with increases and decreases in power from the previous Ws by 10 W. The increase or decrease of power depended on the result of the [LA] values in the first of the 30 min tests. Blood samples were taken for measurement of lactate every 5 minutes (before, 5, 10, 15, 20, 25, 30 and 3 minutes after finishing). LM method and MLSS were only evaluated in Phase 2 because they require a special protocol, which was not conducted in Phase 1, because the data of said Phase 1 were obtained during routine checks over 4 years. Phase 2 involved a specific new research.

Among the methods for calculating the threshold, the ventilator method has not been included because its determination involves a different protocol [65] and because the objective of the research was carried out by measuring lactate.

Measurement of biological parameters

Phase 1. Blood for measuring the [LA] values was taken from the hyperemiated ear lobe (Radio Salil cream, Lab Viñas, Spain) at various times: prior to the start of the test, in the last 15 s of each exertion step, and in minutes 1, 3, 5 and 7 following the last exertion step. The [LA] value was measured through a Lactate Pro LT-1710 (Akray Factory Inc., KDK Corporation, Siga, Japan). The calculation of indirect VO_2 was carried out following the indirect formula proposed by George.[66] This calculation formula is based on a study of a population of 18–68-year-old subjects and performed on a treadmill. In the authors' opinion, this formula provides a relatively accurate regression model to predict VO_{2max} in relatively fit men and women, ages 18–65 years, based on maximal exercise (treadmill speed and grade), biometric (BMI) and demographic (age and gender) data, and this adaptation to cycle ergometer is widely used.[67] As in any type of calculation, resultant values may diverge from those obtained from direct measurements.

Phase 2. Blood samples were taken in the same way as in Phase 1. Likewise, VO_2 was constantly measured through a gas analyzer Oxywith Delta (Jaeger, Viasys Healthcare GmbH, Hoechberg, Germany), from just prior to the start of each test until the 3 min after completion.

Statistical analysis

The following computer programmes were used to carry out the statistical analysis: IBM SPSS Statistics 21.0 (Chicago

Table 3. Methods used to calculate IAT, threshold of mmol/l and MLSS.

	Method	Year	Author(s)	System
Phase 1	Dickhuth-TKM	1989	Dickhuth/Berg	Method of lactate equivalent, TKM software
	Keul	1979	Keul	Tangent in the lactate curve of 51º34
	Simon	1981	Simon	Tangent in the lactate curve of 45º
	Stegmann	1981	Stegmann, Kindermann & Schnabel	Tangent from the lactate value in the recuperation phase to the lactate-time curve equal to the value of the lactate at the end of the effort
	Bunc	1985	Bunc	Bisecting line of the angle formed by the tangents at the lowest point of the curve and at the point equivalent to 15 mmol/l of lactate
	D_{max}	1992	Cheng	Point, on the [LA] curve, which is furthest away from the straight line which joins the initial load point and the end of the lactate curve
	Freiburg	1981	Keul/Berg	A fixed value of 1.5 was added to the mean of the first four lactate values
	Dickhuth-Wla	1988/ 1989	Dickhuth/Berg	Method of lactate equivalent, Winlactat V4.2.0.47 software
	Geiger-Hille	1993	Hille/Geiger	Calculation of IAT through software called "LACTAT" with a tangent to the lactate curve at 35.3º and specific polynomial
	Log-Log	1985	Beaver, Wasermann & Whipp	The logarithms Log [La] and Log VO_2 are confronted
	4 mmol/l/ OBLA	1976/ 1991	Mader/Sjödin & Jacobs	Speed in which the [LA] is 4.0 mmol/l
Phase 2	Minimum lactate	1989	Tegtbur *et al*.	Two previous sprints and later SPIM test. Minimum value of the lactate curve would equal IAT
	MLSS	2003	Beneke	Minimum three tests at constant speed, of 30 min each one on at least three consecutive days

IL, USA) and Sigma Plot 12.3 (Systat Software Inc., San José, California, USA). A descriptive analysis of the data was performed, describing mean ± standard deviation (SD), including range, mean typical error, and minimum and maximum values. Normality of the sample was checked using the Kolmogorov-Smirnov test, and a parametric test was used, given its normal distribution. In order to analyze concordance between the methods, the intraclass correlation coefficient (ICC) was calculated. Likewise, and in order to obtain information about the concordance observed and about the presence of systematic differences between the measurements, Lin's concordance correlation coefficient was applied. This was used in conjunction with the method developed by Bland and Altman, which is based on the analysis of the differences between individual measurements,[14] studying both the tendency and the limits of concordance for 95%. The minimum value of concordance used is the same criterion that was later used to calculate the different exertion intensities when the tests carrying out to determine power at the MLSS (10 W). The statistical significance criterion was set at $p < 0.05$ for significant differences and at $p < 0.01$ for very significant differences.

Results

Below are the results of the analysis of the variables considered during the period of study, the powers obtained by the different IAT calculation methods, as well as the fixed threshold of 4 mmol/l and MLSS in tests carried out on 16 cyclists who took part in the research.

Intraclass correlation coefficient (ICC)

Evaluation of concordance according to ICC values was carried out in line with the rating proposed by Fleiss [35] (>0.90 very good, 0.71–0.90 good, 0.51–0.70 moderate, 0.31–0.50 mediocre, <0.30 Bad or null). In the first phase of this study, as can be seen in Table 4, there is very high concordance among all the methods analyzed (ICC > 0.90), except for the Log-Log method in relation to the Stegamnn, D_{max}, Dickhuth-WLa and Geiger-Hille methods, with which the concordance is high (ICC: 0.71–0.90). In Phase 2 of the study, however, the concordance is much more dispersed (Table 5), as the concordance between the lactate minimum method and Stegmann is very low or null (ICC = 0.264). The lactate minimum method shows a mediocre or moderate concordance with the rest of the methods (ICC >0.456 and <0.682), except with D_{max} (ICC = 0.725) and MLSS (ICC = 0.779), with which concordance is high. The concordance of the Stegmann method is high with all the methods (ICC >0.727 and <0.885), except with the LM (ICC = 0.264), which, as previously stated, is low or null. Likewise, the concordance of the Bunc method with the rest is high (ICC >0.713 and <0.879), except with Log-Log which is moderate (ICC = 0.547) and LM, which is mediocre (ICC = 0.482). The concordance of the MLSS measurement (Table 5) is very high with the methods: Dickhuth-TKM (ICC = 0.948), Keul (ICC = 0.962), D_{max} (ICC = 0.927), Dickhuth-WLa (ICC = 0.940) and Geiger-Hille (ICC = 0.920), whilst concordance is high with: Simon (ICC = 0.896), Stegmann (ICC = 0.780), Bunc (ICC = 0.879), Log-Log (ICC = 0.792), 4 mmol/l (ICC = 0.896) and LM (ICC = 0.779).

Study of concordance with the Bland and Altman method

Phase 1

The results of the method which we have called Dickhuth-TKM shows a high tendency towards concordance, with a lower result than Stegmann (9.4 W), whilst it agrees, with a higher value, with D_{max} (2.2 W), Freiburg (7.2 W) and with Geiger-Hille (8.1), while with Dickhuth-WLa the result is practically equal (higher by only 0.1 W). The concordance of this method is low, with a higher result with Keul (23.5),

Table 4. ICC and Bland–Altman among the calculation methods of the threshold on a cycle ergometer in Phase 1.

		Intraclass correlation coefficient (ICC) and concordance between IAT calculation methods and fixed threshold of 4 mmol/l or OBLA on a cycle ergometer – Phase 1										
		Dickh-TKM	Simon	Keul	Stegmann	Bunc	D_{max}	Freiburg	Dickh-WLa	Geiger-Hille	Log-Log	4 mmol/l
Dickhuth-TKM	ICC		0.996 (0.994–0.997)	0.996 (0.995–0.997)	0.966 (0.954–0.975)	0.981 (0.975–0.986)	0.975 (0.966–0.982)	0.991 (0.988–0.993)	0.980 (0.973–0.986)	0.982 (0.975–0.987)	0.922 (0.894–0.943)	0.989 (0.894–0.992)
	B-A		−33.4 (68)	−23.5 (58)	9.4 (63)	−13.7 (45)	−2.2 (50)	−7.2 (33)	0.1 (48)	−8.1 (49)	−74.1 (148)	28.5 (57)
Simon	ICC			0.993 (0.991–0.995)	0.958 (0.942–0.969)	0.978 (0.971–0.984)	0.964 (0.951–0.974)	0.987 (0.982–0.991)	0.977 (0.968–0.983)	0.979 (0.972–0.985)	0.910 (0.877–0.934)	0.987 (0.982–0.990)
	B-A			9.9 (28)	23.9 (70)	19.6 (50)	31.1 (62)	26.1 (52)	33.4 (67)	25.3 (52)	−40.8 (98)	61.9 (124)
Keul	ICC				0.967 (0.955–0.976)	0.979 (0.971–0.984)	0.979 (0.972–0.985)	0.988 (0.983–0.991)	0.979 (0.972–0.985)	0.984 (0.978–0.988)	0.904 (0.869–0.930)	0.989 (0.984–0.992)
	B-A				14.1 (63)	9.7 (49)	21.2 (50)	16.3 (39)	23.6 (51)	15.4 (47)	−50.7 (101)	52.0 (104)
Stegmann	ICC					0.948 (0.930–0.962)	0.972 (0.962–0.979)	0.949 (0.931–0.963)	0.938 (0.916–0.954)	0.951 (0.934–0.964)	0.882 (0.839–0.913)	0.960 (0.945–0.970)
	B-A					−4.3 (75)	−7.2 (53)	2.2 (77)	9.5 (85)	1.4 (80)	−64.7 (129)	37.9 (76)
Bunc	ICC						0.957 (0.942–0.969)	0.973 (0.963–0.980)	0.961 (0.947–0.971)	0.961 (0.947–0.972)	0.921 (0.893–0.942)	0.969 (0.958–0.977)
	B-A						11.5 (63)	6.5 (54)	13.8 (66)	5.7 (69)	−60.4 (121)	42.3 (85)
D_{max}	ICC							0.957 (0.941–0.968)	0.950 (0.931–0.963)	0.947 (0.928–0.961)	0.889 (0.849–0.919)	0.954 (0.937–0.966)
	B-A							−5.0 (67)	2.3 (71)	−5.8 (77)	−71.9 (144)	30.8 (62)
Freiburg	ICC								0.988 (0.984–0.991)	0.984 (0.978–0.988)	0.916 (0.885–0.938)	0.987 (0.983–0.991)
	B-A								7.3 (38)	−0.9 (46)	−66.9 (134)	35.8 (72)
Dickhuth-WLa	ICC									0.991 (0.988–0.993)	0.900 (0.863–0.926)	0.973 (0.963–0.980)
	B-A									−8.2 (35)	−74.2 (146)	28.5 (57)
Geiger-Hille	ICC										0.893 (0.854–0.921)	0.984 (0.978–0.988)
	B-A										−66.1 (132)	36.6 (73)
Log-Log	ICC											0.905 (0.870–0.930)
	B-A											102.7 (205)
4 mmol/l	ICC											
	B-A											

ICC, Intraclass correlation coefficient. The confidence interval is 95% between parameters.

B-A, Bland and Altman method: measure of differences (in brackets the confidence interval ± at 95%). The difference between methods in B-A was calculated with the value of the superior line minus the corresponding vertical.

Table 5. ICC and Bland–Altman among the calculation methods of the threshold on a cycle ergometer in Phase 2.

Intraclass correlation coefficient (ICC) and concordance between IAT calculation methods, fixed threshold of 4 mmol/l or OBLA and MLSS on a cycle ergometer – Phase 2														
		Dickh-TKM	Simon	Keul	Stegmann	Bunc	D_{max}	Freiburg	Dickh-WLa	Geiger-Hille	Log-Log	4 mmol/l	LA-min	MLSS
Dickhuth-TKM	ICC		0.963 (0.893–0.987)	0.984 (0.954–0.994)	0.850 (0.572–0.948)	0.829 (0.510–0.948)	0.929 (0.796–0.975)	0.986 (0.960–0.995)	0.986 (0.960–0.995)	0.951 (0.861–0.983)	0.890 (0.686–0.962)	0.914 (0.753–0.970)	0.674 (0.067–0.886)	0.948 (0.852–0.982)
	B-A		−31.3 (52.8)	−23.6 (33.5)	−13.3 (26.5)	8.9 (101.9)	0.1 (61.3)	−7.4 (32.7)	0.5 (31.9)	−11.6 (66.7)	−87.7 (103.6)	22.6 (95.0)	−49.6 (112.5)	−2.0 (59.1)
Simon	ICC			0.975 (0.929–0.991)	0.903 (0.724–0.966)	0.781 (0.374–0.924)	0.905 (0.727–0.967)	0.977 (0.934–0.992)	0.968 (0.909–0.989)	0.966 (0.904–0.988)	0.893 (0.694–0.963)	0.937 (0.819–0.978)	0.564 (−0.248–0.848)	0.896 (0.702–0.964)
	B-A			7.8 (42.5)	18.1 (79.5)	40.3 (116.3)	31.4 (72.8)	23.8 (43.0)	30.8 (49.2)	19.7 (57.3)	−56.4 (104.3)	53.9 (83.8)	−18.3 (130.2)	29.3 (84.2)
Keul	ICC				0.885 (0.671–0.960)	0.844 (0.555–0.946)	0.945 (0.842–0.981)	0.979 (0.939–0.993)	0.987 (0.962–0.995)	0.961 (0.888–0.986)	0.869 (0.625–0.954)	0.930 (0.800–0.976)	0.682 (0.089–0.889)	0.962 (0.891–0.987)
	B-A				10.3 (81.7)	32.5 (96.0)	23.7 (53.1)	16.1 (38.9)	23.1 (30.8)	11.9 (59.3)	−64.1 (110.7)	46.1 (85.3)	−26.1 (108.7)	21.6 (49.9)
Stegmann	ICC					0.727 (0.218–0.905)	0.782 (0.376–0.924)	0.895 (0.699–0.963)	0.897 (0.706–0.964)	0.861 (0.603–0.952)	0.815 (0.470–0.935)	0.835 (0.529–0.943)	0.264 (−1.106–0.743)	0.780 (0.370–0.923)
	B-A					22.2 (118.2)	13.4 (95.0)	5.8 (82.8)	12.8 (79.9)	1.6 (104.9)	−74.4 (126.5)	35.8 (123.4)	−36.4 (139.0)	11.2 (108.1)
Bunc	ICC						0.797 (0.418–0.929)	0.800 (0.429–0.930)	0.795 (0.412–0.928)	0.761 (0.316–0.916)	0.547 (−0.297–0.842)	0.713 (0.179–0.900)	0.482 (−0.483–0.819)	0.879 (0.653–0.958)
	B-A						−8.8 (95.7)	−16.4 (112.2)	−9.4 (110.9)	−20.6 (134.7)	−96.6 (182.0)	13.6 (157.7)	−58.6 (129.7)	10.9 (86.1)
D_{max}	ICC							0.889 (0.682–0.961)	0.913 (0.750–0.970)	0.887 (0.675–0.960)	0.776 (0.359–0.922)	0.826 (0.502–0.939)	0.725 (0.213–0.904)	0.927 (0.791–0.974)
	B-A							−7.6 (78.1)	−0.6 (68.0)	11.8 (89.9)	−87.8 (129.4)	22.4 (119.9)	−49.8 (86.5)	−2.1 (60.7)
Freiburg	ICC								0.991 (0.974–0.997)	0.961 (0.887–0.986)	0.892 (0.691–0.962)	0.935 (0.814–0.977)	0.612 (−0.110–0.864)	0.920 (0.771–0.972)
	B-A								−6.9 (26.7)	−4.2 (61.9)	−80.3 (104.9)	30.0 (84.9)	−42.2 (125.3)	5.4 (74.9)
Dickhuth-WLa	ICC									0.971 (0.917–0.990)	0.905 (0.727–0.967)	0.943 (0.836–0.980)	0.639 (−0.034–0.874)	0.940 (0.828–0.979)
	B-A									11.1 (52.5)	−87.2 (97.7)	23.1 (79.0)	−49.1 (118.2)	−1.5 (64.0)
Geiger-Hille	ICC										0.912 (0.749–0.969)	0.980 (0.943–0.993)	0.583 (−0.194–0.854)	0.920 (0.772–0.972)
	B-A										−76.1 (103.0)	34.2 (51.6)	−38.0 (148.2)	9.6 (83.2)
Log-Log	ICC											0.929 (0.796–0.975)	0.456 (−0.556–0.810)	0.792 (0.406–0.927)
	B-A											110.3 (99.5)	38.1 (174.4)	85.7 (135.0)
4 mmol/l	ICC												0.558 (−0.264–0.846)	0.896 (0.701–0.964)
	B-A												−72.2 (168.0)	−24.6 (102.7)
LA-min	ICC													0.779 (0.366–0.923)
	B-A													47.6 (94.4)
MLSS	ICC													
	B-A													

ICC, Intraclass correlation coefficient. The confidence interval is 95% between parameters.

B-A: Bland and Altman method: measure of differences (in brackets the confidence interval ± at 95%). The difference between methods in B-A was calculated with the value of the superior line minus the corresponding vertical.

with Simon (33.4 W), with Bunc (13.7 W), with the Log-Log method (74.1 W), while it is lower than in the fixed threshold of 4 mmol/l (28.5 W).

The method proposed by Stegmann also shows a high tendency towards concordance with most of the methods analyzed. The Stegmann method is higher than Dickhuth-TKM (9.4 W), Bunc (4.3 W) and D_{max} (7.2 W), whilst it is lower than Freiburg (2.2 W), Dickhuth-WLa (9.5 W) and Geiger-Hille (1.4 W). In this case the concordance is low with Simon (23.9 W), with Keul (14.1 W), with Log-Log (64.7 W) with a lower result for these three methods, while with the fixed threshold of 4 mmol/l (37.9 W) the value is higher. Similarly, in the case of the D_{max} method, high concordances have been found, but with lower values, with Dickhuth-TKM (2.2 W); with Dickhuth-WLa (2.3 W); whilst concordance with higher values is with Stegmann (7.2 W), with Freiburg (5.0 W) and with Geiger-Hille (5.8 W). However, compared with the methods Simon (31,1 W), Keul (21,2 W), Bunc (11,5 W), Log-Log (71,9 W) and with the fixed threshold of 4 mmol/l (30.8 W) concordance is low, being higher than them, except in the case of the fixed threshold of 4 mmol/l, with power less than the fixed threshold of 4 mmol/l.

In the calculation of IAT with the method proposed by Bunc, high concordances have been found with the Keul method, Bunc being higher by 9.7 W; whilst this concordance is with lower values with Stegmann (4.3 W); with Freiburg (6.5 W) and with Geiger-Hille (5.7 W). This Bunc method shows low correlation with the methods: Dickhuth-TKM (13.7 W), Simon (19.6 W), D_{max} (11.5 W), Dickhuth-WLa (13.8 W), with Log-Log (60.4 W) and with the fixed threshold of 4 mmol/l (42.3 W).

The Freiburg method shows a high tendency to concordance and a lower tendency than Dickhuth-TKM (7.2 W), D_{max} (5.0 W), Dickhuth-WLa (7.3 W), whilst the concordance is with values higher than Stegmann (2.2 W), Bunc (6.5 W), Geiger-Hille (0.9 W). The concordance is low with the methods Simon (26.1 W), Keul (16.3 W), Log-Log (66.9 W) and with the fixed threshold of 4 mmol/l (35.8 W).

The Dickhuth-WLa method shows similar concordances to Dickhuth-TKM, these being practically equal (0.1 W). Thus, it agrees, being higher, with Stegmann (9.5 W), with D_{max} (2.3 W), with Freiburg (7.3 W) and with Geiger-Hille (8.2 W). On the other hand, compared with the methods Simon (lower by 33.4 W), Keul (lower by 23.6 W), Bunc (lower by 13.8 W), Log-Log (lower by 74.2 W) and with the fixed threshold of 4 mmol/l (higher by 28.5 W), concordance is low.

In line with the previous methods, the Geiger-Hille method shows high concordance, with lower values, with Dickhuth-TKM (8.1 W), with Stegmann (1.4 W), with D_{max} (5.8 W), with Freiburg (0.9 W), with Dickhuth-WLa (8.2 W), whilst it agrees, with higher values, with Bunc (5.7 W). With the Simon (lower by 25.3 W), Keul (lower by 15.4 W), Log-Log (lower by 66.1 W) methods and with the fixed threshold of 4 mmol/l (higher by 36.6 W) the tendency to concordance is low.

As can be seen, the methods Simon and Keul only agree with each other (9.9 W), although the Keul method also agrees with the Bunc method, Bunc being higher by 9.7 W. The method proposed by Beaver, the Log-Log method, does not agree with any of the other methods, being the one which universally provides a slightly lower result in comparison with the other analyzed methods. The fixed threshold of 4 mmol/l or OBLA method does not agree with any of the other methods, being the one which, in every case, provides a slightly higher result in comparison with the other analyzed methods (Table 4 and Figure 1).

Figure 1 helps to clarify this significant volume of data by showing the means of each method, with the concordances

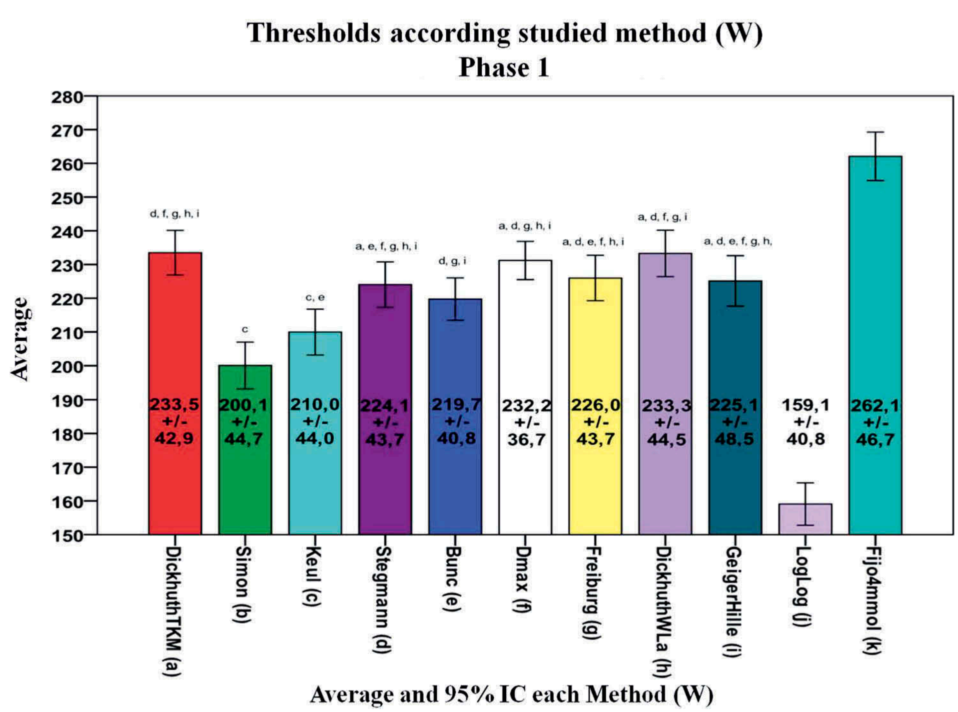

Figure 1. Mean and SD of the power obtained (W) with each method studied, along with the concordance among them (Phase 1).

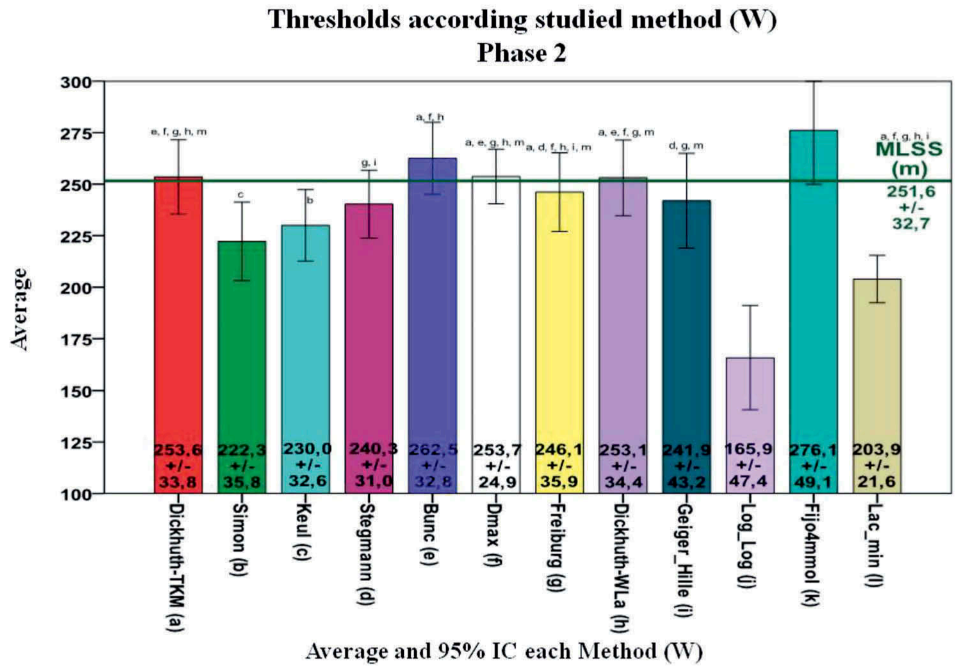

Figure 2. Mean and SD of the power obtained (W) with each method studied, along with the concordance among them and their relationship with the MLSS measured (Phase 2).

obtained, according to the Bland and Altman method of statistical analysis, applying the criterion 10 W as the limit.

Phase 2

In Figure 2, in Phase 2 the means of each method can be seen, with the concordances obtained, according to the Bland and Altman method of statistical analysis, applying the criterion 10 W as the limit, as previously stated. Likewise, this data is compared with the result of the speed in the MLSS.

The Dickhuth-TKM method shows a high tendency to concordance (Table 5), with higher values, with Dickhuth-WLa (in just 0.5 W) with Freiburg (7.4 W) and with MLSS (2.0 W), whilst there is concordance with lower values, with Bunc (8.9 W) and with D_{max} (only 0.1 W). With the rest of the methods the concordance is low. The Stegmann method shows a high association only with the methods Freiburg (5.8 W) and Geiger-Hille (1.6 W), Stegmann being lower in both cases. The Bunc method shows a high tendency to concordance only with the methods Dickhuth-TKM, (8.9 W), D_{max} (8.8 W) and Dickhuth-WLa (9.4 W), the calculation with Bunc being higher in all cases. With the MLSS power, the concordance is on the limit (higher in MLSS by 10.9 W). The rest of the methods show low concordance. The results obtained by the D_{max} method show a high tendency to concordance and higher values with Dickhuth-TKM (only by 0.1 W); with Freiburg (7.6 W); with Dickhuth-WLa (only 0.6 W) and with MLSS power (2.1 W); while the concordance with Bunc is with lower values (8.8 W). The rest of the analyzed methods show low concordance. The Freiburg method shows high concordance, with lower values, with Dickhuth-TKM (7.4 W); with D_{max}, (7.6 W) and with the MLSS power (5.4 W), but with higher values with Stegmann (5.8 W), with Dickhuth-WLa (6.9 W); with Geiger-Hille (4.2 W). With the rest of the methods (Simon, Keul, D_{max}, Log-Log, 4 mmol/l and LM) the tendency to concordance is low. Dickhuth-WLa, shows a high tendency to concordance with Dickhuth-TKM (0.5 W) and with the MLSS power (1.5 W), being higher than them in both cases. It also shows high concordance with Bunc (9.4 W), with D_{max} (0.6 W) and with Freiburg (6.9 W), but the values are lower with Dickhuth-WLa. However, with the rest of the methods studied concordance is low. Although the Geiger-Hille method shows a high tendency to concordance only with the methods Stegmann (lower by 1.6 W); Freiburg (higher by 4.2 W) and with the MLSS power (higher by 9.6 W), with the other methods studied the concordance is close to the proposed limits: Dickhuth-TKM (higher by 11.6 W); with Keul (lower by 11.9 W); with D_{max} (lower by 11.8 W); with Dickhuth-WLa (lower by 11.1 W). With the rest of the methods the concordance is low.

The Simon and Keul methods show high concordance only with each other, Keul being higher by 7.8 W. With the rest of the methods the concordance is outside the set limits. The rest of the analyzed methods of IAT calculation show no concordance (Log-Log, LM, Fixed Threshold of 4 mmol/l). The power obtained with the fixed threshold of 4 mmol/l is slightly higher in all cases and its concordance with the MLSS is poor, significantly higher than the suggested 10 W (24.6 W higher with the fixed threshold of 4 mmol/l).

On the other hand, the calculation of MLSS power, the original base for determining exertion intensity on cycle ergometer, shows a high tendency to concordance, with lower values, with Dickhuth-TKM (just 2 W), with D_{max} (2.1 W) and with Dickhuth-WLa (1.5 W). The high concordance is produced with higher values with Freiburg (5.4 W) and with Geiger-Hille (9.6 W). With the methods Stegmann (11.2 W) and Bunc (0.9 W) concordance is on the limit, measurement with MLSS being higher. With the rest of the methods (Simon, Keul, Log-Log, Fixed Threshold of 4 mmol/l (Figure 2) and LM) concordance is low.

Discussion

To our knowledge, this is the first study existing in the international literature that directly compares the different, preeminent methods of threshold calculation on a cycle ergometer. In addition, this is the first major study to compare these various methods of threshold calculation with the results of direct measurement of MLSS.

The aim of this research was to study which of the methods used to calculate IAT are suitable for a test carried out on a cycle ergometer. The calculation methods chosen represent the most commonly studied and widely used methods described in the relevant international literature (Table 3). A secondary aim of the study was to investigate whether the measurements agree with the OBLA and the MLSS. We did not analyze some methods for various reasons. For example, we omitted those which,[68,69] those where the base method is already included in other methods,[70] those whose publication in the international literature is later than the start of this work, and those in which the protocol used varies greatly from this new protocol.[71] The Log-Log method has been included to assess whether its LT calculation corresponds to the phenomenon of the exponential increase in [LA] mentioned by the authors.[72]

In the two phases of the study, a high concordance was observed between the Dickhuth-TKM, D_{max}, and Dickhuth-WLa methods, whilst the Freiburg, Bunc and Geiger-Hille methods agree with some of the methods, but not all. In the first phase of the study a high concordance was observed between the Stegmann method (between 1.4 and 9.5 W) and these methods. This relationship was not observed, however, in phase 2 in which it only agrees with the Freiburg (5.8 W) and Geiger-Hille methods (1.6 W). On the other hand, the thresholds calculated with the Simon, Keul, Log-Log, 4 mmol/l and LM methods show low concordance with each other and with the rest of the methods described. The Simon method only agrees with the Keul threshold, which is logical if we bear in mind that the calculation methodology is based on the same system.[40,55] The concordance between the Simon, Keul and Stegmann methods is similar to that obtained in Phase 1 of this study, with lower powers than the other methods, similar to Log-Log, LM and 4 mmol/l methods.

In the analysis of the results obtained with the Stegmann method, this showed a low concordance tendency with the MLSS (11.2 W less for Stegmann). These data do not coincide with the results of McLellan and Jacobs, who found that the Stegmann method of IAT calculation overestimates to a certain extent the value of the MLSS, with no other indications about correlations or differences between IAT and MLSS,[73] carried out on a cycle ergometer. Our results do not agree either with those obtained by Heck, who, in a study carried out with 22 healthy subjects on a cycle ergometer, indicated that a significant correlation exists between the IAT according to the Stegmann method and the MLSS, where the IAT was 15.1 W higher than the MLSS.[29] In the same way, although done on a treadmill, Coen *et al*. concluded that the IAT, calculated with the Stegmann method is a valid protocol with high test-retest reliability for determining MLSS, which is not modified by the duration of the steps, the degree of exhaustion in the test or based on warm-up protocol.[74] Similarly, Baldari *et al*. concluded that the calculation of IAT with the Stegmann method is a valid method for determining the MLSS speed, although in some cases it underestimates its value.[18] However, these results contradict those of McLellan *et al*., who concluded that Stegmann's IAT overestimates the MLSS,[75] indicating that depending on the criteria used in IAT validation, this method could overestimate or underestimate the true MLSS.[73]

The high concordance between the calculations with Dickhuth-TKM and Dickhuth-WLa methods is logical if we bear in mind that both use the same method, but with different computer applications.[12,76] Therefore, the results obtained with these and with the D_{max} method are very similar, although the theoretical basis of both methods is different.[27]

With regard to the D_{max} method, this shows a high tendency to concordance, with a minimal increased difference, with MLSS power of just 2.1 W. These results do not coincide with those of Van Schuylenbergh *et al*., who carried out a study with 21 cyclists and reported a high correlation between the D_{max} method and MLSS, but this correlation was with a significantly lower mean D_{max} threshold value (23 W lower).[1] This lower value, according to the criterion used in the research, indicates a very low correlation tendency.[34] However, our results are in agreement with those of Machado *et al*., who found that the D_{max} method, which they named LT D_{max}, has a high concordance with the S10 km (mean speed over 10 km), although in this case the calculation was carried out on a treadmill,[77] a possible limitation in the analysis. Acten and Jeukendrup indicated that the D_{max} method measures the LT, indicating that its level would be slightly below the MLSS.[78] Likewise, Czuba *et al*. did not find significant differences between the workload in the LT (referring to IAT), determined using D_{max}, and the workload in the MLSS.[79]

A high tendency to concordance between the Bunc method and the MLSS was not found. This is in contrast to what Heck indicated in a study carried out with 22 healthy subjects on a cycle ergometer, in which he referred to a significant correlation, but did not indicate the degree of concordance between the two methods.[29]

The LM method does not produce a concordance tendency with any of the methods studied, even the calculation of MLSS, showing a clearly lower result in all cases. Our results contrast with the conclusions of Johnson *et al*., who indicated that the LM method showed a high degree of concordance when they studied it on a cycle ergometer.[80] Our results also differed with those of MacIntosh *et al*., who indicated that the threshold determined with lactate minimum (LMT) is a reliable and valid method to predict MLSS both for athletes and cyclists.[81] Finally our results also differ from the conclusions of Strupler *et al*., who concluded that the LMT is a reproducible method for assessing the FC in an exertion intensity in which there is a balance between the production and elimination of [LA], in other words, the MLSS.[7] Likewise, Johnson *et al*. conclude that the concordance between LM and MLSS is fortuitous.[80]

The Log-Log method [72] does not agree with any of the other studied methods or with calculation of power in the MLSS, with a speed threshold much lower than that obtained with the other methods (between 1.3 and 3.1 km/h). Therefore, the Log-Log method cannot be a reference for comparing the results of the different thresholds, despite the authors [72] indication that said threshold identifies the exponential increase of [LA], which they referred to as LT. Although our study has been carried out on a cycle ergometer, our findings agree with the references that LT indicates a slightly lower race speed than that of MLSS,[35] as in Nogueira *et al*., who correlate the Log-Log method with the LT.[82]

In spite of the high tendencies which some of the methods demonstrate, the limits of concordance among the methods are extensive, much more so than expected with the concordance tendency that they present. Among the methods show a high tendency to concordance in our study, the difference in the concordance index of 95% is at least 26.7 W. This difference is determined by comparison of calculations performed with the Dickhuth-WLa and Freiburg methods, which are based on the same theoretical concept and were calculated using the same software. In the rest of the cases with a high concordance tendency, the differences are between 32 and 112 W. This would lead us to think that although the concordance tendency might be high, the variability of the results with each method is too great.

The main hypothesis of our study was that the analyzed methods would calculate the same exertion power in a test carried out on a cycle ergometer. In the end, this is only true for the Dickhuth (TKM or WLa), and D_{max} methods, which show practically the same results. Meanwhile, six of the 12 methods studied (50%) for the calculation of IAT or AT (Simon, Keul, Stegmann, Log-Log, Fixed Threshold of 4 mmol/l and LM) differed greatly from the results obtained with the other methods and a further three (Bunc, Freiburg and Geiger-Hille) show a relative concordance with the rest of the methods and among each other.

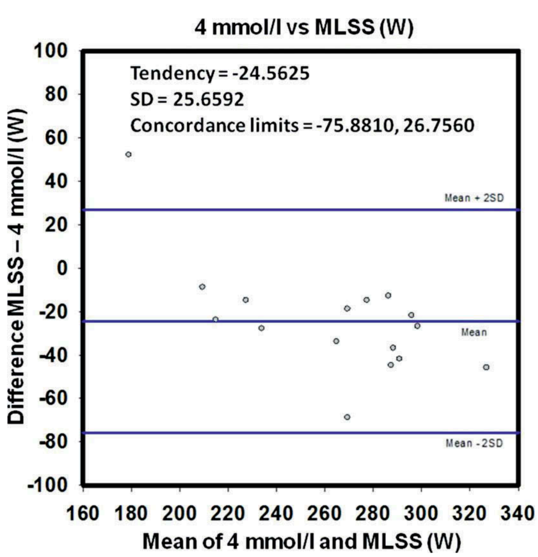

Figure 3. Concordance tendencies and limits, according to the Bland and Altman statistical method, for the fixed threshold of 4 mmol/l and MLSS relationship, on cycle ergometer, in Phase 2.

In both phases of this study, the analysis of concordance of the fixed threshold of 4 mmol/l or OBLA, one of the thresholds which appears most in published works, [8,20,25,57,59,60] produces a slightly higher power (between 13.6 regarding Bunc and 110.3 W regarding Log-Log) than any of the methods analyzed of IAT calculation (Tables 4 and 5). These results agree with those of Beneke, who determined that the threshold of 4 mmol/l does not correspond to the IAT in rowing.[20] Although carried out with long distance runners, the conclusions of Foxdal *et al*. also agree with our results, as they concluded that the OBLA is inadequate for predicting MLSS (Figure 3), probably because the MLSS in this type of athlete is reached at a lower [LA].[83] This same author previously stated that, depending on the athlete (long distance runners vs firefighters) the fixed threshold of 4 mmol/l over- or under-estimates the maximum aerobic speed.[84] However, the results obtained contrast with those of Abe *et al*., who accepted the validity of the FC in the OBLA as a control of exertion intensity for training,[1] They also disagree with those of Sjödin and Jacobs (1981),[56] who closely correlated the threshold of 4 mmol/l with performance in a marathon. Contradictorily, Bentley *et al*. indicated that the OBLA is considered an index for determining performance capacity, but in their conclusions they commented that it is not valid for relating it to the power developed in a CRI of 20–90 min.[8]

The study of the correlation of the power in MLSS shows a high concordance tendency with some of the IAT calculation methods studied. Among the methods that produce a high tendency to concordance, some slightly overestimate the MLSS (Freiburg and Geiger-Hille), whilst the rest slightly underestimate it (Dickhuth-TKM, D_{max}, Dickhuth-WLA). These results coincide with those obtained by Dickhuth *et al*., who determined that IAT calculated with the Dickhuth method is a good predictor for middle distance and long distance races,[16,49,71,85] although in those studies the ergometer used was a treadmill, not a cycle.

Conclusion

The fixed threshold of 4 mmol/l or OBLA produces slightly different and higher results than those obtained with all other methods analyzed, including the direct calculation of MLSS, meaning an overestimation of training power in the IAT.

The Dickhuth-TKM, D_{max} and Dickhuth-WLa IAT calculation methods show a high concordance tendency when carried out on a cycle ergometer. The Freiburg and Geiger-Hille methods are more divergent. The Simon, Keul and Stegmann methods show a slightly lower tendency and only the Simon and Keul coincide with each other. The LM method does not coincide with any of the analyzed methods, giving results that are slightly lower, whilst the so-called Log-Log method does not present any concordance with the other studied methods either, producing a power far below that resulting from the application of the other analyzed methods.

The comparison of the results obtained from the application of different IAT calculation methods and the results obtained in the specific tests for the calculation of MLSS, when the tests are on a cycle ergometer, conclude that only three of the analyzed methods (Dickhuth-TKM, D_{max}, Dickhuth-WLa) show a high concordance with the power calculated directly to know the MLSS, with an almost equal power. A limitation of the study was the heterogeneity in exercise capacity of participants, which may be the reason for the high divergence within the limits of agreement.

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Declaration of interest

The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest in or financial conflict with the subject matter or materials discussed in the manuscript. This includes employment, consultancies, honoraria, stock ownership or options, expert testimony, grants or patents received or pending, or royalties.

References

1. Van Schuylenbergh R, Vanden Eynde B, Hespel P. Correlations between lactate and ventilatory thresholds and the maximal lactate steady state in elite cyclists. Int J Sports Med. 2004;25(6):403–408.
2. Bentley D, McNaughton L, Batterham A. Prolonged stage duration during incremental cycle exercise: effects on the lactate threshold and onset of blood lactate accumulation. Eur J Appl Physiol [Internet]. 2001 [cited 2012 May 3]; 85(3–4):351–357. Available from: http://www.springerlink.com/openurl.asp?genre=article&id=doi:10.1007/s004210100452
3. Billat VL. Use of blood lactate measurement for prediction of exercise performance and for control of training. Sport Med. 1996;22(3):157–175.
4. Impellizzeri F, Sassi A, Rodriguez-Alonso M, et al. Exercise intensity during off-road cycling competitions. Med Sci Sports Exerc. 2002;34(11):1808–1813.
5. Neumann G. Physiologische Grundlagen des Radsports. Dtsch Z Sportmed. 2000;51(5):169–175.
6. Padilla S, Mujika I, Angulo F, et al. Scientific approach to the 1-h cycling world record: a case study. J Appl Physiol. 2000;89(4):1522–1527.
7. Sjödin B, Jacobs I. Onset of blood lactate accumulation and marathon running performance. Int J Sports Med. 1981;2(1):23–26.
8. Bentley D, McNaughton LR, Thompson D, et al. Peak power output, the lactate threshold, and time trial performance in cyclists. Med Sci Sports Exerc. 2001;33(12):2077–2081.
9. Allen W, Seals D, Hurley B, et al. Lactate threshold and distance-running performance in young and older endurance athletes. J Appl Physiol. 1985;58(4):1281–1284.
10. Beneke R, Heck H, Schwarz V, et al. Maximal lactate steady state during the second decade of age. Med Sci Sports Exerc. 2011;28(12):1474–1478.
11. Beneke R, von Duvillard S. Determination of maximal lactate steady state response in selected sports events. Med Sci Sports Exerc. 1996;28(2):241–246.
12. Berg A, Jakob E, Lehemann M, et al. Aktuelle Aspekte der modernen Ergometrie. Pneumologie. 1990;44:2–13.
13. Brubaker P, Berry M, Brozena S, et al. Relationship of lactate and ventilatory thresholds in cardiac transplant patients. Med Sci Sports Exerc. 1993;25(2):191–196.
14. Hopker JG, Jobson S, Pandit JJ. Controversies in the physiological basis of the "anaerobic threshold" and their implications for clinical cardiopulmonary exercise testing. Anaesthesia [Internet]. 2011 [cited 2012 Oct 8]; 66(2):111–123. Available from: http://www.ncbi.nlm.nih.gov/pubmed/21254986
15. Sales M, Campbell C, Morais P, et al. Noninvasive method to estimate anaerobic threshold in individuals with type 2 diabetes. Diabetol Metab Syndr [Internet]. BioMed Central Ltd; 2011 [cited 2012 Oct 13]; 3(1):1. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3033241&tool=pmcentrez&rendertype=abstract
16. Thin A, Linnane S, McKone E, et al. Use of the gas exchange threshold to noninvasively determine the lactate threshold in patients with cystic fibrosis. Chest. 2002;121:1761–1770.
17. Wasserman K, McIlroy M. Detecting the threshold of anaerobic metabolism in cardiac patients during exercise. Am J Cardiol. 1964;14(6):844–852.
18. Baldari C, Guidetti L. A simple method for individual anaerobic threshold as predictor of max lactate steady state. Med Sci Sports Exerc. 2000;32(10):1798–1802.
19. Beneke R. Methodological aspects of maximal lactate steady state-implications for performance testing. Eur J Appl Physiol [Internet]. 2003 [cited 2012 Mar 12]; 89(1):95–99. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12627312
20. Beneke R. Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing. Med Sci Sports Exerc. 1995;27(6):863–867.
21. Brooks GA. Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exerc. 1985;17(1):22–31.
22. Dickhuth H-H, Huonker M, Münzel T, et al. Individual anaerobic threshold for evaluation of competitive athletes and patients with left ventricular dysfunctions. In: Bach N, Graham T, Löllgen H, editors. Advances in ergometry. Berlin: Springer Verlag; 1991. p. 173–179.
23. Mader A, Heck H. A theory of metabolic origin of the anaerobic threshold. Int J Sports Med. 1986;7(Suppl):45–65.
24. Tegtbur U, Griess M, Braumann K, et al. Eine Methode zur Ermittlung der Dauerleistungsgrenze bei Mittel- und Langstreckenläufern. In: Böning D, Braumann K, Busse M, et al., editors. Sport- Rettung oder Risiko für Gesundheit? Köln: Deutscher Ärzte-Verlag; 1989. p. 463–466.
25. Wasserman K. The anaerobic threshold : definition, physiological significance and identification. Adv Cardiol. 1986;35:1–23.
26. Bosquet L, Léger L, Legros P. Methods to determine aerobic endurance. Sports Med [Internet]. 2002;32(11):675–700. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12196030
27. Cheng B, Kuipers H, Snyder A, et al. A new approach for the determination of ventilatory and lactate threshold. Int J Sports Med. 1992;12:518–522.
28. Harnish C, Swensen T, Pate R. Methods for estimating the maximal lactate steady state in trained cyclists. Med Sci Sports Exerc. 2001;33(6):1052–1055.
29. Heck H. Laktat in der Leistungsdiagnostik. Schorndorf H, editor. 1990. ISBN: 3778076817, 9783778076811 32.
30. Heck H, Beneke R. 30 Jahre Laktatscwellen – was bleibt zu tun? Deutsche Zeitschrift für Sportmedizin. 2008;59(12):297–302.
31. Keul J, Berg A. Energiestoffwechsel und körperliche Leistung. In: Hollmann W, editor. Zentrale Themen der Sportmedizin. 3[a] ed. Berlin: Springer-Verlag; 1985. p. 196–244.
32. Kindermann W, Keul J. Anaerobe Energiebereitstellung im Hochleistungssport. Verlag Karl Hofmann Schorndorf, editor. 1977. 118 p. ISBN: 3-7780-7591-8.
33. Tegtbur U, Busse M, Braumann K. Estimation of an individual equilibrium between lactate production and catabolism during exercise. Med Sci Sports Exerc. 1993;25(5):620–627.
34. Urhausen A, Coen B, Weiler B, et al. Individual anaerobic threshold and maximum lactate steady state. Int J Sports Med [Internet]. 1993;14(3):134–1349. Available from: http://www.ncbi.nlm.nih.gov/pubmed/8509241
35. Haverty M, Kenney WL, Hodgson JL. Lactate and gas exchange responses to incremental and steady state running. Brazilian J Med Biol Res. 1988;22(2):51–54.
36. Hollmann W. 42 years ago-development of the concepts of ventilatory and lactate threshold. Sports Med [Internet]. 2001;31(5):315–320. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11347682
37. Davis J. Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exerc. 1985;17(1):6–18.

38. Coyle E, Martin W, Eshani A, et al. Blood lactate threshold in some well-trained ischemic heart disease patients. J Appl Physiol. 1983;54(1):18.23.
39. Davis H, Basset J, Hughes P, et al. Anaerobic threshold and lactate turnpoint. Eur J Appl Physiol Occup Physiol. 1983;50(3):383–392.
40. Keul J, Simon G, Berg A, et al. Bestimmung der individuellen anaeroben Schwelle zur Leistungsbewertung und Trainingsgestaltung. Dtsch Z Sportmed. 1979;30:212–218.
41. Mader A, Liesen H, Heck H. Zur Beurteilung der sportartspezifischen Ausdauerleistungsfähigkeit in Labor. Dtsch Z Sportmed. 1976;27:80–88.
42. Stegmann H, Kindermann W, Schnabel A. Lactate kinetics and individual anaerobic threshold. Int J Sports Med. 1981;2(3):160–165.
43. Segura R, Javierre C, Ventura J, et al. A new approach to the assessment of anaerobic metabolism: measurement of lactate in saliva. Br J Sports Med. 1996;30:305–309.
44. Bourgois J, Vrijens J. The Conconi Test: a controversial concept for the determination of the anaerobic threshold in young rowers. Int J Sports Med. 1998;19:553–559.
45. Conconi F, Ferrari M, Ziglio P, et al. Determination of the anaerobic threshold by a noninvasive field test in runners. J Appl Physiol. 1982;52(4):869–873.
46. Jones A, Doust J. The validity of the lactate minimun test for determination of the maximal lactate steady state. Med Sci Sports Exerc. 1998;30(8):1304–1313.
47. Kuipers H, Keizer HA, Vries TD, et al. Comparison of heart rate as a non-invasive determinant of anaerobic threshold with the lactate threshold when cycling. Eur J Appl Physiol. 1988;58(3):303–306.
48. Schmid A, Huonker M, Aramendi J, et al. Heart rate deflection compared to 4 mmol · 1−1 lactate threshold during incremental exercise and to lactate during steady-state exercise on an arm-cranking ergometer in paraplegic athletes. Eur J Appl Physiol. 1998;78(2):177–182.
49. Tokmakidis SP, Léger L. Comparison of mathematically determined blood lactate and heart rate "threshold" points and relationship with performance. Eur J Appl Physiol. 1992;64(4):309–317.
50. Vachon J, Basset D, Clarke S. Validity of the heart rate deflection point as a predictor of lactate threshold during running. J Appl Physiol. 1999;87(1):452–459.
51. Vobejda C, Fromme K, Samson W, et al. Maximal constant heart rate – a heart rate based method to estimate maximal lactate steady state in running. Int J Sports Med. 2006;27(5):368–372.
52. Borg G. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982;14(5):377–381.
53. Borg G. Borg's rating of perceived exertion and pain scales. Champaign (IL): Human Kinetics; 1998.
54. Okura T, Tanaka K. A unique method for predicting cardiorespiratory fitness using rating of preceived exertion. J Physiol Anthrpol Appl Hum Sci. 2001;20(5):255–261.
55. Seip R, Snead D, Pierce EF, et al. Perceptual responses and blood lactate concentration: effect of training state. Med Sci Sports. 1991;23(1):80–87.
56. Simões H, Hiyane W, Benford R, et al. Lactate threshold prediction by blood glucose and rating of perceived exertion in people with type 2 diabetes. Percept Mot Skills. 2010;111(2):365–378.
57. Abe D, Sakaguchi Y, Tsuchimochi H, et al. Assessment of long-distance running performance in elite male runners using onset of blood lactate accumulation. Appl Hum Sci J Physiol Anthropol. 1999;18(2):25–29.
58. Simon G, Berg A, Dickhuth H-H, et al. Bestimmung der anaeroben Schwelle in Abhängigkeit von Alter und von der Leistungsfähigkeit. Dtsch Z Sportmed. 1981;32:7–14.
59. Mujika I, Orbañanos JSH. Physiology and training of a world-champion paratriathlete. Int J Sport Physiol Perform. 2015;10(7):927–930.
60. Padilla S, Mujika I, Orbañanos J, et al. Exercise intensity during competition time trial in professional road cycling. Med Sci Sports Exerc. 2000;32(4):850–856.
61. Welde B, Evertsen F, Von Heimburg EIMJ. Energy cost of free technique and classical cross-country skiing at racing speeds. Med Sci Sports Exerc. 2003;35(5):818–825.
62. Graff K-H. Ergometrische Untersuchungen. In: Clasing D, Siegfried I, editors. Sportärztliche Untersuchung und Beratung. Spitta Verlag GmbH & Co. KG: Baden-Württemberg, 2002. p. 38–46.
63. Clasing D, Siegfried I. Sportärztliche Untersuchung und Beratung. MbH perimed F-V, editor. 2001. ISBN: 10: 3884291262 ISBN 13: 9783884291269.
64. Mejuto G, Arratibel I, Cámara J, et al. The effect of a 6-week individual anaerobic threshold based programme in a traditional rowing crew. Biol Sport. 2012;29(4):297–301.
65. Berthon P, Fellmann N. General review of maximal aerobic velocity measurement at laboratory. Preposition of a new simplified protocol for maximal aerobic velocity assessment. J Sports Med Phys Fitness. 2003;42:257–266.
66. George J, Bradshaw D, Hyde A, et al. A maximal graded exercise test to accurately predict VO_2max in 18-65-year-old adults. Meas Phys Educ Exerc Sci. 2007;11:149–160.
67. Bradshaw D, George J, Hyde A, et al. An accurate VO_2max nonexercise regression model for 18-65-year-old adults. Res Q Exerc Sport. 2005;76(4):426–432.
68. Davis H, Gass GC. Blood lactate concentrations during incremental work before and after maximum exercise. Br J Sports Med [Internet]. 1979;13(4):165–169. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1858728&tool=pmcentrez&rendertype=abstract
69. Ivy J, Withers R, Van Handel P, et al. Muscle respiratory capacity and fiber type as determinants of the lactate threshold. J Appl Physiol. 1980;48(3):523–527.
70. Coyle E, Coggan A, Hemmert M, et al. Glycogen usage and performance relative to lactate threshold. Med Sci Sports Exerc. 1984;16:120–121.
71. Dotan R. Reverse lactate threshold: a novel single-session approach to reliable high-resolution estimation of the anaerobic threshold proposed alternative. Int J Sports Physiol Perform. 2012;7:141–151.
72. Beaver WL, Wasserman K, Whipp BJ. Improved detection of lactate threshold during exercise using a log-log transformation. J Appl Physiol [Internet]. 1985;59(6):1936–1940. Available from: http://www.ncbi.nlm.nih.gov/pubmed/4077801
73. McLellan T, Jacobs I. Reliability, reproducibility and validity of the individual anaerobic threshold. Eur J Appl Physiol Occup Physiol. 1993;67(2):125–131.
74. Coen B, Urhausen A, Kindermann W. Individual anaerobic threshold: methodological aspects of its assessment in running. Int J Sports Med [Internet]. 2001;22(1):8–16. Available from: http://www.ncbi.nlm.nih.gov/pubmed/11258646
75. McLellan T, Cheung K, Jacobs I. Incremental test protocol, recovery mode and the individual anaerobic threshold. Int J Sports Med. 1991;12(2):190–195.
76. Dickhuth H-H, Wolfarth B, Hildebrand D, et al. Jahreszyklische Scwankungen der Ausdauerleistungsfähigkeit von hochtrainierten Mittelstreckenläufern. Dtsch Z Sportmed. 1988;39:346–353.
77. Machado F, De Moraes S, Peserico C, et al. The Dmax is highly related to performance in middle aged females. Int J Sports Med. 2011;32:672–676.
78. Achten J, Jeukendrup AE. Relation between plasma lactate concentration and fat oxidation rates over a wide range of exercise intensities. Int J Sports Med [Internet]. 2004;25(1):32–37. Available from: http://www.ncbi.nlm.nih.gov/pubmed/14750010
79. Czuba M, Zajac A, Cholewa J, et al. Lactate threshold (D-max method) and maximal lactate steady state in cyclists. J Hum Kinet. 2009;21:49–56.
80. Johnson M, Sharpe G, Brown P. Investigations of the lactate minimum test. Int J Sports Med. 2009;30:448–454.
81. MacIntosh B, Esau S, Svedahl K. The lactate minimum test for cycling: estimation of the maximal lactate steady state. Can J Appl Physiol. 2002;27(3):232–249.
82. Nogueira F, Pompeo F. Measurement precision of the anaerobic threshold by means of a portable calorimeter. Arq Bras Cardiol. 2010;95(3):354–363.
83. Foxdal P, Sjödin ASB. Comparison of blood lactate concentrations obtained during incremental and constant intensity exercise. Int J Sports Med. 1996;17(5):360–365.
84. Foxdal P, Sjödin B, Sjödin A, et al. The validity and accuracy of blood lactate measurements for prediction of maximal endurance running capacity: dependency of analyzed blood media in combination with different designs of the exercise test. Int J Sports Med. 1994;15(2):89–95.
85. Roecker K, Schotte O, Niess A, et al. Predicting competition performance in long-distance running by means of a treadmill test. Med Sci Sports Exerc. 1998;30:1552–1557.